The protection against lightning of an overhead line uprated from 225 kV to 400kV

A. Xémard, S. Dennetière, I. Uglesic, V. Milardic, B. Milesevic, P. Grand, F. Sauvegrain, P. Stevenin, M. Mesic

Abstract-- **The voltage uprating of existing overhead lines is an interesting solution for increasing the transmission of electricity, especially in areas where it is difficult to build new lines.**

If a line is uprated with minor changes of its design and without improvement of the grounding electrodes of towers, its lightning performance remains unchanged. The consequence is that the uprated line will have a lightning flashover rate very high compared to an overhead line of same nominal voltage but of standard design. One attractive solution to solve this problem is to use line arresters.

The goal of this paper is to study the use of line arresters to achieve a satisfactory lightning performance of an overhead line uprated from 225 kV to 400 kV without major design modifications.

In order to compare different strategies of line arrester installation the flashover rate is calculated based on a software able to launch automatically EMTP-RV. This software named LIPS has been developed under the cover of a partnership between Hydro-Quebec, RTE and EDF.

Keywords: **lightning, transmission line, voltage uprating, insulation coordination.**

I. Introduction

Mainly two families of solutions exist aiming at increasing the transmission of electricity of overhead lines. The first one is the change of the phase conductors in order to increase the ampacity of the line, the second one is related to the increase of the rated voltage of the line (voltage uprating). This paper presents a practical application of this solution related to the uprating of a single circuit 225 kV line equipped with 2 sky wires to 400 kV. It focuses more specifically on the question of the lightning performance of the line which presents some specificities. Because of its significantly lower clearances compared to a standard 400 kV line, the uprated line will have a flashover rate which will be higher than the one of a 400 kV line of standard design. This paper presents mainly results related to the use of line arresters in order to reduce the flashover rate of the line. It starts with a description of the line configuration, then it gives some elements on the insulation coordination of the line and then compares some strategies of use of line arresters to improve the lightning performance of the line. The paper is completed by some brief calculations of 50 Hz electric field in the vicinity of the line, this aspect being in many cases a critical issue of line uprating.

II. Presentation of the Line Configuration

The line considered is a single circuit 225 kV line equipped with 2 ground wires, uprated to 400 kV without major modifications of the design of the towers. In many countries, for instance in France, significant modifications of a line design, as the change of tower heads, require the application of a very difficult administrative procedure, so it is preferred to limit as most as possible the modifications made to a line when proceeding to its uprating.

The typical span length of the line considered is 400 m and the catenary parameter of the conductors is 1900 m.

Table 1 presents the position of phase conductors at towers and at mid-span.

TABLE I
POSITION OF CONDUCTORS

Position of conductors at towers	Vertical position of conductors at towers (m)	Vertical position at midspan (m)	Horizontal position of conductors (m)
Phase A	42.5	32	-7.1
Phase B	45	34.5	0
Phase C	42.5	32.5	7.1
Ground wire 1	48	37.5	-4.3
Ground wire 2	48	37.5	+4.3

Phase conductors are bundled and consist of 2 sub-conductors separated by a distance of 0.6 m. The characteristics of conductors is given in appendix 1.

Regarding clearances, the length of the air gap at insulator strings is equal to 1.9 m. It corresponds to a lightning withstand voltage U_{50} = 1010 kV. The minimum clearance at the tower is equal to 2.4 m.

The line is 130 km long and located in an area where the lightning ground flash density is equal to 4 lightning strokes / year / km^2 (this correspond to a severe lightning activity in France where ground flash density in most areas range from 1

A. Xémard, S. Dennetière are with EDF R&D, Clamart, France (corresponding author alain.xemard@edf.fr).
I. Uglesic, V. Milardic, B. Milesevic are with the Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia.
P. Grand, F. Sauvegrain, P. Stevenin are with RTE, France.
M. Mesic is with HEP, Zagreb, Croatia.

Paper submitted to the International Conference on Power Systems Transients (IPST2009) in Kyoto, Japan June 3-6, 2009

to 2). However, the values of flashover rate presented in this paper have been normalized for a ground flash density of 1 lightning stroke / year / km^2.

III. Considerations regarding the withstand of the line uprated

This paragraph gives some general indications regarding the insulation coordination of the line uprated and its withstand against the various types of overvoltages. The requirements due to live working, even if they could certainly be severer than the ones of insulation coordination are not taken into account in this paper, and that aspect will be analyzed separately.

