ICLP2006 KANAZAWA
28th International Conference on Lightning Protection

# Insulation coordination of MV cables against lightning-induced overvoltages generated by LEMP-coupled overhead lines

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***Abstract*--The paper deals with the stresses of cable insulations due to lightning induced overvoltages for the case of distribution networks composed by MV overhead lines and buried cables. We are here interested only in the conditional probability of the cable breakdown in absence of line flashovers, which means that flashovers along the overhead line are disregarded. We illustrate a procedure based on the application of the Monte Carlo method and on a simulation tool for the accurate computation of lightning-induced voltages on an overhead line, namely the LIOV code. A frequency dependent parameter cable model is used for the calculation of the overvoltages stressing the cable insulation, which is assumed not to be illuminated by LEMP. We associate to each calculated overvoltage a breakdown probability for the cable, by using experimentally obtained probabilistic distributions of the breakdown voltages of the cable insulation for different families of voltage wave shapes. These probabilities, together with the expected number and characteristics of the lightning events, allow us to infer the yearly number of expected failure events in the above assumptions. The breakdown behavior of extruded cable insulation is represented by a 2-parameter Weibull distribution obtained from experimental tests on cable models, manufactured with the same materials and same technologies of real cables, by applying the well-known statistical "enlargement law".**

***Index Terms*—Lightning-induced voltages, insulation coordination, Monte Carlo method, MV extruded cables, LIOV code.**

## I. INTRODUCTION

Lightning-induced voltages represents one of the major threats for the power quality of distribution systems. In general, although distribution systems are formed by either overhead and cable lines, studies concerning this topic consider only the distribution system as formed only by overhead lines. In this paper, instead, we deal with distribution lines composed by either overhead lines and MV cables, and we focus only on the cable insulation.

In general, the insulation coordination of cable lines can be assessed via both the deterministic method and the statistical method [1-4]. The statistical method, conceptually more correct, is to be preferred, as it enables a rational approach to the insulation coordination [5]. For the statistical analysis is particularly suitable the adoption of approaches based on Monte Carlo simulations, in which accurate models of the various physical origins of disturbances and their propagation in the network can be easily incorporate (e.g. [6,7,8]). For the case of induced voltages on overhead lines a procedure has been proposed in [9], based on Monte Carlo simulations carried out by using a computer code, called LIOV (Lightning Induced Overvoltage code) [10], which implements accurate modelling of the LEMP (Lightning ElectroMagnetic Pulse) induced voltage mechanism.

Estimation of overvoltages with proper numerical programs is fundamental since it enables to evaluate the actual voltage wave shapes that stress the cable line. On the other hand, the statistical evaluation of the risk can not be assessed if the breakdown behaviour of the insulation is unknown or if it is referred only to the basic impulse level (BIL) of the cable line. Consequently dielectric strength tests are an obliged step.

In [11] a statistical approach for the insulation coordination of extruded cable lines was applied to the case of overvoltages due to direct lightning strokes to MV and HV overhead lines connected to a cable end.

In this paper we are interested instead only in the induced overvoltages collected by the overhead line that result in a stress for the cable insulation. In particular, we aim at determining the probability of the cable breakdown when flashovers along the overhead line are disregarded. This means that we are interested in estimating the conditional probability of cable breakdown in absence of overhead line flashovers. The overvoltages caused by the

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coupling between the LEMP and the cable line are not taken into account, as a first approximation. For the complete assessment of the indirect lightning induced transient effects on buried cables, also the LEMP-to-cable coupling are in general to be taken into account, as shown in [39,40].

We refer to the power distribution system configuration illustrated in Fig. 1. No surge arresters at both ends of the cable line have been considered. Only the cable insulation has been considered for the insulation coordination point of view and the effects of the estimated overvoltages on transformer insulation are therefore non taken into account.

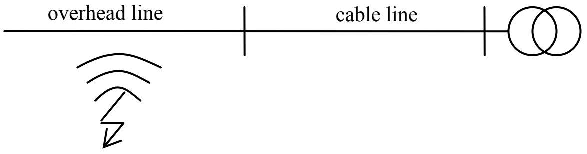

Fig. 1. Distribution system configuration considered for the analysis.

