Application of Line Surge Arresters in Power Distribution and Transmission Systems

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On the Mitigation Effect of Surge Arresters on the Lightning Performance of Overhead Distribution Lines

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SUMMARY

For the accurate statistical assessment of the lightning performance of distribution lines one needs to take into account the presence of protection devices such as surge arresters and shielding wire/neutral groundings. Indeed, the presence of those devices can significantly modify the indirect lightning response of the overhead line and, therefore, the relevant lightning performance.
In particular, this paper aims at investigating the impact of the presence of surge arresters on the indirect lightning performance of overhead distribution lines having realistic configuration. Specifically, reference is made to typical Italian distribution lines. The investigation is performed with the help of a statistical procedure developed by the authors – based on the Monte Carlo method and of the use of an accurate modelling/calculation tool for the induced surges – that has been recently compared with one proposed in the IEEE 1410 Std for the same purpose, and shown to be more complete and suitable for the problem of interest. The paper also aims at investigating the influence of the presence of surge arresters on the indirect lightning surges transferred through power transformers. Such an additional investigation is performed by means of a suitable high-frequency power transformer mode integrated with the lightning-induced computation tool.

KEYWORDS

Lightning statistics, induced overvoltages, lightning performance of distribution lines, surge arresters, shielding wires groundings, Monte Carlo method.

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1. INTRODUCTION

The insulation coordination of overhead distribution systems needs the taking into account of the statistical distribution of the surges originated by indirect lightning [1,2]. This is generally denoted with the term indirect-lightning performance of the line. The indirect-lightning performance has a significant impact on the choice of the insulation levels of the network components as well as on the design of the protection system, essentially composed by grounded conductors and/or surge arresters [3].

The evaluation of the indirect lightning performance of overhead distribution lines has been the object of several studies and is nowadays included in international standards. The IEEE Std. 1410 [1], for instance, recommends a procedure based on a statistical approach different from the Monte Carlo method, and on the use of the Rusck simplified formula for the calculation of the induced surges [4]. Such a kind of simplified approaches appears to be inadequate, in general, to properly reproduce the line response against lightning electromagnetic pulses (LEMPs) [5]: it may result insufficient in case of overhead lines above a ground of finite conductivity, in presence of multi-conductor lines, when the line length is finite, when the line is equipped with protection devices like surge arresters and/or grounded wires and when power distribution transformers are connected to it. The inherent complexity of the problem calls therefore for the adoption of more accurate field-to-transmission-line coupling models (e.g. [6]) and the use of adequate treatment of the boundary conditions for the analysis of complex line/systems configurations (e.g. [7,8]).

The approach adopted in this paper is the following: a) calculation of the indirect lightning surges by using the LIOV (Lightning Induced Overvoltage) code [9] suitably linked with the EMTP (ElectroMagnetic Transient Program) [10-14], b) estimation of the indirect lightning performance of the overhead distribution line by means of the integration of the above mentioned approach with the Monte Carlo method [5,15].

The paper also presents the assessment of the influence of the surge arresters on the indirect lightning surges transferred through distribution transformers. Such an assessment has been performed by using a suitably representation of such power components by using the high frequency model proposed in [16,17].

The paper is structured as follows: Section II presents the application of the above mentioned statistical approach to the case of a typical Italian overhead distribution line for evaluating the influence of the presence of surge arresters on the indirect lightning performance of overhead distribution line. Section III briefly describes the high frequency transformer model adopted for the statistical evaluation of the influence of surge arresters on the transformer-transferred indirect lightning surges. Section IV concludes the paper with final remarks and indications of further research needs.

2. USE OF THE STATISTICAL PROCEDURE FOR THE EVALUATION OF THE INFLUENCE OF SURGE ARRESTERS ON THE LIGHTNING PERFORMANCE OF DISTRIBUTION LINES

2.1 Statistical procedure

The statistical procedure adopted in this paper is described in detail in [5,15]. It is based on the integrated use of the Monte Carlo method and of the LIOV / LIOV-EMTP codes. In detail, the procedure is composed by the following steps:

a. A large number of lightning events n_{tot} is randomly generated. Each event is characterized by four parameters: lightning current amplitude I, time to peak t_f and stroke location P with coordinates x and y. The first two values, namely I and t_f, characterize the lightning current waveform at the channel base[1] and are assumed to follow the Cigré log-normal probability distributions for negative first strokes [18,19], with a correlation coefficient between t_f and I equal to 0.47 [18]. The stroke locations are assumed to be uniformly distributed in a so-called