A. Industrial voltage

Pollution can be a critical issue when uprating a line because the reduced creepage distances can give birth to an unacceptable number of flashovers during severe periods of pollution. The line considered in this paper being located in an area with a light pollution level [4] the creepage distance of the insulator strings was sufficient to avoid an unacceptable risk of flashover due to pollution. It would have also necessary to evaluate if internal clearances are sufficient to withstand the system voltage in extreme wind conditions [7] (clearances between phase conductors might be reduced because of the balancing of conductors) but this aspect is not presented here.

B. Temporary overvoltages

It has been found that temporary overvoltages are not an issue. The power frequency short withstand voltage of the air gap at insulator string is slightly higher than 900 kV crest [7] or 2.6 p.u. (see definition of p.u. in appendix 2), considering that the altitude is lower than 1000 m. On the RTE (french transmission system operator) 400 kV system, phase to ground overvoltages are lower than 500 kV crest (1.45 p.u.) except in very exceptional configurations, so the withstand voltage of insulator strings is sufficient to withstand temporary overvoltages.

C. Slow front overvoltages

The most severe slow front overvoltages generally arise from line energization and re-energization, faults and fault clearing [4].

Transients calculation has been made using the software EMTP-RV [1] in order to evaluate the level of the slow front overvoltages. The modeling used to represent the system has been according to the recommendations of [5].

It was shown that by using potential transformers in order to eliminate trapped charges and arresters at both ends of the line, it was possible to reduce slow front overvoltages due to energization [5] to a value of 2.5 p.u. (overvoltage which has a risk of 2% to be exceeded). This value corresponds to 860 kV and is higher than the switching withstand voltage of the insulator strings which is equal to 830 kV. This result indicates that it is necessary to use point on the wave closing or closing resistor in order to avoid a significant risk of having faults due to energization. When circuit breakers are equipped with closing resistors slow front overvoltages (2% value) can be limited to a value of 2.2 p.u.. It corresponds to 760 kV and is lower than the withstand value of the insulator string. Slow front overvoltages due to fault-clearing on an adjacent line are limited to 2.1 p.u.and are not an issue.

The crest value of phase to phase overvoltages due to line energizing when the line is equipped with surges arresters at both ends is limited to 1200 kV (no closing resistors). This is significantly lower than the phase to phase switching withstand voltage of the line which is equal to 1620 kV.

Nota : the overvoltages calculated in this paragraph have been evaluated without taking the effect of line arresters into account. As a conclusion with potentials transformers phase to phase overvoltages are not an issue. However because of the short length of the insulator strings it is necessary to use point on wave switching or breakers equipped with closing resistors.

D. Fast front overvoltages

The lightning flashover rate of the line has been calculated and compared to the lightning flashover rate of a standard RTE 400 kV line in order to evaluate the effect of the use of shorter insulator strings on the continuity of service of the line.

1) Methodology applied

The methodology we have applied to evaluate the lightning flashover rate has been presented into details in [6]. It includes the following steps :

- Application of the electro-geometric model of Love [2] to determine the number of lightning strokes impacting each element of the line and the probability density function of these strokes ;
- EMTP-RV [1] simulations of the electromagnetic transients due to lightning strokes impacting the line ; The modelling of the line has been made according to [5]. A brief summary is given in appendix 2.

Evaluation of the flashover rate of the line segment under consideration. The stochastic nature of lightning is taken into account and the results of the previous stages are included (see appendix 4, which presents some elements already presented in [6], for the evaluation of the flashover rate).

This method requires splitting the segment of the line into elements (section of sky wires, section of phase conductors, etc.) which will be considered separately in the flashover calculation. Only one point of impact is considered per element when performing the EMTP-RV simulations. It is supposed that overvoltages due to a lightning stroke impacting an element do not change significantly with the position of the point of impact inside the element. Different types of flashovers are distinguished : total flashover rate or multi-phase flashover rate of the line and of each circuit of the line, etc. The software LIPS has been used to make the flashover rate calculations. LIPS applies the methodology presented above, it was developed in partnership by Hydro-Québec, RTE and EDF.