Section II describes the proposed procedure for the evaluation of the yearly number of expected cable failure events due to the induced overvoltages on the overhead line. Section III describes the experimental tests carried out to infer the breakdown behaviour of the extruded cable insulation, represented by a 2-parameter Weibull distribution. Section IV illustrates the method used to attribute a breakdown probability to each simulated overvoltage on the basis of the experimental test results. In Section V the proposed procedure is applied to the case, illustrated in Fig. 1, of an overhead line connected to a cable, and the results obtained for different cable lengths and soil resistivity values are reported. The conclusions of the paper (Section VI) finally include some indications on future developments.

## II. PROPOSED PROCEDURE FOR THE ESTIMATION OF THE YEARLY NUMBER OF EXPECTED FAILURE EVENTS IN THE CABLE DUE TO INDIRECT-LIGHTNING OVERVOLTAGE ON A CONNECTED OVERHEARD LINE

As already mentioned, a set of induced overvoltage waveshapes at the termination of the LEMP-coupled overhead line connected to the cable have been calculated by the following steps.

a) A large number of lightning events $n_{\mathrm{tot}}$ is randomly generated. Each event is characterized by the lightning current parameters (i.e. peak value $I_{\mathrm{p}}$ and front time $t_{\mathrm{f}}$) and the stroke location with respect the position of the overhead line. The $I_{\mathrm{p}}$ and $t_{\mathrm{f}}$ values are assumed to follow the log-normal probability distributions adopted by Cigré [12,13] for negative first strokes. The stroke location is assumed to be uniformly distributed around the line in an area A wide enough to collect all the events that are able to cause a cable fault.
b) From the total set of events, the $n_{\mathrm{ind}}$ events relevant to indirect lightning are selected by adopting the lightning incidence electrogeometric model for the line adopted by the IEEE Std. 1410 [14].
c) For each indirect lightning event, the induced voltage waveshape at the line termination connected to the cable is calculated – as earlier mentioned – by means of the LIOV code [2].

The estimation of the overvoltages stemmed from a cable line due the successive reflections between cable ends and attenuation along cable length, is fundamental for the evaluation of the overvoltage cable stress. Frequency parameter cable line model, following the Shelkunoff theory [25-30], has then been implemented in a MATLAB program in order to evaluate the overvoltage stressing the cable line insulation due to overvoltage impinging a cable end. Cable line length plays an important role on the transient behaviour: successive voltage wave reflections between sending and receiving ends can enhance the overvoltage peak value well above the overvoltage transmitted from the overhead line especially for short cables.

A breakdown probability $R_{\mathrm{i}}$ is associated to each calculated overvoltage, by comparing its amplitude $V_i$ to the breakdown voltage cumulative distribution function (cdf) of the cable insulation $F_F(V)$ experimentally inferred for the same overvoltage waveshape $w_{\mathrm{i}}$ that stress the cable.

The number of annual insulation flashovers $F_{\mathrm{p}}$ is obtained as

$$F_p = \frac{A \cdot N_g}{n_{\mathrm{tot}}} \cdot \sum_{i=1}^{n_{\mathrm{ind}}} R_i \qquad (1)$$

where $N_{\mathrm{g}}$ is the annual lightning ground flash density (in $\mathrm{km}^{-2}\ \mathrm{yr}^{-1}$).

The estimation of $F_F(V)$ is assessed through dielectric strength tests, as described in the next section.

## III. EXPERIMENTAL DETERMINATION OF THE BREAKDOWN BEHAVIOR OF EXTRUDED CABLE INSULATION

The correct estimation of the risk of failure and consequently the expected number of failure per year impose that cdf $F_F(V)$ should be estimated for each stressing wave shape stemmed from propagation along the cable line of the impinging overvoltage. Obviously the costs of dielectric strength tests dictate a reduce number of testing wave shapes that are usually restricted to the standard ones. Furthermore, the utilization of mini-cables manufactured with the same materials and the same technologies of the real cables is a way to save money for dielectric strength tests. In fact, thanks to the well-known statistical enlargement law [31,32], it possible to estimate the breakdown voltage distribution of whichever real cable from the estimation of the breakdown voltage distribution of the mini-cables.