[1] The lightning return-stroke current waveform is assumed to have a ramp to flat-top shape, i.e. a linear ramp until the peak value I is reached at time t_f, then followed by a constant value. Although more accurate lightning waveforms have been proposed, it is here assumed that they produce induced-voltage amplitudes close to those estimated by using the adopted waveform, provided they exhibit the same amplitudes and same average steepness between the 30% and 90% amplitude intercepts.

indirect striking area around the network beyond which it is assumed that no lightning event could cause a flash on the lines.

b. From the total set of n_{tot} events, the $n_{tot,ind}$ indirect lightning events are selected by adopting a lightning incidence model for the line. The results reported in this paper have been obtained by using the electrogeometric lightning incidence model (EGM) adopted also by IEEE Std. 1410 [1], namely the event i is considered a direct lightning if its stroke location distance from the nearest line conductor is lower than $y_{min,i}$ defined as

$$\begin{aligned} y_{\min,i} &= \sqrt{r_{s,i}^2 - \left(r_{g,i} - h\right)^2} && \text{for } h < r_{g,i} \\ y_{\min,i} &= r_{s,i} && \text{for } h \geq r_{g,i} \end{aligned} \tag{1}$$

where h is the line conductor height, $r_{s,i}$ is the striking distance to the line conductor (assumed as $r_{s,i} = 10 \cdot I_i^{0.65}$) and $r_{g,i}$ is the striking distance to ground (assumed as $r_{g,i} = 0.9 \cdot r_{s,i}$).

c. For each of the $n_{tot,ind}$ indirect-lightning events, the maximum induced voltage value along the line is calculated by means of the LIOV code.

d. The annual number of events that induce voltages greater than the insulation level is obtained from the following expression

$$F_p = \frac{n}{n_{tot,ind}} \cdot \frac{L}{100} \cdot N_g \cdot A \tag{2}$$

where n is the number of events generating induced voltages larger than the considered insulation level, L is the line length and N_g is the annual lightning ground flash density (in fl/(km2·yr)). In order to infer the annual number of flashovers due to indirect lightning, the voltage-time characteristic of the insulator chain [1] should be taken into account. In this study we have deliberately disregarded this aspect and the lightning performance of the distribution lines are expressed in terms of annual number of events per 100 km exceeding the voltage value reported in abscissa.

2.2 Results

The results shown in this paper refer to the typical three-phase Italian distribution line geometry shown in Fig. 1. The line response has been analyzed above both an ideal and a finitely conducti ground (σ_g=0.001 S/m). The line length is chosen equal to 1.8 km for the ideal ground case and 0.9 km for the lossy ground case. The 'striking areas' around the line are equal to 7.6 km^2 (corresponding to a band of 1 km around the line) and 19.6 km^2 (corresponding to a band of 2 km around the line), for the ideal and lossy ground case respectively. The chosen line lengths are assumed to be representative also of longer lines as the LEMP effect becomes negligible beyond about 2 km from the stroke location [9]. The simulations are carried out to evaluate surge arresters and effects; a sensitivity analysis is then performed by varying the spacing between adjacent surge arrester stations.

Two different rated voltages have been considered for the surge arresters, namely 10 kV and 20 kV, which refers to the Italian situation. According to the indications reported in [20], the surge arresters are modeled using the *V-I* nonlinear characteristics obtained by means of standard 1.2/50 µs pulse tests (see Fig. 2).

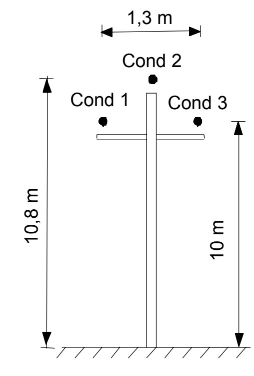

Fig. 1. Conductor geometry of the analysed overhead distribution line.

