Estimating the expected failure rate of distribution type equipment due to lightning induced overvoltages

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Abstract— In this paper, a general probabilistic framework has been proposed for predicting the expected annual average number of failures of distribution type electrical equipment as a result of lightning induced overvoltages. Two computational approaches have been exposed and compared: a standard numerical integration method and Monte-Carlo simulation technique. The proposed approach has been illustrated through a case study aimed at comparing the lightning performance of three earthing systems.

Key words : Lightning, Induced Overvoltages, Risk of Failure.

I. INTRODUCTION

With the systematic introduction of electronic components, low voltage electrical equipment (computers, television set…) has become more sensitive to overvoltages. Protection against overvoltages, especially lightning caused overvoltages, has become therefore a major subject of preoccupation for manufacturers, electric utilities, designers of electric installations and customers.

Figure 1 shows the various lightning perturbations that can affect the proper functioning of electrical apparatuses of a consumer's installation:

(a) lightning strike on the MV line and transmission through the MV/LV transformer,
(b) direct strike on the LV line,
(c) electromagnetic coupling between the line and a lightning strike to ground nearby,
(d) direct lightning strike on the installation.

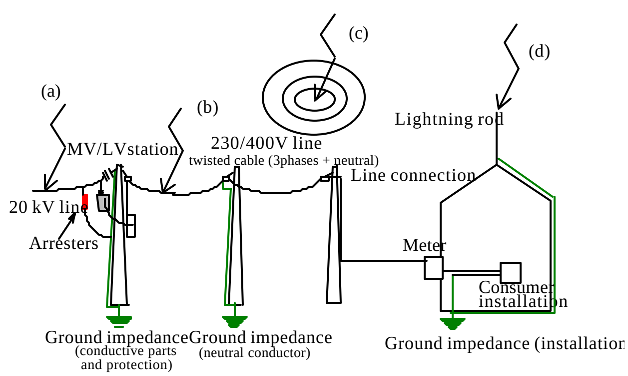

Figure 1: lightning perturbations for distribution type equipment.

For distribution type electrical apparatuses, the great majority of overvoltages causing a failure are due to indirect lightning strokes (case c). Direct lightning strokes to the line or to the installation are less frequent but generate greater stresses.

Evaluation of the expected lightning caused induced overvoltages and of their frequency of occurrence is therefore valuable for defining the most appropriate protection scheme of a low voltage installation.

In this paper, we will focus on the probabilistic aspects of the problem. The adopted method for calculating the induced overvoltages is presented briefly in order to give information on the assumptions on which rely the results of the section 'application to a case study'.

Let us precise that the aim of this work is not to discuss or analyze the different available electrical models that can be used to calculate induced overvoltages but to formalize the probabilistic aspects, for which several computational approaches are suggested. The approaches that have been already investigated by several authors are recalled.

II. INDUCED VOLTAGE CALCULATIONS

Lightning induced overvoltages are generally calculated according to the following steps:

- Calculation of the electromagnetic field radiated by the lightning return-stroke current,
- Evaluation of the induced overvoltages using a field-to-transmission line coupling model and the EMTP program.

For each step, a brief review of the models that are currently used within EDF and inplemented into a dedicated software is provided in this section. Those models are known for providing results in good agreement with existing experimental data.

A. Calculation of the electromagnetic fields radiated by the lightning return stroke current

The first step consists of calculating the electromagnetic field radiated by the lightning return stroke current. Many models have been proposed by several authors and the one implemented into EDF's software is the Transmission Line model, introduced by Uman and McLain [14]. The lightning channel is assumed to be a vertical antenna with a current flowing from the channel base to the cloud at a constant speed chosen equal to 1.10^8 m/s. The variation of the current amplitude is supposed to be given by the following double-exponential function:

$$i(0,t) = I_0 \times \left(e^{\frac{-t}{t_1}} - e^{\frac{-t}{t_2}} \right) \quad (1)$$