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[2] Starting from the waveform of the lightning current at the channel base, the LIOV code implements a return-stroke model [15] to infer the time and spatial distribution of the current along the channel, then the lightning electromagnetic pulse (LEMP) is calculated by using the Master and Uman equations [16] and the Cooray-Rubinstein formula [17-19] to take into account the effect of the ground on the propagating field. The Agrawal et al. model [20], extended to the case of a lossy ground [21], is then used to represent the coupling between LEMP and the multiconductor overhead line, which finally allows the evaluation of the induced voltages along the line. The accuracy of the LIOV code has been verified by the comparison with experimental data, both on reduced scale models [22,23] and on a full scale set-up [24]. This code evaluates the lightning performance evaluation of more realistic line configurations than the one to which the Rusck formula applies.

The breakdown voltage distribution of power cables with extruded insulation well fit 2-parameter Weibull distribution [31,33,34]:

$$F_F(V) = 1 - \exp\left[-\left(\frac{V}{\alpha}\right)^{\beta}\right] \tag{2}$$

where $V$ is the amplitude of the voltage stress in kV, whilst $\alpha$ and $\beta$ are the scale and shape parameters. Scale parameter $\alpha$ represents the breakdown voltage at 63.2% and shape parameter $\beta$ depicts the dispersion of the data: small values of $\beta$ means high dispersion and vice versa. Shape parameter $\beta$ is also a homogeneity index for the insulation compound [35]. Complex robust estimators [36] are always required for the estimation of such parameters.

When mini-cables are used in dielectric strength tests, the estimation of scale parameter $\alpha$ requires the application of the enlargement law. The value of such parameter is a function of radial geometry and length of the real cable. On the contrary shape parameter $\beta$ does not change with the enlargement. Fig. 2 shows an example of the breakdown voltage at 63.2% of probability (formally equal to scale parameter $\alpha$) as a function of cable length for different value of shape parameter $\beta$. The results have been obtained for a typical 20 kV cable with the following characteristics: 3 single core - trefoil lay-out, 150 mm$^2$ conductor cross section and 5.5 mm insulation wall.

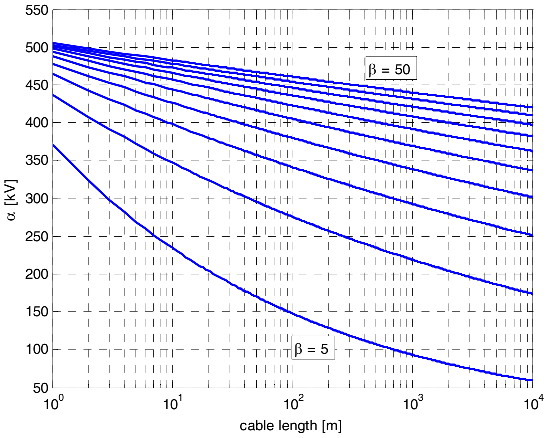

Fig. 2. Example of breakdown voltage at 63.2% of probability (formally Weibull scale parameter $\alpha$) as a function of cable length for different values of shape parameter $\beta$.

Fig. 2 illustrates the importance of shape parameter β: larger values mean weaker decay with increasing cable length.

The probability distribution of breakdown voltage can be estimated from (2) using, for each cable length, the scale and shape parameters reported in Table I for various voltage wave shapes and cable lengths, namely 100 m, 500 m and 1000 m. The values of the parameter reported in Table I are obtained from [34], by applying the statistical enlargement law [31,32]. In [34] the dielectric strength tests on mini-cables with EPR (Ethylene Propylene Rubber) insulation were performed, following the test procedure reported in [37], by applying the different voltage wave shapes mentioned in Table I. The EPR compound considered is a typical one used for medium voltage cable insulation.

Figs. 3, 4 and 5 plot the four probability density function of breakdown voltage for different voltage shapes and for the three lengths considered in Table I. It is interesting to note that for a fixed value of voltage level, the breakdown voltage probability increases with the increasing cable length. This is due to the higher probability to find inherent inhomogeneities of solid-extruded dielectric materials with increasing of the cable length: a larger number of weak points can be found in larger size insulation rather than in smaller size.