2) Evaluation of the lightning performance of the line

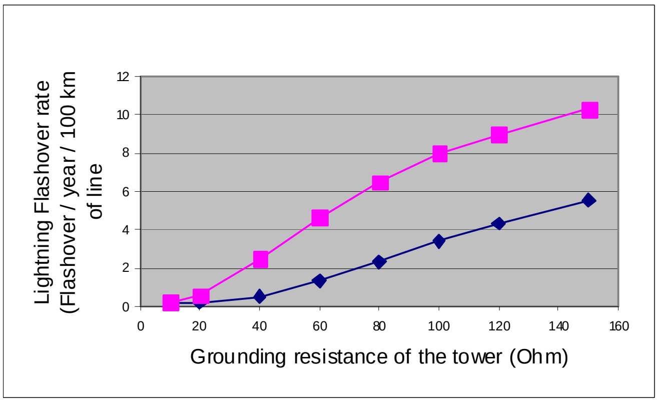

Fig. 1 : Lightning flashover rate of the line versus grounding resistance of towers for the uprated line with insulator strings of 1.9 m (-■-) and for the same line but with insulator strings of 2.5 m (-♦-).

Fig. 1 compares the lightning flashover rate versus grounding resistance of towers of the uprated line with 1.9 m long arc-horns at the insulators string, with the lightning flashover rate of the same line but with 2.5 m long arc-horns. All the flashovers were considered when calculating these indexes (single phase and multi phase). It can be seen that the use of a reduced insulation leads to a severe increase of the flashover rate for values of the grounding resistance higher than 20 Ω. The line is installed in a rocky region, therefore it is most of the time technically very difficult to achieve tower grounding resistances of 10 Ω, which is the value targeted by RTE for the 400 kV system. It was therefore decided to study the use of line arresters in order to improve the lightning performance of the line. This issue is the object of the next paragraph.

IV. Study of the Use of Line Arresters

This paragraph is devoted to the study of the use of line arresters in order to improve the performances of the line. Surge arresters with a rated voltage of 360 kV and a residual of voltage of 900 kV for 20 kA were considered. One can witness here a specific aspect of the protection of uprated line by line arresters. As it is commonly known, the level of the temporary overvoltages liable to exist on an electrical system imposes some requirements as to the minimum level of line arresters because they might be damaged when conducting current if temporary overvoltages are present on the system. As a consequence, in case of line uprating the protection voltage of line arresters might be very close to the withstand voltage of insulator string as the clearances are reduced compared to a standard line. The performance of line arresters is therefore different for a uprated line than for a standard line and needs to be checked carefully.

In order to evaluate the efficiency of different line arrester configurations the lightning flashover rate of the line versus the grounding resistance value was calculated considering that the line is homogenous with the same grounding resistance at each tower, for 2 possible arrester configurations.

A. Arresters at one external phase

In this configuration arresters are installed at only one external phase of each tower.

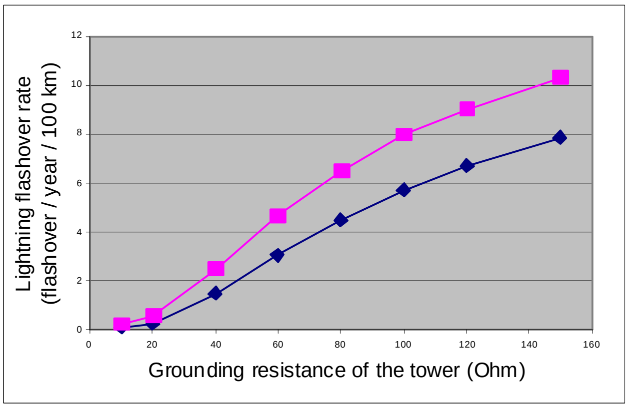

Fig. 2 : Lightning flashover rate of the line versus grounding resistance of towers for the uprated line with insulator strings of 1.9 m (-■-) and for the same line but with line arresters installed only on the external phase of each tower (-♦-).

The figure above compares the lightning flashover rate of the uprated line without arrester, with the lightning flashover rate of the line with one arrester installed at one external phase of each tower. It can be seen that for grounding resistance up to 40 Ω, the presence of a unique line arrester per tower provides a significant improvement of the lightning performance of the line. For instance the lightning flashover rate is decreased from 2.5 to 1.5 flashover / year / 100 km for a 40 Ω grounding resistance.

However the benefit is limited in case of higher grounding resistances. Hence the flashover rate is diminished from 9 to 6.7 flashovers / year / 100 km for a grounding resistance of 150 Ω.

B. Arresters at both external phases

In the configuration considered here arresters are installed at both external phases of each towers.