The current, at height z, is given by:

i(z,t)=i(0,t-z/v) z≤ vt (2)

i(z,t)=0 z>vt (3)

where z is the height of the considered point in the channel and v is the velocity of the current waveform. The channel height is assumed to be of 7 km long. The vertical and horizontal components of the electric field radiated by the current channel are then calculated by considering the channel as a set of vertical elementary dipoles and by integrating over the channel height the contribution of each dipole and image. EDF's software permits to take into consideration the finite conductivity of the ground. Those two calculated field components are required as input source terms for the adopted field-to-overhead line coupling model used for evaluating the induced voltages as explained in the next paragraph.

B. *Field-to-line coupling model*

Illumination of an overhead line by an electromagnetic field creates induced voltages that can be evaluated using a field-to-transmission line model [8, 9, 10, 11, 12, 16].

1) *Agrawal's coupling equations*

EDF's software uses the model proposed by Agrawal and al [1].

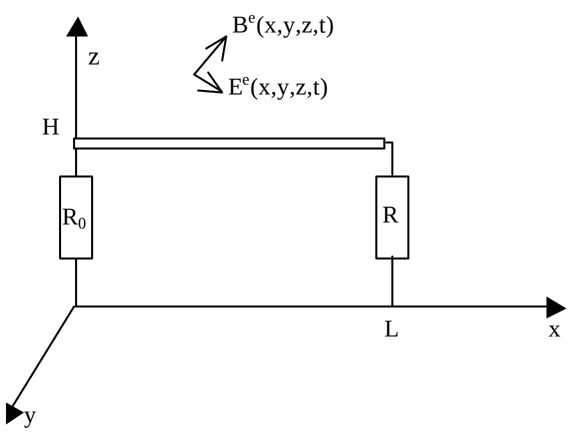

Figure 2: geometry of the problem.

The coupling equations of which for a single wire horizontal line at height height H above the ground, may be written as follows in the time domain:

$$\frac{\partial u^s(x,t)}{\partial x} + Ri(x,t) + L\frac{\partial i(x,t)}{\partial t} = E_x^e(x,H,t) \quad (4)$$

$$\frac{\partial i(x,t)}{\partial x} + Gu^s(x,t) + C\frac{\partial u^s(x,t)}{\partial t} = 0 \quad (5)$$

where R, L, G, C are respectively the line resistance, inductance, conductance and capacitance per unit length,

$E_x^e(x,H,t)$ is the horizontal component of the *exciting electric field* along the x-axis at the conductor's height H,

$u^s(x,t)$ is the so-called scattered voltage, defined by:

$$u^s(x,t) = -\int_0^H E_z^s(x,z,t)dz$$

where $E_z^s(x,z,t)$ is the vertical component of the scattered electric field.

The *exciting* electric field is the sum of the incident field radiated by the lightning stroke and of its ground reflected field, both considered in absence of overhead wire.

The *scattered electric* field represents the reaction of the overhead wire to the exciting field.

The boundary conditions for the scattered voltage are:

$$u^s(0,t) = -R_0 i(0,t) - u^e(0,t) \quad (6)$$

$$u^s(L,t) = -R_L i(L,t) - u^e(L,t) \quad (7)$$

Where $u^e(0,t)$ and $u^e(L,t)$ are the voltage sources at the two extremities of the line, obtained from the *exciting voltage* $u^e(x,t)$ given by:

$$u^e(x,t) = \int_0^h E_z^e(x,z,t)dz \quad (8)$$

The solution of equation (4) and (5) gives the scattered voltage $u^s(x,t)$ at a given point along the line, from which one can obtain the total voltage according to:

$$u(x,t) = u^s(x,t) - u^e(x,t) \quad (9)$$

2) *Implementation in EMTP [5, 12]*

The coupling between an indirect lightning strike and an overhead transmission line is taken into account in EDF's lightning induced software by adding to the network description file two localized current sources.

