Lightning Overvoltages : Statistical Study of a 550kV Substation

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Abstract — **Determination of the lightning coordination withstand voltages is a very important point of the IEC71-2. SELINCO (Schneider Electric Lightning INsulation COordination) is a software tool allowing lightning statistical calculation according to the previous standard. It includes three subroutines :**

- **LEADER computes the distribution of the lightning strokes (electro-geometrical model).**
- **ELIOT calculates overvoltages with help of EMTP-ATP.**
- **STATA determines the risk incurred by the equipment.**

The originality of the software consists of the coupling of the 3 modules, which provides an integrated tool but also allows a significant reduction of the number of simulations, because of the interaction of the three subroutines.
In this paper we just present the three subroutines and the methods we use, and then a 550kV lightning study where we want to verify the necessity of additional arresters. The study takes into account the amplitude and slope of the lightning currents, distribution of the strokes on the feeding line and presence of the power frequency

Keywords : Transient analysis, Statistics, Modelling, Lightning, Insulation coordination, EMTP.

I. INTRODUCTION

The cause of many significant overvoltages in the equipment and sometimes destroying them, lightning overvoltages could lead to long and difficult studies. Beyond the complexity of the electrical phenomena involved, the difficulty results from the great number of values taken by the parameters.
In order to take into account all these parameters, we carry out a statistical study which explores all values of all parameters.
Eliot was developed to perform this task.
Now, we add Leader and Stata to Eliot. The first determines the lightning strokes on the lines while the second calculates the risk to the equipment. All those three subroutines are gathered into SELINCO.

II. SOFTWARE PRESENTATION

A. LEADER : Lightning stroke distribution calculation

Leader is the first subroutine to be used : it allows knowledge of distribution of impacts on lines and towers.

1) *Data file* : we represent inside Leader's data file all equipment that can be hit : earth cables, wire cable, towers and gantries. Three kinds of objects are available to modele this equipment :

- bar : rectilinear object defined by the coordinates of two points and for which we can specify a needle effect.
- line : curvilinear object defined by the coordinates of two points and a sag
- ground : a collection of flat surfaces allowing a representation of the relief of the ground

It is then possible to model a line with 1 or two 3-phases systems, zero, one or two earth wires, as many spans and towers as needed and located in a valley or a mountain.

2) *Lightning impacts on the line* : the method we use is based on the electrogeometrical model. Lightning strokes are thrown from each mesh of a rectangular cloud. The amplitude of the current and the angle of the trajectory can be varied. The quantity of lightning strokes is equal to the product of the number of mesh by the number of lightning current amplitude and by the number of angles. We assume that lightning strokes follow a linear trajectory, until the associated sphere (whose radius is determined by the electrogeometrical model) hits any objects previously described. The stricken object can be a bar, a line or the ground. Three electrogeometrical models are available. For all of them the striking distance is defined by : $da=a*I^b$ (Tab.1.)

Tab.1. electrogeometrical models

Modèle	Pylône		Câble		Sol	
	a	b	a	b	a	b
Love	10<a<11	0.65	10	0.65	10	0.65
IEEE	8<a>8.8	0.65	8	0.65	8	0.65
Erikson	$0.84*h^{0.6}$	0.74	$0.67*h^{0.6}$	0.74	0	0

with h height of the tower

Estimation of the striking distance depends on the author : the choice of model will influence the results.

3) *Results* : the file produced by Leader gives the number of impacts for each object, each distance, and each current. This file can be used to determine the value of the maximum shielding failure current.
Many verifications have been made to verify the results.

4) *Qualitative verifications* : Fig.1. presents for a given line the distribution of impacts on the earth wire for different current amplitudes. We can see a no-impact area on the line near the towers. This area is due to the needle effect of the towers which protects this area.
In the middle of the span, we can see a hollow due to the sag. It is invisible for high current as the sag is small compared to the radius of the electrogeometrical sphere. It is also invisible for small currents because of the ground attraction.

5) *Quantitative validation N° 1* : Tab.2. comparison of the Leader's and EDF 's observations [3].
4 lines have been compared :
- one 400 kV line with two earth wires
- two 63 et 90 kV lines with 1 earth wire
- one 63 kV line without earth wire.

Simulations have been done with IEEE's model (a = 11) and a straight down leader.
The IEEE's model gives good results with at least one earth cable. We will choose this model for the study.