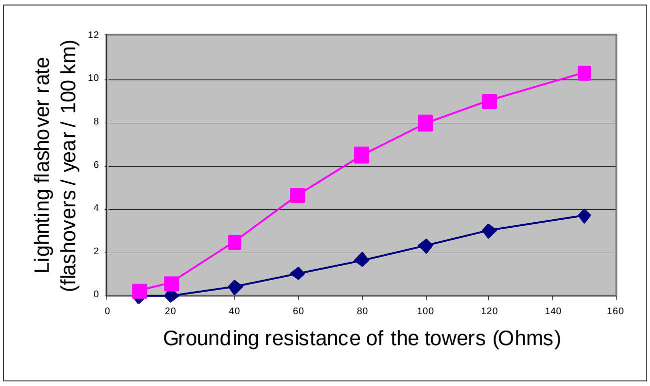

Fig. 3 : Lightning flashover rate of the line versus grounding resistance of towers for the uprated line with insulator strings of 1.9 m (-■-) and for the same line but with line arresters installed on both external phases of each tower (-♦-).

Fig. 3 above compares the lightning flashover rate of the uprated line without arresters, with the flashover rate of the line with both external phases equipped with line arresters. An increase of the flashover rate versus grounding resistance still exists with this configuration of line arresters but one can see that the improvement is significant for the whole range of grounding resistance. For instance the flashover rate is reduced from 9 to 3 flashovers / year / 100 km for grounding resistance of 120 Ω. This configuration of line arresters is more efficient than the previous one for high value of grounding resistances.

C. Energy duty of line arresters

As the line is equipped with ground wires the stress applied by lightning on line arresters is fairly limited. To this respect calculations of energy stress due to lightning presented in [9][10] are also valid for the configuration considered here and allow to conclude that the use of line arresters of class 2 is appropriate.

D. Decision regarding the installation of the line arresters

The line considered in this paper is not uniform ; the height of the towers, the length of the spans and the value of the grounding resistance of the towers vary along the line. But, by considering all the configurations, it is possible to estimate the total flashover rate of the line for different strategies of line arrester installation (towers and phases were arresters are installed), in order to evaluate how their improve the continuity of service of the line. The level of improvement of the continuity of service with its financial implication is one major aspect for the final decision regarding where arresters will be installed along the line. The second major aspect of the decision is related of the installation itself and must take into account not only the cost and the supply of line arresters but other industrial complex aspects as the mechanical installation of the line arresters in the tower (for the case considered in this paper it could be difficult because of the short clearances), the possibility to make the installation live or the obligation to work during a programmed outage.

V. 50 Hz Field in the Vicinity of the Line

When performing the upgrading of the line 50 Hz electric field in the vicinity of the line might be an issue for the following reason.

If it is not possible to change the towers when uprating the line, the increase of the nominal voltage will lead obviously to an increase of the electric field in the vicinity of the line. It should be added also that the constraints related to pollution might oblige to increase the length of insulator string contributing to the increase of the electric field by diminishing the distance between phase conductors and ground.

The positive effect provided by an increase of the mechanical tension of phase conductors in order to decrease their sag might not be sufficient to reach levels of 50 Hz electric fields in the vicinity of the line equivalent to a standard line.

Calculations of the electromagnetic field induced by the uprated line in normal operating conditions in its vicinity has been made using the software EFC 400 [8], which is based on the antenna theory.

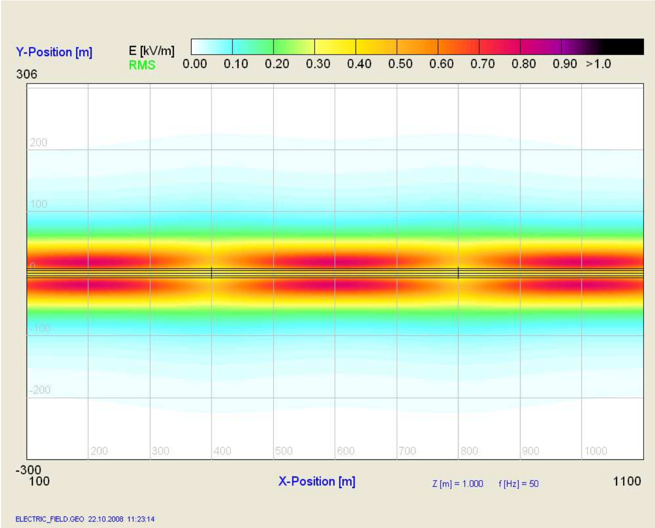

Fig. 4 : RMS value of the electric field intensity, 1 meter above ground in the vicinity of the uprated overhead line, X represents the position along the line (m) and Y represents the transversal distance from the line (m).