In a first step, the induced lightning currents at the two extremities of each line are evaluated numerically by solving the coupling equation using the FDTD method (Finite Difference Time Domain), the line being matched at both ends for suppressing the reflections.

In a second step, the calculated currents are incorporated into the EMTP file as current sources to account for the coupling between the overhead line and the incident lightning electromagnetic fields. The propagation and the reflection of the voltage and current waves are then evaluated by EMTP for the complete network in the case of the real loads. More details of this method may be found in [16].

III. EVALUATION OF THE PROBABILITY DISTRIBUTION OF LIGHTNING INDUCED OVERVOLTAGES

EDF's lightning induced software interfaced with EMTP permits to evaluate the different stresses a given indirect lightning stroke would impose to the electrical equipment of a customer's installation. To obtain an estimation of the probability distribution of the stresses, a large number of indirect lightning strokes must be simulated.

A. Formulation of the problem

Let us denote by U_p the random variable 'lightning-induced overvoltage' stressing the apparatus at location P of the distribution network, and let us characterize a lightning stroke event by the following set of influential random variables (X,Y,I,T_f) where X,Y are the coordinates of the point of impact, I the lightning crest current and T_f the time-to-crest.

Let us now denote by $h_P(.)$ the function that links the ouput random variable U_p to the input random variables (X,Y,I,T_f):

$$U_p = h_P(X,Y,I,T_f) \tag{10}$$

Finally let N_{u_0} be the annual number of lightning-induced overvoltages U_P exceeding a reference voltage value u_0.

N_{u_0} may be expressed as the product of the number N_S per year of lightning strokes terminating in a band of land neighboring the overhead distribution line, with the probability $P(U_p > u_0)$ of overvoltages U_p exceeding the reference voltage value u_0:

$$N_{u_0} = N_S P(U_p > u_0) \tag{11}$$

The number N_S of lightning strokes per year in a rectangular band of land delimited by $x_{\min}$ and $x_{\max}$ along the x-axis and by y_{min} and y_{max} along the y-axis is given by:

$$N_S = (x_{\max} - x_{\min})(y_{\max} - y_{\min})N_g \tag{12}$$

where N_g is the annual ground flash density.

Given that $U_p = h_P(X,Y,I,T_f)$, the probability $P(U_p > u_0)$ is given by the following integral:

$$P(U_p > u_0) = P\left(h_P\left(X,Y,I,T_f\right) > u_0\right)$$
$$= \int\limits_{\{h_P(x,y,i,t_f) > u_0\}} \!\!\!\int \dots \int f_{X,Y,I,T_f}(x,y,i,t_f)\,dx\,dy\,di\,dt_f \tag{13}$$

where $f_{X,Y,I,T_f}(.)$ is the joint probability density function of the set of random variables (X,Y,I,T_f).

Let us note that $P(U_p > u_0) = 1 - F_{U_p}(u_0)$ where $F_{U_p}(.)$ is the cumulative probability distribution of U_p.

The X, Y and I random variables are mutually independent and the random variables I and T_f are correlated. Therefore the joint probability density function $f_{X,Y,I,T_f}(.)$ may be expressed as follows:

$$f_{X,Y,I,T_f(x,y,i,t_f)} = f_X(x)\, f_Y(y)\, f_{T_f/I}(t_f,i)\, f_I(i) \tag{14}$$

where the probability density functions $f_X(.)$ and $f_Y(.)$ are uniformly distributed as follows:

$$f_X(x) = \begin{cases} \dfrac{1}{(x_{\max} - x_{\min})} & x_{\min} < x < x_{\max} \\ 0 & otherwise \end{cases} \tag{15}$$

$$f_Y(y) = \begin{cases} \dfrac{1}{(y_{\max} - y_{\min})} & y_{\min} < y < y_{\max} \\ 0 & otherwise \end{cases} \tag{16}$$

and the probability density functions $f_I(.)$ and $f_{T_f/I}(.)$ are lognormally distributed as follows:

$$f_I(i) = \frac{1}{\sqrt{2p}\, i\, s_I} e^{-\frac{1}{2}\left(\frac{\ln(i/m_I)}{s_I}\right)^2} \tag{17}$$

with $m_I = 33.3$ and $s_I = 0.605$

$$f_{T_f/I}(t_f,i) = \frac{1}{\sqrt{2p}\, t_f\, s_{T_f}} e^{-\frac{1}{2}\left(\frac{\ln(t_f/m_{T_f})}{s_{T_f}}\right)^2} \tag{18}$$

with $m_{T_f} = 0.154\, i^{0.624}$ and $s_{T_f} = 0.554$

B. Computational approaches

Conventional approaches based on Monte-Carlo simulation techniques

Several authors have proposed to assess the probability distribution of lightning induced overvoltages using a direct Monte-Carlo simulation technique [2, 7]. A large set of lightning strokes are randomly generated, for each of which the corresponding lightning induced overvoltages is evaluated. The probability $P(U_p > u_0)$ is then approximated by the ratio of observed overvoltages exceeding the reference voltage value u_0 over the number of simulated lightning strokes.

Limitations of such a procedure are:

A) time-consuming approach due to the evaluation of many lightning induced overvoltages,

B) some lightning strokes may be simulated several times.

To circumvent drawbacks A and B, and to speed up the overall estimation process, a variance reduction technique was investigated by [3, 13]. It consisted of grouping some randomly generated lightning strokes into some user-defined classes of 'representative lightning strokes' for which the corresponding induced overvoltages were determined. Consequently for 10^6 randomly generated lightning strokes, only 2500 EMTP simulations were conducted. However, such an approach revealed to be very sensitive to the definition of the boundaries of the different classes.

Suggested method: 'indirect method'

Based on the physical assumption that the variation of $u_p = h_p(x,y,i,t_f)$ should be smooth when one varies one of the input parameter, we suggest to estimate the rate

$N(U_p > u_0)$ of induced voltages exceeding a given value u_0 according to the following procedure:

1) ***EMTP simulation**: Lightning-induced overvoltages $u_p = h_p(x, y, i, t_f)$ are evaluated for a set of user-defined lightning strokes, selected in such a manner that all the possible cases of significantly different lightning strokes are considered. For such an attempt, each random variable is discretized with a non-uniform step. The distance between two points of impact (x,y) is taken small in the vicinity of the line and is increased as one moves away from the line. The lightning crest current is discretized from 1 to 200kA with a smaller discretization step for values in the vicinity of the median value than for values in the tail of the distribution. Also, to limit the number of EMTP simulations, the time-to-crest is fixed to its median value given the crest current as follows: $T_f = 0.154 I^{0.624}$. Let us note that for symmetry reasons, induced overvoltages are evaluated for only one side of the line.*
2) ***Numerical evaluation of the risk integral** by a classical numerical integration method or by Monte-Carlo based on the simulated results.*

Monte-Carlo:

A large set of n lightning strokes is randomly generated according to the probability density function of the each random variables X, Y and I.

Let $(x^{(1)}, y^{(1)}, i^{(1)}),..., (x^{(n)}, y^{(n)}, i^{(n)})$ be n 3-tuples defining the n randomly generated lightning strokes. The corresponding set of n lightning-induced overvoltages $u^{(1)}, u^{(2)},\ldots, u^{(n)}$ are obtained by interpolating the simulated results. The frequency distribution of lightning induced overvoltages is then approximated by the discrete distribution obtained by placing a mass equal to $1/n$ in each of the points $u^{(1)}, u^{(2)},\ldots, u^{(n)}$. Therefore the corresponding cumulative distribution function, that we may denote by $F_n(u)$, is a staircase function. If we denote by l the number of sample values that are less or equal to u, we have:

$$F_n(u) = \frac{l}{n} \tag{19}$$

The cumulative distribution function $F_{U_p}(.)$ of induced overvoltages may then approximated by the cumulative distribution function $F_n(u)$:

$$F_{U_p}(u) \cong F_n(u) \tag{20}$$

The annual frequency N_{u_0} of lightning-induced voltages U_p exceeding a reference voltage value u_0 is then given by:

$$N_{u_0} = N_s \left[1 - F_{U_p}(u_0)\right] \tag{21}$$

Numerical integration :

