# Substations Lightning Overvoltages : a Software Allowing a Statistical Approach

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*Abstract* — **Lightning transient overvoltages cause one of the most important dielectric stresses that substations have to withstand, therefore equipment have to be correctly protected. The insulation coordination (IEC 71), requires a quantitative determination of that stress in order to evaluate the risk of failure incurred by the substation.**

**The most accurate method of risk calculation needs to simulate a large number of lightning strokes, making many parameters vary : amplitude and slope of lightning intensity, location, earth resistances, ... ; this approach leads to the statistical study method.**

**But as the number of parameters grows, the total simulation time grows much faster.**

**Three statistical methods have been explored , to improve precision and reduce simulation time. Each method - random, systematical and systematical$^{++}$ - is presented and developed with an example and the help of ELIOT , a specific software allowing statistical calculations with the use of EMTP.**

**Keywords :** Insulation coordination,IEC 71, Lightning, Statistics.

## I. INTRODUCTION

Lightning, which is a phenomenon generating major electrical constraints, is responsible for two types of faults : loss of continuity of service and destruction of equipment. This document is concerned with lightning overvoltages causing the destruction of equipment.

The lightning overvoltages transmitted by the line and reaching the substation may be very high and exceed equipment dielectric withstand. Knowledge of the risk incurred is thus vital in order to accurately determine the withstand voltages to be specified.

Numerous parameters are used to study lightning overvoltages. In order to take each one into account, a "statistical" study can be performed which consists in exploring, by an appropriate method, all possible combinations that these parameters can assume.

This kind of study is both tedious as the same type of calculation has to be repeated for each case, and time consuming as the number of cases may be considerable.

Consequently, a software, ELIOT, has been developed in order to determine the parameter values, generate the relevant modelling files, run the calculation simulations by EMTP and, finally, use the results obtained.

Notwithstanding, study of all cases may be simply too time consuming if the number of parameters is great. Methods must therefore be devised to reduce the number of cases to be studied.

## II. CALCULATING THE RISK

### A. *The principle: IEC 71*

This method is based on knowledge of the probability density f(U), of the amplitudes of the overvoltage surges on the one hand, and on the other, of the insulation breakdown probability P(U).

f(U) is the curve representing the probability of appearance of each value of the voltage U between phase and earth. It is obtained using the following assumptions (IEC 71):

- peaks other than the highest one in the shape of any given overvoltages are disregarded
- the shape of the highest peak is taken to be identical to that of the standard switching impulse
- the highest overvoltage peaks are taken to be all of the same polarity, namely the most severe for the insulation

P(U) for a self-restoring insulation can be represented by a Weibull function, (fig. 1) :

$$P(U) = 1 - 0.5^{\left(1+\frac{U-U50}{0.12*U50}\right)^{4.83}} \qquad (1)$$

U : voltage applied to insulation
U50 : voltage such that P(U50) = 50%

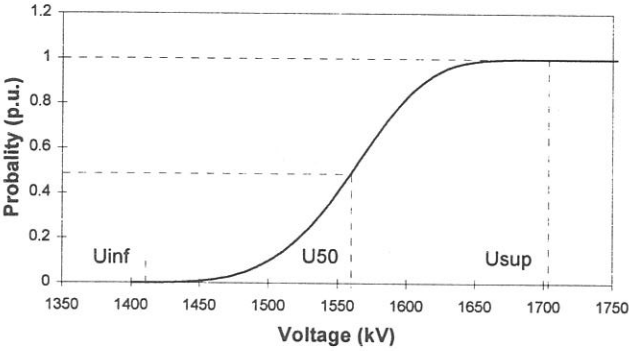

Fig. 1. Disruptive discharge of a self restoring insulation. (Weibull curve)

Two points of this function are of interest : the lower bound Uinf = 0.88 * $U_{50}$ , for which P(Uinf)=0, and the upper bound Usup, symmetrical with Uinf compared with $U_{50}$.
Usup = 1.091 * $U_{50}$ , and corresponds to a probability of 99.99%.
Based on knowledge of the overvoltage probability density and of the discharge probability, the risk of failure R can be calculated for the insulation between phase and earth:

$$R = \int_{U\inf}^{\infty} f(U) * P(U) * dU \qquad (2)$$

B. *The parameters*

A lightning study reveals three types of parameters: *lightning*, *network* and *characterisation*.
*Lightning* parameters are all the characteristic parameters of the lightning phenomenon. At least 5 parameters can be identified:

- the current of the lightning stroke (log-normal distribution, average 25 kA, standard deviation 2.5kA)[4],
- the steepness of the wave fronts (log-normal distribution, average 10kA/µs, standard deviation 3.5kA/µs)[4],
- the lightning wave shape (normally triangular or bi-exponential)
- the point of impact
- and, where applicable, the moment of application of the lightning impact with respect to network voltage.

