International Conference on Lightning Protection
33rd International Conference on Lightning Protection
25 - 30 September 2016
Estoril, Portugal

Guidelines for transmission lines lightning performance improvement using a statistical approach

Carlos Cardoso, João Mendes, Nuno Filipe, Andreia Leiria
Energy Consulting – Technical Studies
EDP Labelec
Sacavém, Portugal
carlos.cardoso@edp.pt

David Duarte, Luis Perro, M. Matos Fernandes
Direcção de Planeamento e Engenharia – Departamento de Análise de Redes
REN – Rede Eléctrica Nacional
Lisboa, Portugal

***Abstract* – This paper describes the benchmarking and evaluation of conventional and non-conventional practices to improve lightning performance of transmission lines. A Monte Carlo method using Matlab and EMTP-RV was used to evaluate the effectiveness of those practices applied to two Portuguese transmission lines case studies, covering both back flashover and shielding failure flashover rates. It was concluded that the installation of line surge arresters provided significant flashover rates improvement, but the combination of other measures also provided interesting results. Based on all the information gathered and data outputs, it was possible to draw some guidelines to estimate and improve the lightning performance of transmission lines, in the design phase.**

Keywords: Lightning performance, transmission lines, Monte Carlo method, guidelines, procedures and practices for improvement of lightning performance, SFFOR, BFOR, statistical approach.

I. Introduction

Lightning activity is a common cause of unplanned outages in the transmission system, sometimes leading to forced interventions for equipment maintenance or replacement. The overall reliability of the transmission system is affected, possibly resulting in complaints of connected customers. In order to prevent these issues, transmission system operators (TSO) are taking this concern to a higher priority level. For this, the diversity of improvement solutions are such that a cost over benefit analysis should be done before implementation, to prevent unnecessary costs.

Therefore, this paper approaches the application of practices used around the world, for improvement of the lightning performance of the Portuguese Transmission System, using a Monte Carlo statistical approach developed in [1].

Many practices for lightning performance improvement have been published and tested, and so, the selection of the best ones for a particular case needs to take into account the predominant fault cause (back flashover rate – BFOR, or shielding failure flashover rate – SFFOR), soil resistivity and tower footing impedance, tower locations and possible mechanical stresses (for additional wires), regulatory constraints, etc.

For BFOR mitigation, some authors present practical case studies of the application of known measures like the installation of surge arresters [2], underbuilt wires [3], counterpoises [4] or improving grounding electrodes of the towers.

On the other hand, SFFOR is commonly mitigated by changing the shielding angle, either with the application of "V" insulator strings, displacing the shielding wires, or installing additional ones.

II. Benchmarking of Lightning Performance Improvement Practices

The practices for lightning performance improvement, listed before, are accepted in some countries under particular conditions. Applying the same solutions to different scenarios may end up in underperformance or exaggerated expenses, if all implementation and maintenance requirements are not considered.

Despite that the improvement of tower grounding electrodes is, most of the times, the easiest measure to reduce BFOR faults, its inefficiency in high resistivity soil results in considerable expenses and small reductions of BFOR faults. Consequently, implementing non-conventional measures, such as counterpoises, underbuilt wires and surge arresters, may be considered viable solutions.

A. Counterpoises

Solutions based in the installation of counterpoises [4] usually comprise additional guy wires, usually 4, connecting the tower structure and buried electrodes. The principle is to reduce tower footing impedance and overvoltage amplitude developed across insulator strings, by splitting the current wave. When high soil resistivity presents significant physical and budgetary constraints on grounding system improvement, or the application of surge arresters is not viable, counterpoises may present an interesting option. Some authors [4] suggest that mountains with rocky terrain are a good example of a viable counterpoise application, and around 40% of overvoltage reduction may be achieved. However, not only guy wires and counterpoises may increase human and animal exposure to dangerous step and touch voltages, but also their implementation is forbidden by some regulatory systems.