According to equations 11 and 13, we have:

$$N_{u_0} = N_g (x_{\max} - x_{\min})(y_{\max} - y_{\min}) \iiint_{h(x,y,i)>u_0} f_X(x) f_Y(y) f_I(i) dxdyd \tag{22}$$

Given that $f_X(x) = 1/(x_{\max} - x_{\min})$ and that $f_Y(y) = 1/(y_{\max} - y_{\min})$, equation 22 becomes:

$$N_{u_0} = N_g \iiint_{h(x,y,i)>u_0} f_I(i) dxdydi \tag{23}$$

which can be written as follows:

$$N_{u_0} = N_g \int_0^{\infty} S(i, u_0) f_I(i) di \tag{24}$$

where

$$S(i, u_0) = \iint_{h(x,y,i)>u_0} dxdy \tag{25}$$

$S(i, u_0)$ is the surface over which lightning strokes of current amplitude $I = i$ would induce an overvoltage at the customer's installation greater than u_0. An illustration is provided in the example section (Figure 8).

The function $u = h(x, y, i)$ is numerically described by interpolating the EMTP simulation results and integral 24 is evaluated using the classical trapezoidal integration technique for which a discretization step of 1kA is considered for the lightning crest current.

IV. Application to a Case Study

A. *Case study description*

It is proposed herein to evaluate the lightning induced overvoltages incoming to a customer's installation and their annual frequency of occurrence. The lightning induced overvoltages are collected by a 470m long overhead line (400V). The customer's installation consists of four conductors, one of which being connected to a load. Lightning induced overvoltages are observed at one of the open ends (Figure 3 and Figure 4).

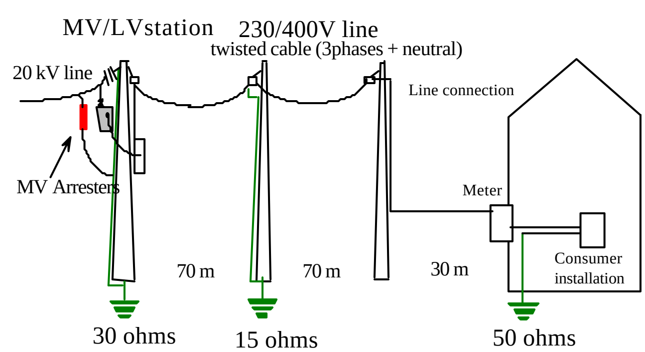

Figure 3: case study

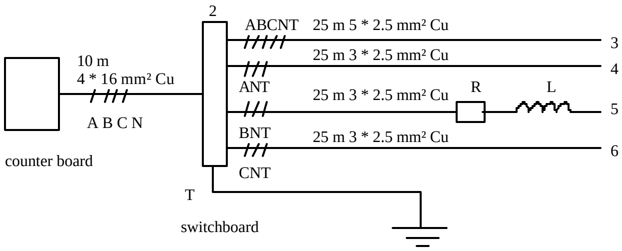

Figure 4: customer's installation

B. Simulation of the lightning induced overvoltages

The simulated lightning strokes are spread around the line according to the black dots depicted in Figure 5, with a finer mesh in the vicinity of the line. For reason of symmetry, lightning strokes are simulated for just one side of the distribution overhead line. The simulated current amplitudes are 20, 30, 50, 100, 150, and 200kA.