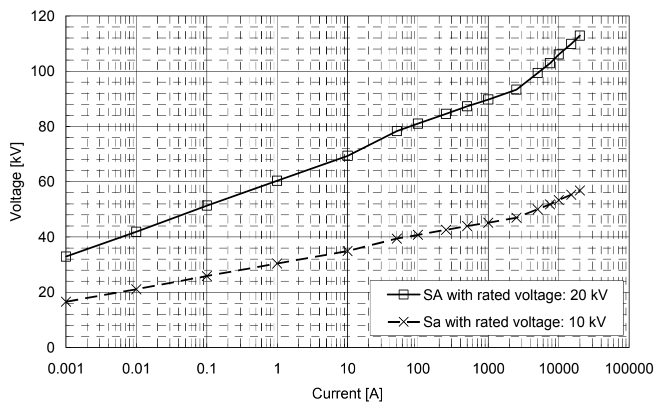

Fig. 2. V-I non-linear characteristics of the surge arresters used in the simulations.

The assumed surge arresters spacing are: 1800 m, 900 m, 600 m, 300 and 150 m, for the case of ideal ground (see Fig. 3a), and 900 m, 300 m and 150 m for the case of lossy ground (see Fig. 3b). At both ends of the overhead line the surge arresters are connected in parallel with the conductor's self-surge impedances. The surge arresters connect the phase conductors and the grounding point, whose footing resistance is assumed negligible, as calculation results show that only very high grounding resistances affect in significant way the distribution of the induced voltage along the line.

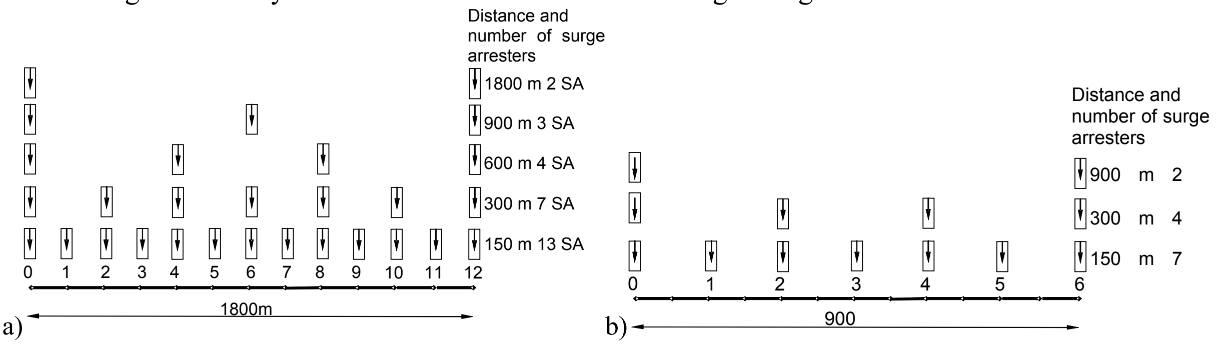

Fig. 3. Location of surge arresters stations along the lines: a) ideal ground case; b) 0.001 S/m conductive ground case.

Figs. 4 and 5 show the results of the statistical analysis with different surge arresters number and spacing (the case 'no surge arresters' is included). All the results refer to the center conductor of the three-phase line because that conductor is the one experiencing the largest induced voltages amplitudes, due to its highest location [9]. Fig. 4 refers to the ideal ground case and to the arrester spacing of Fig. 3a. Fig. 5 refers to the lossy ground (σ_g=0.001 S/m) and to the arrester spacing of Fig. 3b. Figs. 4a) and Figs 5a) refer to surge arrester rated voltage equal to 10 kV; Figs. 4b) and Figs 5b) refer to 20 kV.