B. *Underbuilt wires*

The principle of installing underbuilt wires [3] is similar to the one using counterpoises, i.e. splitting current wave to adjacent towers in order to reduce the overvoltage developed across the insulator strings. Such simple solution can be a viable alternative for poorer lightning performance towers, when surge arresters or grounding system improvement costs, due to high resistivity soil, forbid their implementation. For high tower footing impedance, this practice has higher overvoltage reductions [3], around 1/3 with one underbuilt wire and 1/2 with two. Nevertheless, additional mechanical stresses on the tower structure, or insufficient insulating distances, may compromise the application.

C. *Line Surge Arresters*

Line Surge Arresters (LSA) are a frequent discussion subject, given their significant contribution reducing overvoltage amplitude. In order to obtain the best gains out of this expensive solution, [5], [6] and [7] suggest calculating the expected risk of failure according to the number and distribution of surge arresters. Additionally, when dimensioning surge arrester equipment to be installed, it is recommended to follow the experience of [8].

For example, installing surge arresters on all phases, at every tower of a transmission line with poor lightning performance, will ensure the mitigation of both shielding failure flashover and back flashover faults. There are situations, for industrial customers, that may require total protection, which may justify implementing surge arresters on every phase and, if necessary, at every tower. The same practice is suggested by [14] or transmission lines crossing mountainous regions. Besides being the most expensive configuration in terms of installation expenditure, it is also the most maintenance intensive, as shown on [9]. Wind also has a strong influence on surge arrester installation, as they may disconnect due to a broken lead, disconnector or lugs [10]. This is a strong topic that changes transmission lines maintenance strategy, because if surge arresters are failing, no disturbances are caused per se, but the line won't be protected either.

Some authors [12] conclude that installing surge arresters on upper and lower phase conductors, for vertical double circuit transmission lines, is, at the same time, the minimum and essential condition to ensure total protection against shielding failure and back flashover failure outages, respectively. In any case, studying each situation carefully will demonstrate which configuration prevails.

D. *Changing Phase Cable and Shield Wire Position*

When transmission lines present poorer shielding failure flashover rates (SFFOR), changing shield wire position and/or applying "V" insulator strings configuration to phase conductors, thus obtaining a shallow or negative shielding angle, are the most efficient solutions. Although providing a significant increase in lightning performance and less significant maintenance expense than the installation of surge arresters, the implementation expenditure varies significantly whether it is an existent transmission line or in draft.

Studies have shown that reducing the shielding angle has a strong influence on the number of outages due to direct strikes on phase conductors, pointing the importance of this practice. Authors [11] conclude that installing "V" insulator strings configuration to phase conductors could reduce shielding angle by 5° and number of outages per 100 km per year by 55%. Thereafter, changing shield wire position obtaining a shielding angle of 3° provided further reduction of the number of outages per 100 km per year by 95%.

E. *Insulation Level Increase*

Increasing insulation level is often considered as not effective nor efficient practice to increase lightning performance of transmission lines. Insulator strings with additional insulator disks cannot withstand high amplitude overvoltages, especially for rated voltages below 100 kV, for which insulator strings length is smaller, as mentioned in [2]. Additionally, the implementation expenses for existent lines are far more relevant than the benefit obtained. Nevertheless, when designing new transmission lines, the effort required for higher length insulator strings is not substantial.

An insulation coordination study is also highly recommended, to make sure the overall system insulation coordination is not compromised. Tower structure may have to be redesigned, to accommodate the insulation level increase, and the line profile reviewed (distances can be compromised) as referred by [13].

III. LIGHTNING PERFORMANCE IMPROVEMENT METHODOLOGY APPLICATION CASE STUDY

A statistical Monte Carlo methodology, described in [1], was developed for lightning performance analysis and improvement of Portuguese transmission lines, using EMTP-RV and MATLAB software. Two typical case studies were considered, comprising shielding failure and back flashover issues, and for both lines, several practices were tested to rank the most effective ones.

With this methodology, it is possible to test all practices gathered in the benchmarking phase of the work, by simulating their application to the Portuguese transmission system, with the objective of determining their effectiveness.