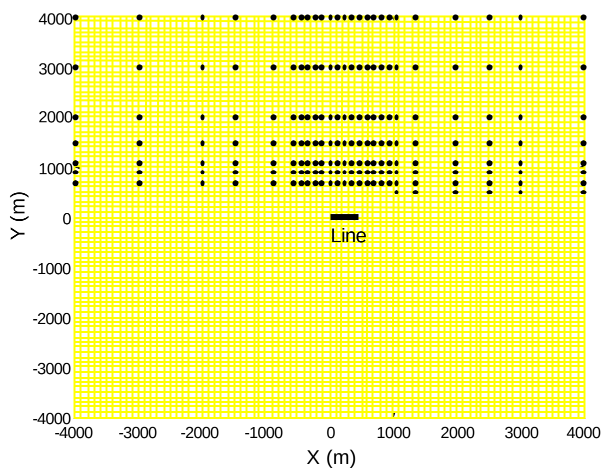

Figure 5: meshgrids of the simulated points (black dots)

For each crest current value, we obtain some three dimensional surfaces representing the induced overvoltages as a function of the lightning stroke point of impact. (Figure 6). The surfaces which correspond to values of current that have not been simulated are obtained by a linear interpolation of the different simulated surfaces.

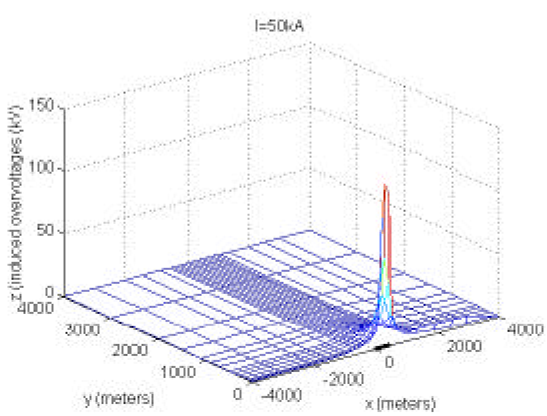

Figure 6 : induced overvoltages as a function of the lightning stroke point of impact for a given crest current.

C. Estimation of the probability distribution

Based on the simulated results, the frequency of occurrence (per year) of lightning induced overvoltages exceeding a reference voltage value u_0 has been estimated using the two methods described previously:

a crude Monte-Carlo method for which 10^6 lightning strokes have been randomly generated. For each indirect lightning stroke, the corresponding induced overvoltage is evaluated by interpolating the simulated results.

a conventional integration technique.

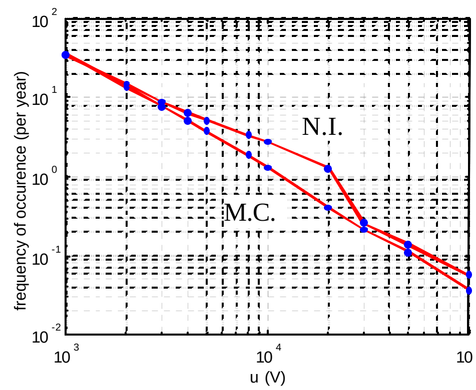

Figure 7: annual frequency of occurrence of induced overvoltages as estimated by numerical integration (N.I.) and by a crude Monte-Carlo method (M.C.).

We can see that the estimation given by the two methods does not differ significantly.

The main advantage of the Monte-Carlo approach is its ease of implementation, whereas the numerical integration approach offers intermediate results of interest such as the surfaces over which lightning strokes of a specific current amplitude would cause damages to the customer's installation (Figure 8).

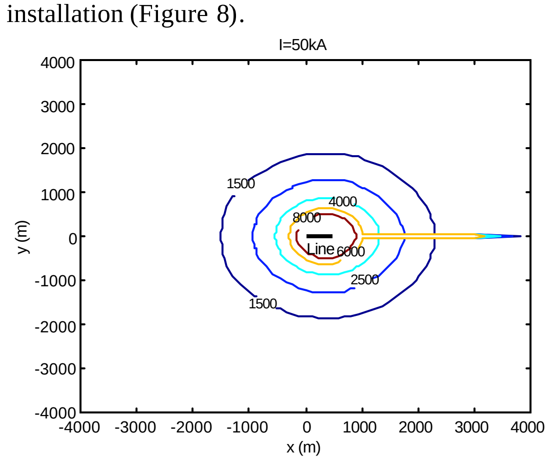

Figure 8 : surface overwhich lightning strokes of peak amplitude 50kA would result in induced overvoltages greater than 1.5, 2.5, 4, 6 and 8kV.