The *network* parameters correspond to the variations in atmospheric conditions, the uncertainties on the network element values (resistances of earth connections, spark-gap impulse voltage...), and to network topology changes (switch opening or closing). They allow for the fact that the network is a "dynamic" system.
Finally, the *characterisation* parameters are used to determine the influence of a specific factor, for example the location or protection level of a surge arrester, the length of a cable, the spark-gap impulse voltage.
The number of combinations of the values for each parameter can grow very quickly, generating computer calculation times that are totally unreasonable.
The aim of the improvements made to the three methods described hereafter is to reduce calculation time and to limit the number of simulations by determining those that are really useful.

## III. THE METHODS

Each method uses the risk calculation principle such as defined in IEC 71. They differ only by the manner in which the overvoltage probability density is determined, this being the phase requiring the most calculation time.
In order to characterise these methods we have introduced the notion of significant cases, significant simulations and rates of significant cases. In actual fact, not all the simulations have the same interest and only those concluding in equipment discharge probability are significant : for example, calculation of return time based on 1000 discharges is of greater value than a calculation based on 1 discharge.
*Case* refers to all combinations of lightning, network and characterisation parameters, and *simulation* to all cases for which overvoltage on equipment has been calculated.
*Significant case* and *significant simulation* refer to all cases and all simulations where the equipment insulation discharge probability is strictly greater than zero.
*Rate of significant cases* (RSC) refers to the relationship between the number of significant cases and the number of simulations performed.

$$RSC = \frac{\text{Number of Significant Cases}}{\text{Number of Simulations}} \qquad (3)$$

A. *Random Method*

This method reproduces the natural sequence of lightning striking a line. A law and a variation range are assigned to each lightning, network and characterisation parameter.

For each simulation, the ELIOT software calculates the values assumed by each parameter in accordance with its variation law.
Once the simulations are completed, voltage classes of a specific width $\Delta U$ are defined in order to determine the number of simulations for each class. The number of failures Nd occurring during the Ns simulations can then be calculated in discrete mode :

$$Nd = \sum_{i=1}^{n} F(Ui) * P_{iso}(Ui) \tag{4}$$

| | |
|---|---|
| n | : number of overvoltage classes |
| Ui | : representative voltage of the i class |
| F(Ui) | : number of simulations resulting in a voltage belonging to i class |
| Piso(Ui) | : insulation discharge probability subjected to an i class voltage |

With knowledge of Ns, the number of simulations performed and Nl, the line lightning striking rate, the real duration T corresponding to Ns lightning strokes and the return time or average time between two faults Tr can be calculated, as well as the risk A(t) of equipment discharge during its lifetime t.

$$T = \frac{Ns}{Nl} \tag{5}$$

$$Tr = \frac{T}{Nd} \tag{6}$$

$$A(t) = 1 - e^{-t/Tr} \tag{7}$$

N.B. : A(t) is calculated on the assumption of a constant failure rate as a function of time.

This method has two main drawbacks, which are *redundancy* and *discrepancy*.
*Redundancy* is due to the fact that very similar or even identical simulations are calculated several times over. In actual fact, the random nature of natural lightning striking is modelled by choosing a parameter at random using a random number generator. However, as it is impossible to guarantee that a parameter will not take the same value in two different simulations, there is a risk of simulating the same case several times over.
The *discrepancy* between significant cases and average case is clearly shown with the example of a Normal or Log-Normal distribution such as current strength, (fig. 2).