From the lightning performance improvement practices mentioned before, underbuilt wires and guy wires/ counterpoises were excluded. The Portuguese regulatory system does not allow installing guy wires and counterpoises, as they may compromise human safety, regarding touch and step voltages. Underbuilt wires are also not a viable option, despite their interesting results, because towers may lack a margin for additional mechanical stresses. On the other hand, increasing insulation level proved to be only possible by adding up to 2 insulator disks, due to insulation coordination issues.

A. Test Configurations

The transmission lines chosen for this case study are the same which were modeled and simulated in [1] (For Line A, only segment 2 is considered). As the Monte Carlo method uses EMTP-RV models and MATLAB for the modified Electro Geometrical Model, it is possible to apply every possible lightning performance measure described in II, or any combination of those measures. The case study lines were chosen to demonstrate the most diverse results. In Line A – Segment 2 (Line A-2), SFFOR is the predominant flashover rate, and BFOR is the most significant index in Line B.

1) Line A-2 - Transmission Line with high SFFOR

Line A-2 is a single circuit, 400 kV segment of line with phases horizontally arranged. Average characteristics are the following:

- Tower footing impedance: 80 Ω;
- Span length: 400 m;
- Tower height (to SWs): 45.55 m;

Detailed information about this line can be read in [1]. The computed flashover rates in [1] were (per 100 km.year):

- SFFOR: 3.8;
- BFOR: 0.2;

As expected, transmission lines with a significant average tower height and poor shielding angles are prone to shielding failure flashover events. In this case, the following configurations were studied:

a) Application of "V" insulator strings to the outermost phases;

b) Placement of the shield wires further from the center of the tower, by 1 m and 2 m;

c) Combination of a) and b);

d) Installation of 1, 2 and 3 line surge arresters per tower, at 1/3, 1/2, and all the towers;

e) 2 additional insulator disks in every insulator string.

2) Line B - Transmission Line with high BFOR

Line B is a double circuit, 150 kV line with phases vertically arranged. Average characteristics are the following:

- Tower footing impedance: 110 Ω;
- Span length: 400 m;
- Tower height (to SWs): 51.4 m;

Detailed information about this line can be read in [1]. The computed flashover rates in [1] were (per 100 km.year):

- SFFOR: 1.6;
- BFOR: 5.1;

As expected, transmission lines with poorer grounding resistance, and lower insulation level, are prone to back flashover events. In this case, the following configurations were studied:

a) Tower grounding system improvement, with the installation of a copper ring electrode, in 1/2 and all the towers;

b) Installation of 1, 2 and 3 line surge arresters per circuit, per tower, at 1/3, 1/2, and all the towers;

c) 2 additional insulator disks in every insulator string;

d) Combinations of a), b) and c).

B. Results and Conclusions

After running 40000 simulations [1] for each configuration, the results obtained are expressed in TABLE I. and TABLE II. . The measures are ranked in the tables by the improvement provided in the total flashover rate.

TABLE I. LINE A-2 FLASHOVER RATES WITH IMPROVEMENT MEASURES (PER 100 KM.YEAR)

Configuration	Final Indexes			Improvement		
	BFOR	***SFFOR***	***TFOR***	***BFOR***	***SFFOR***	***TFOR***
3 * LSA in all Towers	0	0	0	100%	100%	100%
2 * LSA in all Towers	0.1	0	0.1	50%	100%	98%
"V" strings + SWs 1 m out	0.2	0.1	0.3	0%	97%	93%
1 * LSA in all Towers	0.15	1.1	1.25	25%	71%	69%
SWs 2 m out	0.2	1.1	1.3	0%	71%	68%
2 * LSA in ½ Towers	0.15	1.3	1.45	25%	66%	64%
"V" strings	0.2	1.3	1.5	0%	66%	63%
1 * LSA in ½ Towers	0.15	2.1	2.25	25%	45%	44%
2 * LSA in ⅓ Towers	0.2	2.1	2.3	0%	45%	43%
SWs 1 m out	0.2	2.8	3	0%	26%	25%
1 * LSA in ⅓ Towers	0.2	2.9	3.1	0%	24%	23%
+2 insulator discs in all strings	0.1	3.8	3.9	50%	0%	3%

For line surge arresters, it is possible to conclude that the choice of a LSA configuration is not trivial and thus, every configuration should be simulated to determine which the most efficient one is. For example, 2 LSAs in every tower give virtually the same benefit as 3 LSAs; 1 LSA in every tower gives slightly more benefit than 2 LSAs every 2 towers.