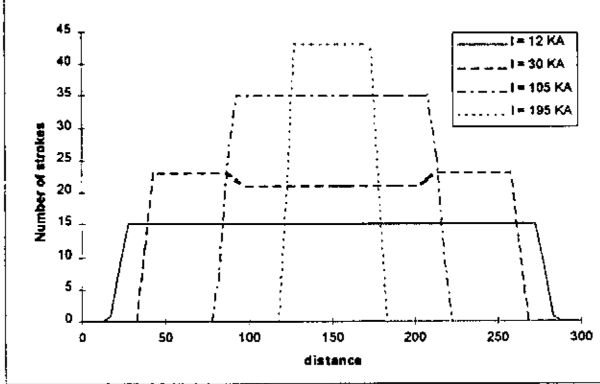

Fig.1. earth cable of lightning strokes impacts distribution

Tab. 2. Comparison observations/SELINCO

		Observations [3]	SELINCO (Leader)
63 kV	% cable	45 %	61 %
no earth wire	% bar	55 %	39 %
63 kV	% cable	65 %	67 %
1 earth wire	% bar	35 %	33 %
90 kV	% cable	65 %	68 %
1 earth wire	% bar	35 %	32 %
400 kV	% cable	80 %	78 %
2 earth wires	% bar	20 %	22 %

6) *Validation quantitative N°2* : Tab.3. comparison between Leader and EDF's equivalent software
- Love electrogeometrical's model with a=10.5
- straight down leader (angle=0).
- dimensions of the mesh of the cloud : 5m*5m.

Tab. 3. Comparison EDF/SELINCO

	EDF software	Leader software
Towers	12.7%	16.14 %
earth wire	77.5%	75 %
Phase wire 1	9.27%	8.42 %
Phase wire 2	0.5%	0.42 %
Phase wire 3	0 %	0 %
Total	87.3%	83.86 %

The same electrogeometrical model being used, this comparison allows us to compare the numerical methods. A good level of accuracy is found here.

B. ELIOT : overvoltages calculations

Eliot is both a pre-processor and a post-processor for EMTP. It is a pre-processor because it prepares the files for EMTP : from a basic file where all parameters are identified (lightning current amplitude, slope, ...), it reconstructs a correct EMTP file. Consequently the number of files constituted is equal to the combination of the parameters. It is also a post-processor because after each simulation, it stores the maximum overvoltage value.
In fact the number of reconstructed files is smaller than the number of combinations of parameters. With the help of the S^{++} method [5], not all combinations are explored, which saves time.
Many simulations are not made without changing the precision of the results. We can distinguish three kinds of configuration according to the value of the current amplitude and the position of the point of impact :
- type 1 : low current lightning stroke, far from substation
- type 2 : high current lightning stroke, close to substation
- type 3 : all other cases

When making these simulations in a precise order and knowing the results of previous ones , it is possible to determine which type configuration it belongs to.
Configurations of type 1 are not dangerous for the substation ; overvoltages are supposed to be smaller than the withstand level and the risk is zero. It is not necessary to simulate those configurations which will not contribute to the risk. Inversely, configurations of type 2 creates overvoltages greater than the withstand level and the risk is 100%. It is also not necessary to simulate those configurations because we already know the risk. All other simulations must be carried out.

C. STATA : statistical calculations

STATA makes use of Leader's results (number of impacts by object, by amplitude and by distance) and Eliot's results (overvoltage for each object, amplitude and distance).

Three results are calculated :

- D : number of fault per year
- Tr : return time (time between two consecutive faults).
- R : risk incurred

i.e . :

Ng	:	lightning flash density ($an^{-1}.km^{-2}$) supposed to be constant
dx et dy	:	mesh dimensions
P(I)	:	Probability of having a lightning current of I amplitude (log-normal distribution).
$NI_{i,d,c}$	:	Number of impacts of I amplitude, on the object c at the distance d.

The mesh dimension being constant, the surface of a mesh is dx*dy km^2. The number of lightning strokes per year and per mesh is :

$$N = dx * dy * Ng_{\text{stroke.year/mesh}} \quad (1)$$

For a given mesh these N stokes are characterized by an amplitude I and a downward angle α. We will suppose that α=0.
If we consider a lightning stroke whose amplitude is $I=I_0$ with a probability $p(I_0)$, the number of lightning stroke I_0 per year and per mesh is :

$$N(I_0) = dx * dy * Ng * p(I_0)_{\text{stroke.year/mesh}} \quad (2)$$

For each stroke simulated by Leader, the real number of strokes is $N(I_0)$. So when Leader has calculated $M_{I0,d,c}$ impacts of amplitude I_0, on the object 'c' at the distance 'd', we actually have :

$$M_{I0,d,c} * N(I_0)_{\text{impacts}}. \quad (3)$$

Furthermore for each impact calculated by Leader, Eliot computes the associated overvoltage U_0. This overvoltage has a probability $W(U_0)$ of exceeding the withstand of the insulation. The total number of faults is :

$$D=\sum M_{I0,d,c} * N(I_0) * W(U_0)_{\text{fault/year}} \quad (4)$$

$$D=dx * dy * Ng * \sum M_{I0,d,c} * W(U_0) * p(I_0)_{\text{fault/year}} \quad (5)$$