Fig. 4 above represents the RMS value of the electric field intensity 1meter above ground. Its maximum value is limited to 0.8 kV / m RMS. It has also been shown that the maximum value of the electric field, 5 m above ground, is equal to 0.9 kV / m.

The magnetic field has been also calculated for a current of 1000 A (see Fig. 5).

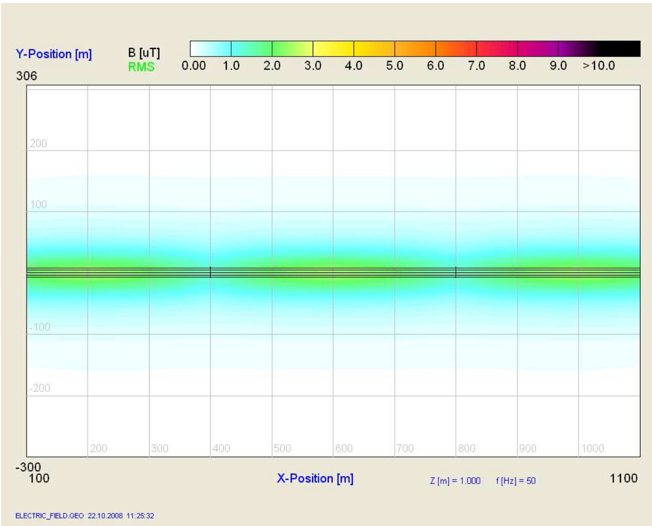

Fig. 5 : RMS value of the magnetic field intensity for a current of 1000 A, 1 meter above ground, in the vicinity of the uprated overhead line, X represents the position along the line (m) and Y represents the transversal distance from the line (m).

It was found that the intensity of the magnetic field in normal operating condition for a current of 1000 A is equal to

2 μT and 5 μT respectively for a height of 1 m and 5 m above ground.

[11], which gives the rule to be applied in France regarding the electromagnetic field induced by overhead lines, specifies that for overhead lines newly built, the intensity of the electric and magnetic field generated by the line should not exceed at ground, in normal operating condition, respectively 5 kV / m and 100 μT. It can be seen that the electric field and the magnetic field generated by the line considered here are far below these limits.

VI. Conclusions

This paper has presented several electrical aspects of the uprating of an overhead line from 225 kV to 400 kV. It begins with some considerations regarding the insulation coordination of the line. It was shown that temporary overvoltages were not a real issue. Due to short clearances between uprated phase conductors, it was necessary to reduce strongly the slow front overvoltages due to line energization in order to avoid faults. It can be achieved by using point on wave switching or circuit breakers equipped with closing resistors.

Regarding fast-front overvoltages the lightning flashover rate of the uprated line has been found very high compared to the flashover rate of a standard 400 kV line. So the use of line arresters has been studied and the paper shows that the use of one line arrester on only one external phase of a tower might be acceptable for towers of grounding resistance up to 40 Ω, but for towers of higher grounding resistance it seemed necessary to use arresters at least on both external phases.

The paper ends with some calculations of the electromagnetic field at ground level in normal operating condition. The values found were far below the maximum limits imposed by regulations in France.

VII. Acknowledgment

The authors gratefully acknowledge the contributions of G. Cabriel (EDF).

VIII. Appendix

Appendix 1 – Description of the conductors

TABLE I
CHARACTERISTICS OF CONDUCTORS

Conductors	Phase conductors	Ground wires
Internal diameter (mm)	0	12.2
External diameter (mm)	31	19.6
Lineic resistance (Ω / km)	0.0583	0.3

Appendix 2 – Definition of p.u.

For phase to ground p.u. is defined by :

$$1p.u. = \frac{420\sqrt{2}}{\sqrt{3}} = 344kVcrest$$

Appendix 3
Modelling of the system for flashover rate calculation.

The line (shield wires and phase conductors) is modelled by means of several spans at each side of the point of impact. Each span can be represented as a multi-phase untransposed distributed-parameter line section with either frequency-dependent or constant (and calculated at 500 kHz) parameters.

The line termination at each side of the above model, needed to avoid reflections that could affect the simulated overvoltages around the point of impact, is represented by means of either matching impedances or a long enough section, whose parameters are calculated as for the line wires.