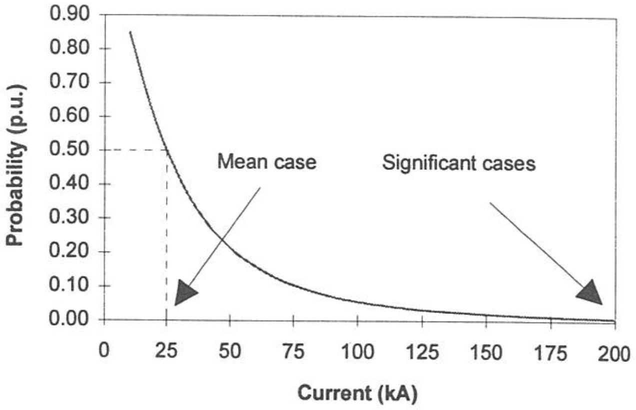

Fig. 2. Lightning strokes amplitude distribution

Thus the probability of having a current lightning stroke between 20 and 25 kA is 150 times greater than the probability of having a current lightning stroke between 200 and 205 kA. On average, 150 simulations of roughly 20 kA would be required to obtain 1 simulation of 200 kA.

However the average current of a lightning stroke is 25 kA, and the average current of the significant cases of the example dealt with in chapter IV is placed rather around 200 kA or more. We thus observe that as distribution of lightning strokes is not centred on distribution of significant cases, a large number of simulations are of no use.

### B. *Systematical Method*

This method is based on the systematic exploration of all the combinations of all parameters, thereby correcting the *redundancy fault* of the above method as each case is simulated once and once only.
Each case must be reassigned its probability of occurrence in order to obtain the overvoltage distribution. As concerns independent parameters, it is sufficient to calculate the product of probabilities of each parameter.
Thus, the probability of simulation i, of parameters I (the lightning current), d (the distance ),... of causing an insulation discharge is:

$$Pi = P_{iso}(Ui) * \prod_{x=I,d,...} P(x_{i-1} < x < x_i) \tag{8}$$

The return time can thus be calculated, with knowledge of Nl the line lightning striking rate, and Ns the number of simulations :

$$Tr = \frac{1}{Nl * \sum_{i=1}^{Ns} Pi} \qquad (9)$$

This method enables the rate of significant cases to be increased by a factor of approximately 70 (IV. B), thus saving on simulation time.
It also has the advantage of not depending on a random number generator.

N.B. : with the random method, risk calculation accuracy depends directly on the number of simulations. With the systematical method, accuracy depends on the step chosen for each parameter and thus, in the end, on the number of simulations.

### C. *Systematical*$^{++}$ *Method. (S*$^{++}$*)*

This method enables the second fault of the random method, the *discrepancy fault*, to be corrected by moving the simulation average towards the significant cases.
Study of the results of the systematical method reveals a number of factors : first, only a limited number of cases are significant (presence of a non nil risk of equipment discharge), second, in the parameter space these cases are grouped into clearly defined areas and, finally, out of the significant cases (resulting in equipment breakdown), the results of a certain number of them can be anticipated without simulation.
To simplify the problem, we shall consider a study where two parameters only will be made to vary : current (I) of the lightning stroke, and distance (d) between the point of impact and the substation (fig. 3).
This reasoning, based on plane (I,d) can be extended to N parameters by imagining as many planes (I,d) as there are combinations of (N-2) other parameters.
The overvoltage resulting from the relevant simulation is assigned to each point on the plane (I,d). The plane can then be broken down into three areas according to the voltage values : area 1 where no discharge occurs, area 2 with 100% discharge probability for each point, and area 3 for the rest of the plane (see figure 3).
Knowledge of the limit of areas 1 and 2 would make simulation unnecessary since in both cases the discharge probability can be anticipated without possibility of error (0% in area 1 and 100% in area 2).

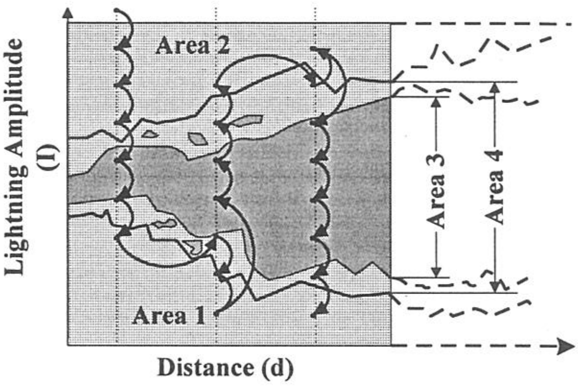

Fig. 3. Overvoltages map location

On the other hand, the points in area 3 must be calculated as in this area the discharge probability can assume any value between 0 and 100%. The overvoltages of the points in area 3 are all contained between Uinf and Usup.
Area 3 is not only made up of a single continent but also of several small islands. In order to calculate the overvoltages of all the elements in area 3, the systematical$^{++}$ method requires definition of a wider area 4, whose continent covers the entire area 3 including the islands.