The results of this estimation show that the annual frequency of occurrence of lightning induced overvoltages would be, for this configuration, between 2 to 10 per year, according to the lightning withstand voltage of the customer's equipments (commonly between 1.5kV to 8kV).

This high figure may be explained by the long section of the overhead distribution line (470m) and by the high value of assumed ground flash density ($N_g = 2.5$).

Table 1 : surface $S(i,u_0)$ in square kilometer overwhich lightning strokes of peak amplitude i would result in induced overvoltages greater than u_0.

		Reference voltage u_0 (V)				
		1500	2500	4000	6000	8000
Lightning current (kA)	20	2.05	0.84	0.36	0.17	0.11
	30	4.92	2.48	1.30	0.78	0.56
	50	11.19	5.43	2.68	1.44	0.81

D. Comparison of the probability distribution of induced overvoltages for the three configurations of earthing systems

We have applied the above procedure in order to compare the three following configurations:
TT earthing system (conventional configuration in France),
TN earthing system,
Configuration 1 with four surge arresters installed to the switchboard of the installation (one for each phase, and one for the neutral wire).

Figure 9 depicts the frequency of occurrence (per year) of lightning induced overvoltages exceeding a specific value for the three configurations. The ground flash density is taken equal to 2.5 flashes per square kilometer.

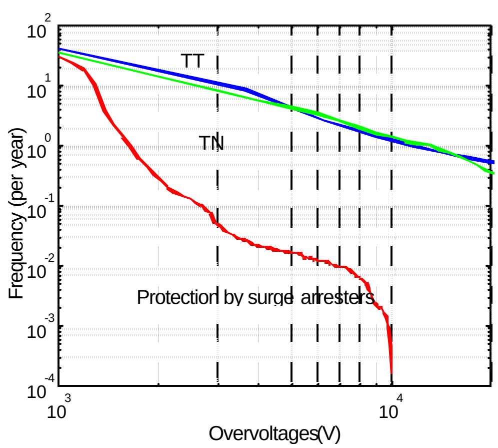

Figure 9 : estimated annual frequency of lightning induced overvoltages exceeding a specific value.

One can observe in Figure 9 that the performance of the two earthing systems (the difference between TN and TT systems is that in the first one the consumer's neutral is connected to the consumer's earth) is equivalent with regard to lightning induced overvoltages. It also shows the significant improvement obtained by applying surge arresters.

V. Conclusion

In this paper, the problem of estimating the annual frequency distribution of lightning induced overvoltages has been formalized, for which a general procedure has been proposed. It consists of the following two steps:

1) Lightning induced overvoltages are first evaluated for a set of user-defined lightning strokes, selected in such a manner that all the possible cases of significantly different lightning strokes are considered. Induced overvoltages corresponding to lightning strokes that have not been simulated may then be obtained by interpolating the simulated results. This approximation is made thanks to the physical assumption that the variation of induced overvoltages should be smooth when one varies one of the input parameter.
2) Based on those simulated and interpolated results, and considering both the probability distributions of each basic input random variable and the ground flash density, the annual frequency distribution of lightning induced overvoltages is then evaluated using Monte-Carlo or a classical numerical integration technique.

The main advantage of such an approach, compared to a more classical direct application of Monte-Carlo, is that it is less time-consuming (based on our experience the total simulation time may be reduced by more than 4 times) and it can provide additional information such as the surface over which lightning strokes of a given current amplitude would induce overvoltages greater than a specific voltage value.

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BIOGRAPHIES

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