The effectiveness of changing shield wires position is very dependent on the margin available for shifting their position. But, in this case, the combination of a 1 m displacement with the application of "V" insulator strings results in an almost complete mitigation of the line SFFOR. The application of "V" insulator strings, a 2 m shift in the SWs positions, or the installation of 2 LSAs in every 2 towers provide equivalent improvement levels, around 65%.

An increase in the insulation level by 2 discs doesn't change the SFFOR, thus it doesn't significantly contribute to improve the total flashover rate of this line.

TABLE II. LINE B FLASHOVER RATES WITH IMPROVEMENT MEASURES (PER 100 KM.YEAR)

Configuration	Final Indexes			Improvement		
	BFOR	***SFFOR***	***TFOR***	***BFOR***	***SFFOR***	***TFOR***
3 * LSA in all Towers	0	0	0	100%	100%	100%
3 * LSA in ⅓ Towers + ground. elec. improv. and +2 insul. discs in all strings in towers without LSAs	0.3	0.4	0.7	94%	75%	90%
3 * LSA in ½ Towers + ground. elec. improv. in towers without LSAs	0.4	0.6	1	92%	63%	85%
3 * LSA in ⅓ Towers + ground. elec. improv. in towers without LSAs	0.7	0.8	1.5	86%	50%	78%
3 * LSA in ½ Towers	1.1	0.6	1.7	78%	63%	75%
2 * LSA in all Towers	2.2	0	2.2	57%	100%	67%
+2 insulator discs in all strings + grounding electrode improvement	1.3	1.5	2.8	75%	6%	58%
1 * LSA in all Towers	2.8	0.7	3.5	45%	56%	48%
Grounding electrode improvement in all towers	2.1	1.6	3.7	59%	0%	45%
Grounding electrode improvement in ½ towers	2.8	1.6	4.4	45%	0%	34%
+2 insulator discs in all strings	3	1.6	4.6	41%	0%	31%

The results show that it is possible to reduce the total flashover rate by up to 45%, by only improving the grounding electrodes of every tower.

Unlike in Line A-2, the application of 2 or 3 LSAs every tower doesn't provide almost the same improvements in the flashover rates. The reason is that, in Line A-2, only the 2 outermost phases contribute to the SFFOR.

Once again, unlike Line A-2, an increase in the insulation level by just 2 discs improves the flashover rates by 31% (due to the originally reduced 150 kV insulation level), and combined with an improvement in all the grounding electrodes, the rate reduces by 58%. Combining this two measures with the installation of 3 LSAs in 1/3 of the towers, results in an improvement of the flashover rate by up to 90%.

Other combinations also give interesting results. It can be seen in the table that the most effective measures are the ones that mitigate not only the BFOR, but also the SFFOR. The choice of the most suitable ones should, of course, be based on a cost-effectiveness analysis. This analysis should take into account all installation, maintenance and other expenses, for each measure, or combination of measures.

IV. LIGHTNING PERFORMANCE GUIDELINES FOR TRANSMISSION LINES IN THE DESIGN PHASE

A. Risk Analysis

Based on all the information gathered and data outputs from the Monte Carlo methodology applied to Portuguese transmission lines, it is possible to draw some guidelines to estimate and improve the lightning performance of transmission lines, in the design phase.

During the design phase of a transmission line, performing a detailed risk analysis is the best practice to protect the overall system against lightning caused faults and estimate the necessary measures to achieve a desired level of performance, while optimizing the necessary monetary investment. So, in short, the following risk factors need to be accounted for:

- Ground Flash Density (GFD) map – lightning performance indexes depend linearly on GFD values;
- Average peak current map – higher average peak current strokes result in higher back flashover rates;
- Soil resistivity map – higher resistivity soils also greatly increase tower footing earthing impedances, and thus back flashover rates;
- Orographic map – transmission lines at higher altitudes are more exposed to direct lightning;
- Line surroundings – transmission lines crossing desolated areas and rough terrain are more exposed and prone to higher shielding failure rates;
- Tower structure – tower height and structure configuration influence the probability of lightning hitting the phase conductors.