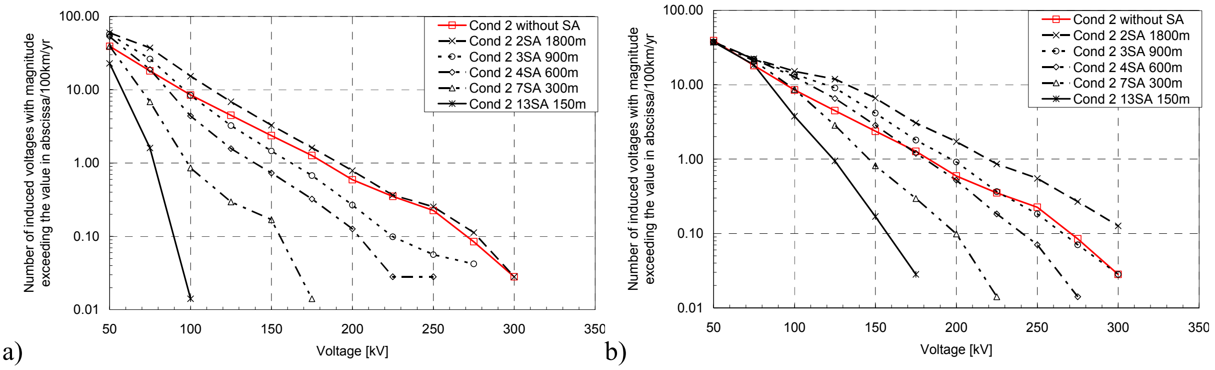

Fig. 4. Effects of the surge arresters spacing on the indirect-lightning performance of the overhead line above an ideal ground: a) surge arresters with rated voltage of 10 kV; b) surge arresters with rated voltage of 20 kV.

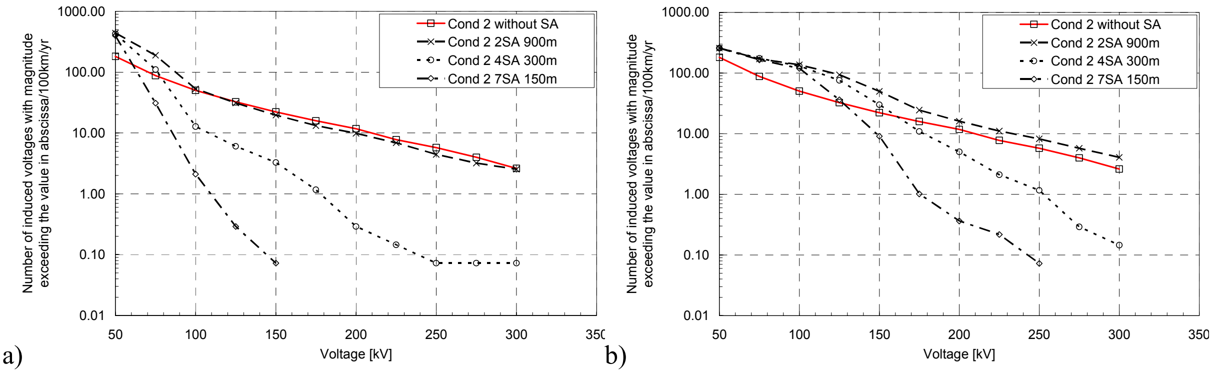

Fig. 5. Effects of the surge arresters spacing on the indirect-lightning performance of the overhead line above a 0.001 S/m conductivity ground: a) surge arrester having rated voltage of 10 kV; b) surge arrester having rated voltage of 20 kV.

The obtained results show that for some line configurations, namely for surge arrester spacing larger than 600 m, the presence of these protection devices result in a decrease of the lightning performance of the line, for both ideal and lossy ground.
According to the findings of [5,9,21], this is due to the surge reflections occurring in correspondence of surge arrester operations, particularly important for the large spacing. Depending on the line configuration, on the stroke location and on the distance between two consecutive surge arresters, the reflected voltage wave generated by the non-linear components can produce the maximum amplitude of the induced voltage at a point different from the one closest to the stroke location. For the considered line, lightning performance due to lightning-induced voltages can be significantly improved by choosing surge arresters spacing in the range between 150-300 m. As expected, with the decrease of the value of surge arrester rated voltages, the results of Figs. 4a and 5a show an improvement of the lightning performance even for larger arrester stations spacing (600 m for the ideal ground case and 300 m for the lossy ground case).

3. STATISTICAL ASSESSMENT OF TRANSFERRED INDIRECT SURGES THOUGHT POWER DISTRIBUTION TRANSFORMERS

The presence of an accurate high frequency power transformer model can be taken into account into the LIOV code by means of a suitable formulation of the boundary condition of the LEMP-coupled line in which the transformer is connected. Another possible solution to implement the transformer model is to take advantage of the Nodal Analysis Technique adopted in EMTP-like programs model within an EMTP-based simulation environment properly linked with the LIOV code. This second solution, illustrated in [7,8], is the one adopted in this paper.