The return time (mean time between two faults) :

$$Tr=1/D_{\text{yaer}} \quad (6)$$

We can determine the risk :

$$R=1-e^{(-T/Tr)} \quad (7)$$

IV. STUDY

The following study has been carried out on a high voltage 550KV Gis Insulated Substation. This substation is fed by a one-circuit, one earth wire line. There are already some arresters after the gantry and we want to verify the necessity of additional arresters near the transformer .

A. Electrogeometrical parameters

We use Leader in order to determine the distribution of the impacts along the line.

Tab.4. Leader's parameters

electrogeometrical model	IEEE a=8 et b=0.65
downward angle	α=0. Straight down
Lightning amplitude	10-300kA, Δi=10kA
mesh of the cloud	10m x 10m

B. Electrical parameter (ELIOT - ATP)

1) Network : topology of this 550kV network is very simple (Fig.2) and we assume that it does not vary. Keraunic level is 10 (density of 1.428 /km²/an).

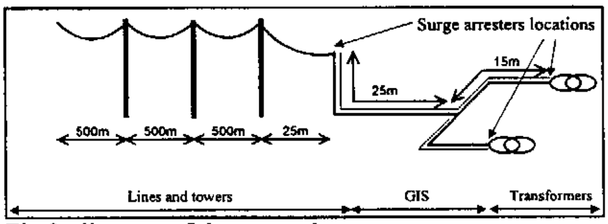

Fig.2. diagram of the network

2) Line : it is modeled at 100kHz with EMTP-ATP routine 'Line Constant'. Towers are modeled with inductances (1µH/m).
Earth impedance is represented by a resistance 5Ω for the first two towers and 20Ω for the following.

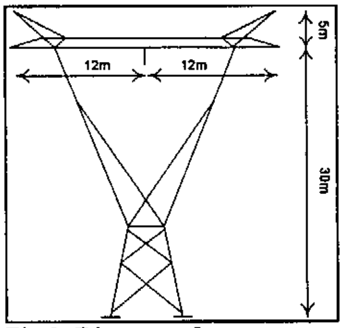

Fig.3. Diagram of a tower

Spark_gap are represented by a perfect switch controlled by its voltage-time curve (Uchoc=2100kV).

3) Surge arresters : these are Zinc Oxyde arresters, of class 5 with a rated voltage of 396kV. They are modeled with EMTP-ATP 'ZnO fitter'.

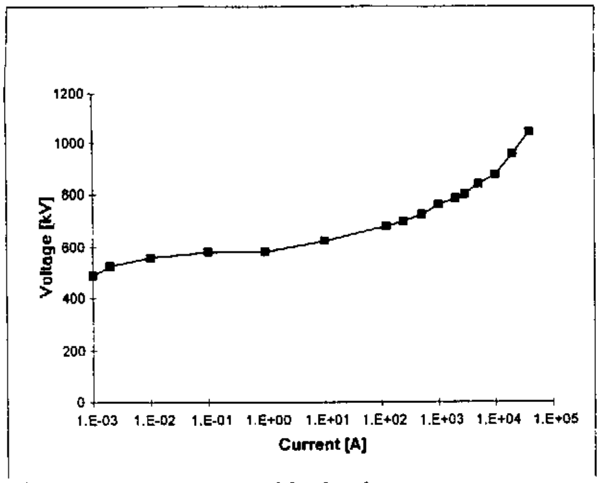

Fig.4. Surge arresters residual voltage

4) Substation : it is a single 550kV bar substation. of 396kV. It is modeled with EMTP-ATP routine 'Cable Constant'. All earth groundings are connected to a 2Ω resistance.

Tab.5. Substation characteristics

Mode	Propagation velocity [m/sec]	Characteristic impedance real imaginary SQRT(z / y) [ohm]
1	1.85E+08	2.16E+02 -1.41E+01
2	2.99E+08	7.41E+01 -5.37E-02

5) *Transformers* : we only represent their high voltage side phase-to-earth capacity (C=0.007μF). Their lightning withstand level is 1550kV.