B. Transmission Lines prone to Shielding Failure Outages

As explained in previous topics, some factors, including tower and line geometry and its surroundings, greatly influence the resultant SFFOR.

For example, orography strongly influences the transmission line lightning performance, especially shielding failure rates. Not only locations with undergrowth, or rough terrain, such as valleys, increase the exposure of phase conductors but also, because lightning strikes are not only vertical, the line lateral exposure to higher peak current strokes is worsened – Figure 1.

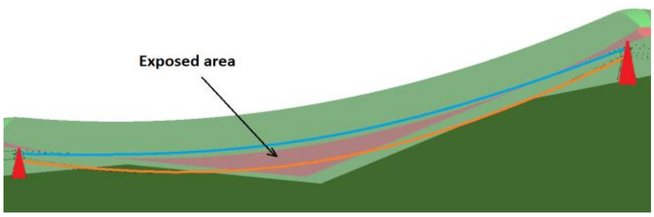

Figure 1. Transmission line phases exposure area, for a 10 kA stroke, crossing a valley (blue-shield wires, orange-phase wires).

One can see that, in the middle of a line span crossing a valley, although there is less sag in the shield wires than the phase wires, the phase wires are usually much more distant to the ground than in the adjacent towers, which significantly increases their exposure area.

In sum, transmission lines comprised of towers with higher shielding angles will present poorer shielding failure rates.

The most effective actions to reduce shielding failure outages are the ones that, by changing phase conductors or shield wires positions, reduce shielding angle to the lowest possible value, preferably even negative. Nevertheless, some of the practices imply significantly more budgetary burden when performed on existent lines, rather than at the design phase.

1) Changing shield wires number and position

It is undoubtedly the most flexible measure to reduce direct strokes to phase conductors, and has the lowest expense when early considered at the design phase. For existent lines, the procedure is not that simple, as the tower structure may not be able to accommodate future changes, or the position change may prove to be insufficient.

Increasing the number of shield wires above 2, for the voltage levels used in Portuguese transmission lines, showed no significant advantages when applying the Electro-Geometrical Model (EGM).

Studying this conventional practice, considering only vertical strokes when applying EGM, results in optimistic, but realistically implausible, SFFOR. With this model, it is possible to obtain 100% line coverage for vertical strokes.

However, lightning strikes are not only vertical, and the performance improvement is dependent on displacement between phase conductors (vertical double circuit lines have higher lateral exposure than horizontal single circuit ones), tower height (also increases lateral exposure) and vertical and horizontal distance between phase conductors and the nearest shield wire (higher distances increase the overall exposure). In Figure 2, an example of the effect of a shift in the shield wires position is shown.

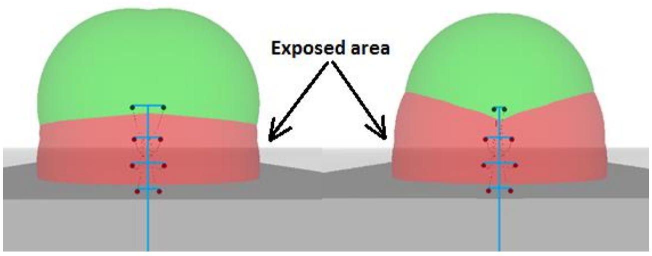

Figure 2. Transmission line phases exposure area, for a 15 kA stroke, considering a 2º shielding angle (left) and a 28º shielding angle (right).

When planning future transmission lines, it is recommended to consider two shield wires far apart as possible, at least, positioned in alignment with the outer phase conductors. The phase conductors are recommended to be as low, and as close between them, as possible.

2) "V" Insulator Strings

This conventional practice also presents good performance improvements, similar to changing shield wires positions. Since reducing shielding angle greatly reduces shielding failure outages, applying both practices may nearly mitigate such issues.