3.1 Adopted high frequency transformer model

The overvoltages surges due to lightning propagates through a transformer by capacitive and magnetic coupling. As known, the simplest high frequency transformer model consists of a lumped π-capacitance circuit. Such a model is aimed at representing the capacitive coupling between the transformer windings and appears to be adequate as far as the grounding of the neutral termination of one or both transformer windings may be disregarded [22]. In [17] the π-capacitance model has been compared with the frequency dependent (FD) admittance matrix model proposed by Morched *et al.* in [16] by means of measurements on the same 100 kVA distribution transformer. The results of [17] show that the models provide the same results in case the reflected surges at the ungrounded side of the transformer or the transferred surges from the grounded transformer side to the ungrounded side are of interest. Additionally, in case transferred overvoltages from the medium voltage (MV) to the low voltage (LV) side are concerned – with the LV neutral grounded at, or in the proximity of, the transformer tank – an accurate high-frequency transformer model is needed [17]. For this reason the Morched *et al*. transformer model has been adopted in this paper.
The availability of the calculation of the induced overvoltages within the EMTP environment (LIOV-EMTP code [7,8]) allows for the implementation of the high frequency transformer model by using: i) the space state representation or ii) the Morched *et al.* model representation by means of frequency dependent (FD) branches. The latter model, that is the one adopted in this paper, is an equivalent network whose nodal admittance matrix reproduces the transformer one over a given range of frequencies. The equivalent network is a multi terminal π circuit (see Fig. 6a), in which each admittance $y_{ij,\pi}$ is implemented by means of FD branches in parallel containing lumped resistances, inductances and capacitances (see Fig. 6b).

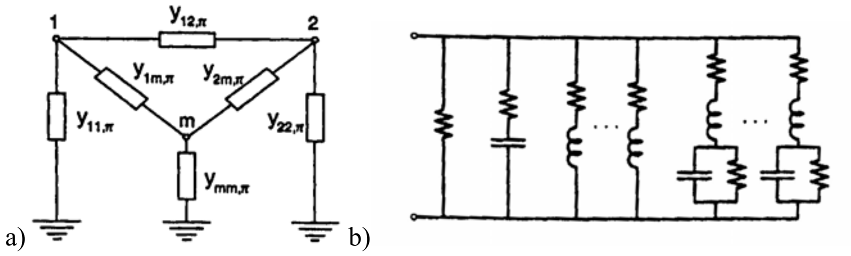

Fig. 1. A) Multi-terminal π-equivalent network; b) FD branches. Adapted from [16].

The adopted high frequency transformer model makes reference to a 100 kVA 15/0.4 kV three-phase Δ/y_g transformer and has been identified by means of laboratory measurements in the frequency range from 1 kHz to 1 MHz. The admittance matrix elements Y_{ij} are related to the multi terminal π equivalent branch admittances $y_{ij,\pi}$ by the well known relationships

$$y_{ij,\pi} = -Y_{ij}$$
$$y_{ii,\pi} = \sum_{j=1}^{n} Y_{ij} \quad (3)$$

where n is the order of the admittance matrix, i.e. the number of transformer terminals.
The following rational approximation of the multi-terminal π equivalent model has been obtained using "vector fitting" [23], and relationships (3) [17]:

$$f(s) = \sum_{n=1}^{20} \frac{c_n}{s - a_n} + d + s \cdot e \quad (4)$$

Once obtained a rational approximation fulfilling the criterions for the time-domain stability (5), the FD branches parameters have been calculated in order to match the admittance of each branch with a partial fraction (or a couple of partial fractions in case of complex conjugated poles) of the relevant $y_{ij,\pi}$ transfer function.

$$\begin{aligned} &\mathrm{Re}(a_n) > 0; \\ &eig[(\mathrm{Re}(Y))] > 0; \\ &eig[E] > 0; \end{aligned} \quad (5)$$

3.2 Results
The results reported in this section make reference to the statistical distribution of the indirect lightning induced surges in correspondence of the low voltage side of the assumed transformer model. Therefore, they are expressed as the annual number of events that induce voltages greater than the value reported in abscissa and are calculated by using the following expression (with the same meaning of variables adopted in (2)):

$$F_p = \frac{n}{n_{tot,ind}} \cdot N_g \cdot A \quad (3)$$

The system configuration adopted for the simulation is reported in Fig. 7. We have considered a 2 km long line matched in correspondence of the left-hand line termination and with a power distribution transformer connected to the right-hand line termination. The power transformer is protected, on the medium voltage side, by means of a surge arrester station which V-I characteristic is the 20 kV one of Fig .2. The conductors line geometry is same adopted for the other cases reported in this paper (see Fig. 1).