6) The lightning stroke : it is modeled by a current source with a varying amplitude (from 10 to 300kA, ΔI=10kA). Current distribution is log-normal (M=24kA et σ=0.6kA). In order to reduce the number of simulations the slope (Sm) is a dependent of the lightning current (If) :

$$Sm = 6.5 * If^{0.376} \qquad (8)$$

7) Basic configuration (Tab.6) : unless when mentioned the following characteristics are used for all studies of influence :

Tab.6. Basic configuration

Surge arresters	near the GIS's bushings
Shape of the lightning current	triangular
Withstand level curve	Weibull

C. Power frequency voltage influence

Overvoltages on the equipment depend on
- the presence of the power frequency voltage
- the instant when the lightning stroke hit the line compared to power frequency voltage

This second point requires a variation a variation of this instant compared to the power frequency sine wave. This instant is characterized by an angle (0-360° et Δ=60°).

Tab.7. Power frequency voltage influence

Statistical study	Return time
without power frequency	3101 years
with power frequency	1139 years

Statistical results (Tab.7) reveal the importance of the parameter. The return time varies from 3101 years when it is not taking into account to 1139.
Although the number of simulation increases a lot (multiplied by 6), this parameter must be considered.

D. Current lightning shape influence

Two shapes of lightning current have been tested :
- triangular wave
- P10 wave

$$I(t) = A * \frac{\left[\frac{t+td}{tf}\right]^{10}}{1+\left[\frac{t+td}{tf}\right]^{10}} * e^{-\frac{t+td}{tq}} \qquad (9)$$

td : delay time
tf : front time
tq : tail time
A : amplitude

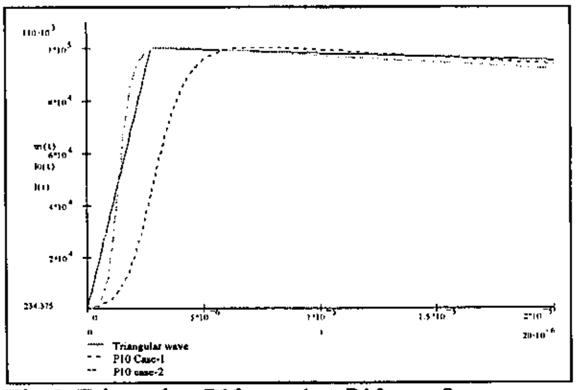

Fig.5. Triangular, P10-case1 et P10-case2 waves

For each wave the rising slope has been chosen according to (8) which gives the value of the maximum slope Sm. If the interpretation is easy with the triangular wave, it is a little more difficult with the P10 one, because of its varying slope. Sm must be the maximum slope of the wave and not the mean one. In order to verify the influence of the slope, two different P10 waves have been tested :
- P10 case 1 : P10 maximum slope = Sm
- P10 case 2 : P10 mean slope = Sm.

For a 100kA P10-case2 lightning current, the maximum slope is about 2.5 times higher than the same P10 case1 slope. This case2 shape is much more constraining, inducing higher overvoltages (U=Ldi/dt). The statistical results also reveal such a constraint : the return time varies from 911 to 209 years (Tab.8). The maximum slope is a very important parameter : case1 and case2 seem to be very close on fig.5, but results are really very different.

Tab.8. Current lightning shape influence

Shape	Return time [year]
Triangular	1139
P10-case1 Sm=max slope	911
P10-case2 Sm=mean slope	209

Furthermore when the maximum slopes are close (triangular and P10 case1) the return times are close (1139 et 911 years). The shape of the curve is not really important, and we will choose the triangular one because of its simple equations.

E. influence of the shape of probability of disruptive discharge of insulation

For a self restoring, IEC71-2 standard recommends the use of a Weibull function for the disruptive discharge probability. As there is no method at present available for the determination of the probability of disruptive discharge of non-self-restoring insulation, IEC71-2 assumes that the withstand probability changes from 0 to 100%. (Fig.6).

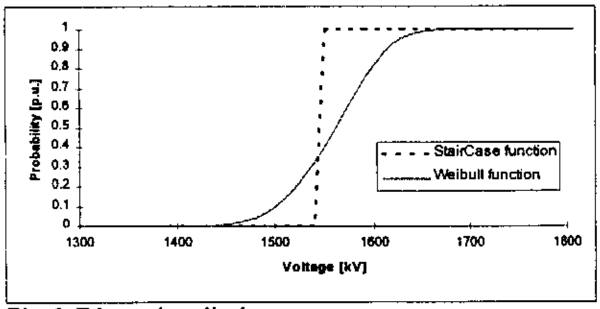

Fig.6. Disruptive discharge curves

Considering the Weibull or the staircase function, the return time is almost the same: 1139 et 1154 years (Tab.9). As the shape of the curve does not modify the results we can use any curve.