Again, implementation expenses for existent lines are burdensome. Therefore, more favorable cost/benefit ratings may be obtained if this solution is already implemented at design stage.

C. Transmission Lines Prone to Back flashover Outages

Back flashover outages are often mitigated by reducing tower footing impedance (improving the existent grounding electrode) or by installing surge arresters, counterpoises and underbuilt wires.

1) Installing Surge Arresters

Transmission lines achieve different performance indexes depending on the chosen surge arrester configuration, as seen on TABLE I. and TABLE II. Installing surge arresters on all phases at every tower, guarantees total protection against lightning events. Being the most expensive solution, it is hardly justifiable, since other configurations have shown to result in interesting performances, but require a detailed risk analysis through computation of the expected BFOR and SFFOR.

Unlike the other mentioned solutions, surge arresters present nearly the same expected expense when applied to an existent line or a line at design stage. Thus, the important decision to install surge arresters can wait for real operating data of the line (actual SFFOR and BFOR).

2) Insulation Level Improvement

Improving insulation level is a classical practice for lightning performance improvement of transmission lines. The results on TABLE I. and TABLE II. show that, for the Portuguese case studies, adding 2 insulator disks result in a low performance improvement. So, this measure is not expected to have an interesting cost/benefit rating, when applied to existent transmission lines. Nevertheless, at design phase, the effort needed is much lower, as the only additional expense is the cost of those additional disks.

Since the implementation expenses, when applying this measure individually, are significant for existent lines, it might be something to be considered together with other solutions, like "V" insulator strings configuration.

3) Tower Grounding System Improvement

As explained before, this classic solution strongly influences the BFFOR. The possible modifications are limited on operational lines, since tower foundations are already built. At design stage, if soil resistivity is high, then additional efforts are possible at a reduced incremental cost.

The first approach to reduce tower footing impedance should start with the reinforcement of the existent vertical electrodes or by adding horizontal copper rings. Reinforcing vertical electrodes with deeper ones allow reaching soil layers with lower resistivity, consequently reducing the impedance value.

On the contrary, if the resistivity of the superficial soil layer is lower, adding additional conductors forming a ring, for example, proves to be an interesting measure.

Simulation data shows that the installation of a copper ring can reduce tower grounding impedance by up to 45%, and combining this measure with the extension of vertical electrodes can reduce the impedance by up to 60%, when compared with a standard grounding electrode. These reductions have significant impacts on BFOR, as depicted on TABLE II.

Improving high voltage towers grounding systems also presents additional benefits regarding human and property safety, as it tends to decrease possible touch and step voltages.

Finally, the use of deep driven electrodes is not recommended, since their significant length leads to relatively high impedance values for current impulses originating from lightning.

4) Unconventional Practices

When the above solutions prove to be too much monetary burdensome or no significant performance improvements can be obtained through their application, unconventional practices like counterpoises and underbuilt wires can be an alternative, and their effect should be tested using the Monte Carlo method.

Counterpoises may be considered a viable performance improvement practice for high resistivity soils and uninhabited areas (mountains with rocky terrain, for example) and when regulatory entities allow its implementation. Underbuilt wires in turn may also be an interesting option for the same reasons, but additional tower mechanical stresses must be studied.

CONCLUSIONS

Improving transmission lines lightning performance requires balancing the expected flashover rate reduction and cost incurred. Two groups of interventions may be considered: one for transmission lines more prone to back flashover and the other for shielding failure outages.

A statistical Monte Carlo methodology, described in [1], was developed for lightning performance analysis and improvement of Portuguese transmission lines, using EMTP-RV and MATLAB software. Two typical case studies were considered, comprising shielding failure and back flashover issues, and for both lines, several practices were tested to rank the most effective ones.

With this methodology, it was possible to test all practices gathered in the benchmarking phase of the work, by simulating their application to the Portuguese transmission system, with the objective of determining their effectiveness.