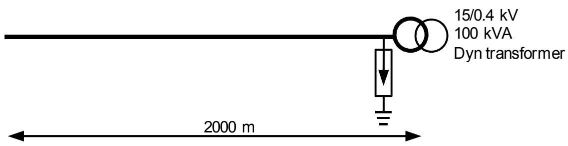

Fig. 7. Simulation geometry adopted for the assessment of the effects of surge arresters on the indirect-lightning surges transferred through the power transformer (LV side).

In order to estimate the effects of the surge arresters placed on the MV side of the distribution transformer, Fig. 8 reports the comparison between the statistical distributions of the maximum amplitudes of the lightning surges in correspondence of the LV side of the transformer with and without the presence of the surge arresters.

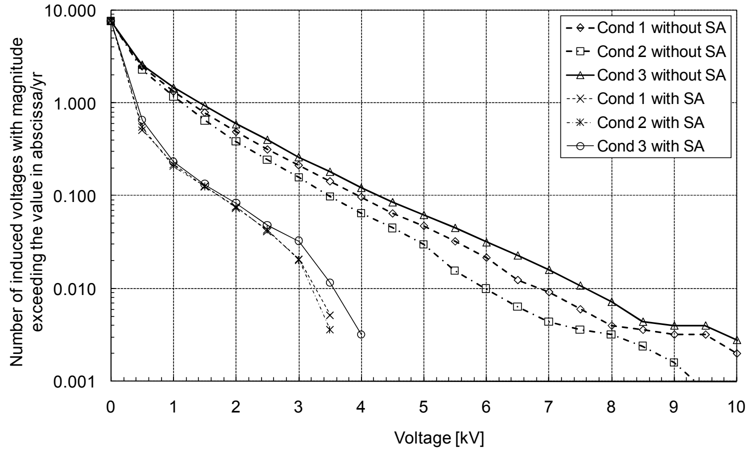

Fig. 8. Effects of the surge arresters on the indirect-lightning surges transferred on the through the power transformer (LV side); system configuration of Fig. 7.

The results of Fig. 8 show that an important reduction of the lightning surges in correspondence of the transformer LV side can be obtained by using surge arresters placed on the transformer MV side. In particular, such a reduction can be estimated, as function of the considered overvoltage amplitude, in the range of one or two order of magnitude.

4. CONCLUSIONS

The paper has presented a statistical analysis to estimate the influence of the presence of surge arresters on the lightning performance of distribution lines and on the indirect lightning surges transferred through distribution transformer.
The statistical procedure, based on a Monte Carlo method presented in previous works, has been applied to analyzed the influence of the surge arrester V-I characteristics and of their spacing on the lightning performance of a typical Italian overhead distribution line. The results show that, a significant improvement of the lightning performance of the considered distribution line can be obtained only with arrester stations spacing lower than 300 m.
The statistical procedure has been applied to estimate effects of the surge arresters placed on the MV side of distribution transformers on the transferred lightning surges on the LV side. The obtained results show that an important reduction can be obtained and that, for the analyzed case, it is in the range of one or two order of magnitude. Further studies are needed to confirm such a result by extending the analysis carried out to the case of more complex cases, which take into account the presence of LEMP-coupled overhead low voltage lines.

BIBLIOGRAPHY

[1] IEEE Working Group on the lightning performance of distribution lines, “Guide for improving the lightning performance of electric power overhead distribution lines”, IEEE Std 1410, 2004.

[2] Joint Cigré-Cired WG C4.4.02, “Protection of MV and LV networks against lightning. Part I: common topics”, Cigré technical brochure, Nr. 287, February 2006.

[3] A. R. Hileman, “Insulation coordination for power systems”, Marcel Dekker Inc., New York– Basel, 1999.

[4] S. Rusk, “Protection of distribution systems”, Lightning, Vol. 2, Ed. R.H. Golde, New York: Academic Press, Chapter 23, 1977.