Just as area 3 is defined by overvoltages Uinf and Usup, area 4 is characterised by two voltages Umin and Umax. These values must be chosen carefully to ensure they cover the whole of area 3.
Δ is defined as a parameter characterising the width of area 4, compared to area 3.

$$\Delta = \frac{U\max - U\sup}{U\sup - U50} = \frac{U\inf - U\min}{U50 - U\inf} \qquad (10)$$

In practice, a value of the order of 2 or 3 seems to be correct. Once the areas have been defined, slight adjustment around area 4 is required. For each distance, the software varies the lightning current in order to calculate all the overvoltages of all the points in area 4 and thus of all the points in area 3.
The maximum rate of significant cases is equal to :

$$RSC = \frac{Ncase(area2) + Ncase(area3)}{Ncase(area4)} \qquad (11)$$

Ncase(area i) : Number of cases in area i

A rate of significant cases greater than 1 can thus be obtained, as the cases of area 2 (all significant but not calculated) are added to the significant cases simulated in area 3.

## IV. STUDY

### A. *Assumptions*

The substation studied is of Gas Insulated type (GIS) with a very simple topology. We assume that it will not vary in time. Moreover it is supplied by a single three-phase transmission line ( fig. 4, network N°2).

For simplicity's sake and in order to limit the number of calculations, only 2 separate parameters, lightning current and distance, will be considered (in spite of their importance network voltage and lightning wave rise time have not been considered).

The nominal voltage is 500kV and the Basic Impulse Voltage of GIS and transformers is 1550kV.

Only the earth wire is struck by lightning.

Finally we are concerned only with the risk incurred by the Gas Insulated Substation.

### B. *Comparing the methods*

Tab 1. summarises the results obtained with the three methods.

| Number of Simulations | Random | Systematical | Systematical$^{++}$ |
|---|---|---|---|
| Total | 60000 | 60000 | 4125 |
| ..<Umin | 59783 | 54916 | 296 |
| Umin<..<Uinf | 141 |  | 1776 |
| Uinf<..<Usup | 34 | 1482 | 1384 |
| Usup<..<Umax | 33 | 3602 | 612 |
| ..>Umax | 7 |  | 57 |
| Number of significant cases | 74 | 5084 | 4986 |
| Rate of significant cases | 0.12% | 8.47% | 120.87% |

$U_{min}$ = 1092kV , $U_{max}$ = 2029kV, $U_{inf}$ = 1419kV et $U_{sup}$ = 1703kV .

Tab. 1. Comparison of the three methods

The Random Method enabled 74 significant cases to be calculated for 60000 simulations, i.e. a rate of significant cases of 0.12%.

With the systematical method, the rate of significant cases is far greater, reaching 5084/60000 = 8.47%, i.e. 70 times greater than the Random Method. With the same number of significant cases, the random method would have required 4.2 million simulations to be performed.

The Systematical$^{++}$ method obtains even higher rates of significant cases, reaching 120% where $\Delta = 2.3$ and even 167% where $\Delta = 1.5$, thus representing a gain of 1000 or 1400 compared with the Random Method.

|  | Systematical | Systematical$^{++}$ ($\Delta$=2.3) | Systematical$^{++}$ ($\Delta$=1.5) |
|---|---|---|---|
| Return Time (years) | 1864 | 1861 | 1852 |
| RSC | 8.47% | 120% | 167% |

Tab. 2. Return times and RSC for network N°2 configuration.

Comparison of the return times (tab. 2) shows that the S$^{++}$ method is relatively little affected by the width of area 4. A width of area 4 of 1.5 can be used without notable effect on the value of the return time (the error is roughly 1% compared with the systematical method).

### C. *Risk for the substation*

In order to illustrate the S$^{++}$ method and to show which results can be obtained, the following network has been studied.. Four study cases have been chosen to evaluate the importance of positioning surge arresters (fig. 4).

The network is first studied without a surge arrester to act as a reference (network N°1), then the surge arresters are placed in turn on the incoming gantry (network N°2), at the entrance to the gas insulated substation (network N°3) and in front of each transformer (network N°4).