Tab.9. Disruptive discharge curve influence

Shape	Return time [year]
Weibull function	1139
staircase function "	1154

F Surge arresters position influence

Three configurations have been tested (Tab.10) :
- no surge arresters
- one set of surge arresters near the GIS's bushings
- surges arresters at the bushings and at the transformers

Tab.10. Surge arresters influence

Configurations	Return time [years]
A - no surge arresters	585
B - 1 set of surge arresters (basic configuration)	1139
C - surge arresters at the bushings and at the transformers	1370

For this network surge arresters near the transformers are not necessary because :
. the return time does not increase much (+ 231 years)
. the value with one set of surge arresters is already acceptable (>1000 years)
. the cost of additional surge arresters would have been prohibitive, because of the insulated technology dictated by the configuration.

IV. CONCLUSION

The lightning statistical tool, SELINCO has been developed to optimize substations insulation coordination according to IEC71-2 . It includes three subroutines allowing :
. calculation of the impacts along the line
. calculation of overvoltage
. calculation of the risk

The study of a 550kV substation for which we want to verify the necessity of additional surge arresters is used to study the influence of power frequency voltage, slope of lightning current, and shape of the disruptive discharge of the insulation.

It appears that :
. for this 550kV substation power frequency voltage can't be neglected. For this nominal voltage the phase to earth voltage (450kV) is close to the voltages created by the lightning current alone (some 1000kV). And their addition is directly comparable to the equipment withstand level.
. taking into account the power frequency compels us to take into account another lightning parameter : the phase angle between the power frequency voltage and the lightning stroke.
. everything else being equal, overvoltages weakly depends on the shape of the current. But they depend a lot on the maximum slope of the rising current.
. IEC71-2 stipulates two kinds of curve for the disruptive discharge insulation : a Weibull curve for self-restoring insulation and a staircase one for the others.
  For lightning calculation of return time both are equivalent : this is not a important parameter.

Finally, this substation has been studied taking into account :
- the power frequency voltage with variable angle
- the amplitude of the lightning strokes
- their maximum slope
- a triangular wave
- a Weibull function for the disruptive discharge of the insulation
- no surge arresters (case A), one set of surge arresters near the bushings (case B) additional arresters near the transformers (case C).

In these conditions return time are respectively equal to 585 , 1139 and 1370 years. Considering the low increase occurred by case C, the acceptable return time of case B and the high cost of insulated surge arresters: configuration B has been recommended.

V . REFERENCES

[1] IEC 71-2 : Insulation Co-ordination - Part 1 and Part 2

[2] B. De Metz Noblat, "La foudre et les installations électriques HT", Cahier technique N° 168, Schneider Electric, juillet 1993.

[3] Georges Leroy, Claude Gary, Bernard Hutzler, Jacques Lalot, Christian Dubanton, "Les propriétés diélectriques de l'air et les très hautes tensions", Collection de la Direction des Etudes et recherche d'Electricité de France, juillet 1984.

[4] CIGRE, Working Group 01 (Lightning) of study Committee 33 (Overvoltages and Insulation Coordination) "Guide to procedures for estimating the lightning performance of transmission lines". October 1991

[5] P. BERGIN, B. de METZ NOBLAT, "Substations Lightning Overvoltages :a Software Allowing a Statistical Approach", IPST, 1997.

[6] P. BERGIN, "550kV PHU LAM SUBSTATION : Statistical calculation of the lightning risk and tower footing resistance influence", April 1997

[7] IEEE - Working group report, *Estimating lightning performance of transmission lines II*, IEEE -Vol 8-N°3 -July 1993

[8] A.M.MOUSA - K.D.SRIVASTAVA , *Modelling of power lines in lightning incidence calculations* , IEEE , Vol 5-N°1-January 1990

[9] M.AGUET- M IANOVICI ,*Traité d'électricité, volume XXII : Haute tension* , Ecole Polytechnique Fédérale de Lausanne

[10] J.MICHAUD- R.SOLER- S.SADOVIC , Surtensions de foudre dans les postes : approches simplifiées de la nouvelle CEI comparées à une approche statistique détaillée , Electricité de France-Direction des Etudes et recherches-Novembre 1994

[11] R.SOLER- A.XEMARD , *Comparaison des moyens de réduction des défauts dus à la foudre sur les lignes HT et MT* , Electricité de France-Direction des Etudes et recherches