A tower is represented as an ideal single-conductor distributed-parameter line where travelling waves are propagating at the speed of light in vacuum. The equal area model is used to model the air gap of insulator strings. The grounding electrodes of towers are represented as their low-frequency resistance ; this is justified by their small size [13]. Soil ionisation is not taken into account.

A lightning stroke is represented as an ideal current source with a concave waveform. A return stroke waveform is defined by the peak current magnitude, I_{100}, the rise time, t_f (= 1.67 (t_{90} – t_{30})), and the tail time, t_h, that is the time interval between the start of the wave and the 50% of peak current on tail. The lightning statistics presented in [2] have been used in this study, but the lightning probabilistic distribution considered for the crest value of the lightning stroke has calculated on ground using the electrogeometric model.

Appendix 4 – Evaluation of the flashover rate

Back-flashover rate

The back flashover rate corresponds to the flashover rate due to lightning impacting towers and shield wires. Its evaluation is based on the determination for each element j of the line the set $D_{j\theta k}$ of lightning strokes (str) impacting the element j and leading to a flashover for a given power frequency angle θ_k. The crest value If of the lightning current has been considered as the only random variable, the other parameters characterizing the lightning waveshape are considered equal to the medium value of the corresponding correlated distribution. The probability of back flashover due to element j is given by:

$$p_j = \frac{1}{M}\sum_{1}^{M} p_j(str \in D_{j\theta_k})$$

Where :

- M is the number of uniformly distributed phase angles considered ;
- P_j corresponds to the probability law of the lightning strokes impacting the element j.

The back flashover rate of the line is given by :

$$BFR = \frac{100}{l} \sum_{j=1}^{N} N_j P_j$$

Where :

- l is the length of the line (km) ;
- N_j is the average number of lightning strokes impacting the element j of the line ;
- N is the number of elements.

Nj and pj are estimated from the application of the electrogeometric model. The software EMTP-RV [12] is used to estimate $D_{j\theta k}$. The electromagnetic transient following a lightning stroke is simulated to determine if this lightning stroke leads to a flashover.

Shielding failure rate

The approach used to evaluate the shielding failure is similar to the one used to estimate the back flashover rate.

IX. REFERENCES

[1] J. Mahseredjian, S. Dennetière, L. Dubé, B. Khodabakhchian, and L. Gérin-Lajoie, on a new approach for the simulation of transients in power systems", Conference IPST 2005, Montréal.

[2] CIGRE, "Guide to Procedures for Estimating the Lightning Performance of Transmission Lines", brochure 63, October 91.

[3] CIGRE working group C4 301, "Line Surge Arrester Application Guide", draft CIGRE document, 2008.

[4] IEC, "Insulation Coordination – Part 2 : application guide", IEC 60071-2, 1996.

[5] IEC, "Computational Guide to Insulation Coordination and Modelling of Electrical Network", IEC 60071-4, 2003.

[6] A. Xémard, S. Dennetière, J. Michaud, P.Y. Valentin, Q. Bui-Van, A. Dutil, M. Giroux, J. Mahseredjian, "Methodology for the calculation of the lightning flashover rate of a line with or without line surge arresters", CIGRE session 2006, Paris.

[7] CENELEC, "Overhead electrical lines exceeding AC 45 kV, Part 1 : General requirements – Common specifications", EN 50341, 2001.

[8] Narda Safety Test Solution: EFC-400 - Electric and Magnetic Field Calculation, Version 5.03 (Bulid 2263) LF

[9] A. Xemard, J. Michaud, F. Maciela, T. Lassaigne, F. Sauvegrain, P. Auriol, J. G. Roumy, O. Saad, Q. Bui Van, A. Dutil, "Reduction of the double-circuit flashovers on a 400 kV overhead line", CIGRE Colloquium "Application of LSAs in pwer distribution and transmission system", Cavtat 2008.

[10] Ivo Uglesic, V. Milardic, B. Filipovic-Grcic, A. Tokic, "Evaluation of Energy Stress on line Arresters", CIGRE Colloquium "Application of LSAs in pwer distribution and transmission system", Cavtat 2008.

[11] Journal official de la république française, "Energie électrique conditions techniques de distribution", arrêté technique du 17 mai 2001

[12] EMTP-RV, documentation, WEB site www.emtp.com.

[13] X. Legrand, A. Xémard, P. Auriol, C.A. Nucci, O. Bérard, "Comportement des prises de terre des pylônes en HF", Saint Malo (France), 13th international colloquium on EMC, 2006.