[5] A. Borghetti, C.A. Nucci, M. Paolone, “An Improved Procedure for the Assessment of Overhead Line Indirect Lightning Performance and its Comparison with the IEEE Std. 1410 Method”, IEEE Trans. on Power Delivery, vol. 22, no. 1, pp. 684-692, January 2007.

[6] A.K. Agrawal, H.J. Price, S.H. Gurbaxani, “Transient response of a multiconductor transmission line excited by a nonuniform electromagnetic field”, IEEE Trans. on EMC, Vol. 22, No. 2, pp. 119-129, May 1980.

[7] A. Borghetti, J.A. Gutierrez, C.A. Nucci, M. Paolone, E. Petrache, F. Rachidi, “Lightning-induced voltages on complex distribution systems: models, advanced software tools and experimental validation”, Journal of Electrostatics, Vol. 60/2-4, pp. 163-174, Elsevier, 2004.

[8] F. Napolitano, A. Borghetti, C.A. Nucci, M. Paolone, F. Rachidi, J. Mahseredjian, "An advanced interface between the LIOV code and the EMTP-RV", Accepted for the presentation at the 29th International Conference on Lightning Protection, 23–26 June 2008, Uppsala, Sweden.
[9] C. A. Nucci, F. Rachidi, Interaction of electromagnetic fields generated by lightning with overhead electrical networks, The Lightning Flash, ed. V. Cooray, pp. 425 – 478, IEE Power and Energy Series 34, The Institution of Electrical Engineers, London, 2003.
[10] Electromagnetic Transient Program (EMTP) Rule Book, Bonneville Power Administration, Portland, Oregon, 1984.
[11] H. W. Dommel, ElectroMagnetic Transients Program. Reference Manual (EMTP Theory Book). Bonneville Power Administration, Portland, Oregon, 1986.
[12] J. Mahseredjian, S. Lefebvre and X.-D. Do, "A new method for time-domain modelling of nonlinear circuits in large linear networks", Proc. of 11th Power Systems Computation Conference PSCC, August 1993.
[13] J. Mahseredjian, S. Dennetière, L. Dubé, B. Khodabakhchian and L. Gérin-Lajoie: "On a new approach for the simulation of transients in power systems". Electric Power Systems Research, Volume 77, Issue 11, September 2007, pp. 1514-1520
[14] J. Mahseredjian: "Simulation des transitoires électromagnétiques dans les réseaux électriques", Édition 'Les Techniques de l'Ingénieur', Dossier n°D4130, Réseaux électriques et applications.
[15] A. Borghetti, C.A. Nucci, "Estimation of the frequency distribution of lightning-induced voltages on an overhead line above a lossy ground: a sensitivity analysis", Proc. International Conference on Lightning Protection, Birmingham, UK, September 1998.
[16] A. Morched, L. Martí, J. Ottevangers, "A high-frequency transformer model for the EMTP", IEEE Trans. on PWRD, Vol. 8-3, pp. 1615-1626, Jul. 1993.
[17] A. Borghetti, A. S. Morched, F. Napolitano, C.A. Nucci, M. Paolone, "Lightning-Induced Overvoltages Transferred Through Distribution Power Transformers", in press on IEEE Trans. on PWRD.
[18] R. B. Anderson and A. J. Eriksson, "Lightning parameters for engineering application," Electra, vol. 69, pp. 65–102, 1980.
[19] Cigré Working Group 01 of SC 33, Guide to Procedures for Estimating the Lightning Performance of Transmission Lines Cigré, ref. no. 63, Oct. 1991.
[20] IEEE Fast Front Transients Task Force, "Modeling guidelines for fast front transients," IEEE Trans. Power Del., vol. 11, no. 1, pp. 493–506, Jan. 1996.
[21] M. Paolone, C. A. Nucci, E. Petrache, and F. Rachidi, "Mitigation of lightning-induced overvoltages in medium voltage distribution lines by means of periodical grounding of shielding wires and of surge arresters: modeling and experimental validation," IEEE Trans. Power Del., vol. 19, no. 1, pp. 423–431, Jan. 2004.
[22] A. Greenwood, Electrical Transients in Power Systems, John Wiley & Sons, 1991.
[23] B. Gustavsen, A. Semlyen, "Rational approximation of frequency domain responses by vector fitting", IEEE Trans. Power Delivery, vol. 14, pp. 1052-1061, July 1999.