For line surge arresters, it is possible to conclude that the choice of a LSA configuration is not trivial and thus, every configuration should be simulated to determine which the most efficient one is. Despite this, surge arresters proved to be the most effective measure to reduce back flashover and shielding failure outages, they also have some important disadvantages, being very maintenance demanding. On the other hand, reducing shielding angle (through a shift of the shield wires positions or the application of "V" insulator strings) and improving tower grounding system have interesting results on reducing shielding failure and back flashover outages, respectively. Combinations of practices showed even more interesting results. Moreover, higher performance improvement values require higher budgetary efforts. Therefore, is highly recommended studying each practice constraints to achieve the most suited results for each situation.

Finally, based on all the information gathered and data outputs from the Monte Carlo methodology applied to Portuguese transmission lines, it was possible to draw some guidelines to estimate and improve the lightning performance of transmission lines, in the design phase.

ACKNOWLEDGMENT

Special thanks to Ruben Costa, EDP Labelec, for developing simulations of transmission tower grounding systems, and 3D EGM models of transmission lines, during his EDP trainee program, to be used in the work which resulted in this paper.

REFERENCES

[1] N. Filipe, C. Cardoso, J. Mendes, A. Leiria, D. Duarte, L. Perro, M. Matos Fernandes "A methodology for estimating transmission lines lightning performance using a statistical approach", Proceedings of the 33rd ICLP, Estoril, Portugal, September 2016.

[2] B. Demailly, L. Tullus, F. Maciela and S. Tartier, "Installation of composite surge arresters on transmission lines", Cigré, 2002, 33-203.

[3] S. Visacro, F. Silveira and A. De Conti, "The use of underbuilt wires to improve the lightning performance of transmission lines", IEEE Trans. Power Del., vol. 27, no. 1, pp. 205-213, January 2012.

[4] S. Visacro, A. Soares Jr., R. Oliveira, M. Felipe, A. Silva and M. Vale, "Non-conventionnal measures for improvement of lightning performance of transmission lines", Proceedings of the 27th ICLP, pp. 684-687, Avignon, France, Sept. 2004.

[5] J. Martinez and F. Cartro-Aranda, "Lightning performance analysis of overhead transmission lines using the EMTP", IEEE Trans. Power Del., vol. 20, no. 3, pp. 2200-2210, July 2005.

[6] S. Pack, I. Hübl, M. Marketz, M. Muhr, R. Schmaranz, "Possibilities and remedial measures to reduce lightning-caused outages in a distribution network", Cired, 3rd session, August 2007 [19th International Conference on Electricity Distribution Vienna, pp. 0909, 2007].

[7] C. A. Christodoulou, I. F. Gonos and I. A. Stathopulos, "Lightning performance of high voltage transmission lines protected bu surgre arresters: a simulation for the Hellenic transmission network", ICLP, June 2008 [29th International Conference on Lightning Protection Uppsala, pp. 6b-7-1 – 6b-7-8, 2008].

[8] B. Demailly, L. Tullus, F.Maciela and S. Tartier, "Installation of composite surge arrestors on transmission lines", Cigré, 2002, 33-203.

[9] J. Franco, A. Bezerra and A. Andrade, "Improvement of the transmission lines lightning performance using line arresters: experience of the brazilian utilities", Cigré, 2006, A3-102.

[10] J. Williamson, "Lightning protection and surge arresters application on NB power transmission lines", IEEE PES Transmission and Distribution Conference and Exposition Chicago, 2008.

[11] S. Corrales, J. Martinez and J. Barragán, "Analysis of the performance of a 400 kV transmission line against lightning", Cigré, 2006, C4-107.

[12] R. Bhattarai, R. Rashedin, S. Venkatesan, A. Haddad, H. Griffiths, N. Harid, "Lightning performance of 275 kV transmission lines", in Proc. of 43rd International Universities Power Engineering Conference, Padova, Italy, Sept. 2008.

[13] HECO Lightning Performance Analysis: Kahe-Waiau 138 kV line. EPRI, Palo Alto, CA: 2009.

[14] K. Munukutla et al., "A Pratical Evaluation of Surge Arrester Placement for Transmission Line Lightning Protection", IEEE Trans. Power Del., vol. 25, no. 3, July 2010.

[15] J. Gillespie, G. Stapleton, "Improving double circuit transmission line reliability through lightning design", Cigré, 2004, B2-301.