The return time (1/annual failure rate) will be used to compare the four cases. It will be calculated for the entire Gas Insulated Substation (transformer not included).

Concerning the method we can notice that : as the distance between the surge arrester and the object to be protected decreases, the current of the lightning stroke must increase in order to cause insulation discharge. This phenomenon results in area 3 moving towards the top of the plane (I.d).

As the maximum current of the lightning strokes is limited (physical limit chosen = 400 kA), area 3 tends to gradually disappear from the top of the plane. The number of simulations, more or less proportional to area 3, thus decreases.

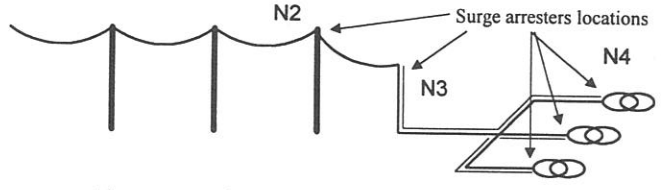

Fig. 4. Surge arresters locations

| Network N° | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Number of surge arresters | 0 | 1 | 1 | 3 |
| Surge arresters location | no surge arresters | Gantry | GIS arrival | near transformers |
| return time (years) | 1442 | 1864 | 2493 | 2347 |

Tab. 3. Return times with 4 network configurations

Tab. 3. reveals the influence of surge arresters location compared with the substation.

From a general point of view, the surge arresters must be located as close as possible to the substation : this is the notion of protective distance, highlighted by configurations N°2 and N°3 compared to configuration N°1.

They should preferably be inserted between the cause of the overvoltages (lightning impact on the line) and the object to be protected (the GIS) : configuration N°4 compared to configuration N°3.

A more accurate look at the return time values shows off that the installation of surge arresters near the gantry (network N°1 → N°2) does not increase the return time as much as the transfer of the surge arresters from the gantry to the bushings (network N°1 → N°2). This can be explain by the protective distance notion described in [2] :

$$D = \frac{Vm - Vp}{2} * \frac{v}{r} \qquad (12)$$

Vm : lightning withstand voltage : 1550kV
Vp : surge arreter residual voltage (discharge current is about 5 to 10kA) : 1000kV
v : propagation velocity : 300m/µs
r : voltage wave steepness, simulations show that for 50% of the lightning strokes r is greater or equal to 1750kV/µs
soit D : protective distance: $\frac{1550-1000}{2} * \frac{300}{1750} = 47\text{m}$

When surge arresters are located at the gantry (N°2) they are at 40m from the GIS, so only 7m of GIS are protected against overvoltages greater than 1750kV/µs. This low protected lenght explains the low increase of the return time (ΔTr = 422 ans). When the surge arresters are transfered near the bushings the gain is still greater (ΔTr = 629 ans) : this is because the longest part of the GIS (25m) is inferior to the protective distance. The above shows that if adding surge arresters is important, installing them at the right place is important too.

Configuration N°4 (probably the most efficient for the substation-transformer unit) is more expensive, as this time, 3 sets of surge arresters need to be installed.

The final decision must be made by the customer and will necessarily be a compromise between the risk he is willing to take and the investment to be made.

## V. CONCLUSION

The ELIOT software, a statistical risk calculation tool, has been developed to satisfy the new publication of the IEC 71 insulation co-ordination standard. This software consists of :

- a pre-processor for generating the parameters of the network struck by lightning,
- a modelling file generator, using a library of electrotechnical devices (circuit-breakers, busbars, towers, lines, ...),
- a specialised calculation software, EMTP, is used to perform the overvoltage calculation simulations.
- a post-processor for storing, processing and interpreting the results.

As concerns optimisation of the number of simulations, three methods - random, systematical and systematical$^{++}$ - were tested. A variable was defined to quantify the performances of these methods : the rate of significant cases (RSC) is the relationship between the number of significant cases and the number of simulations performed. In our example, the Systematical$^{++}$ method obtains a rate of 120% as against 0.12% for the Random Method, i.e. a gain of 1000 which, in concrete terms, means a reduction in simulation time or an increase in accuracy of results.

Although in this example the systematical$^{++}$ method only deals with the case of self-restoring insulations, it can also be applied to insulation that is not self-restoring.

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