TABLE I

WEIBULL PARAMETERS OF THE PROBABILITY DISTRIBUTION FUNCTION FOR DIFFERENT VOLTAGE SHAPES AND DIFFERENT CABLE LENGTHS.

| Cable length | Weibull parameters | Wave shape | | | |
|---|---|---|---|---|---|
| | | 0.4/40 µs | 1.2/50 µs | 15/600 µs | 100/1100 µs |
| 100 m | α (kV) | 317.3 | 249.5 | 294.1 | 372.2 |
| | $\beta$ | 14.2 | 9.1 | 11.0 | 18.8 |
| 500 m | α (kV) | 283.3 | 209.1 | 254.1 | 341.7 |
| | $\beta$ | 14.2 | 9.1 | 11.0 | 18.8 |
| 1000 m | α (kV) | 269.8 | 193.7 | 238.5 | 329.3 |
| | $\beta$ | 14.2 | 9.1 | 11.0 | 18.8 |

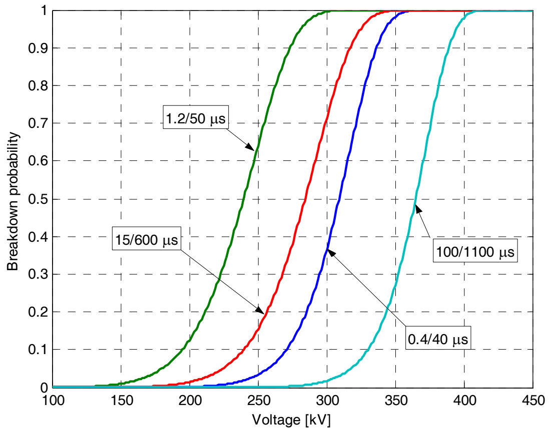

Fig. 3. Cumulative probability distribution of breakdown voltage for different impulsive voltage shapes for 100 m of a 20 kV cable, with 150 mm$^2$ conductor cross section and 5.5 mm insulation wall.

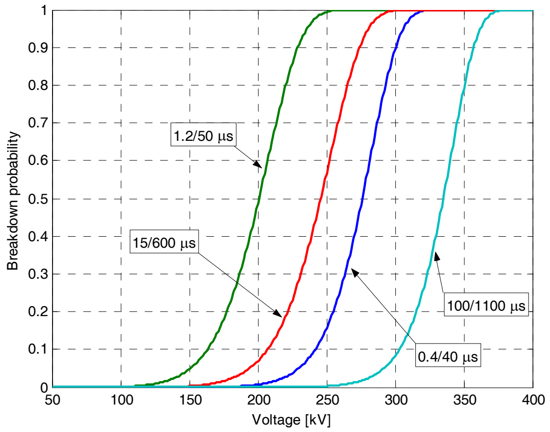

Fig. 4. Cumulative probability distribution of breakdown voltage for different impulsive voltage shapes for 500 m of a 20 kV cable, with 150 mm$^2$ conductor cross section and 5.5 mm insulation wall.

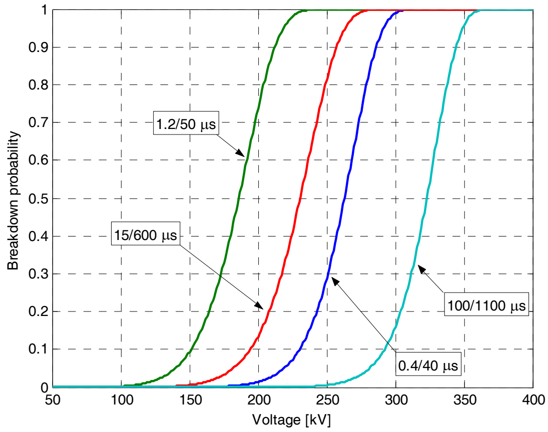

Fig. 5. Cumulative probability distribution of breakdown voltage for different impulsive voltage shapes for 1000 m of a 20 kV cable, with 150 $mm^2$ conductor cross section and 5.5 mm insulation wall.

## IV. PROCEDURE USED TO ATTRIBUTE A SPECIFIC BREAKDOWN DISTRIBUTION TO EACH CALCULATED OVERVOLTAGE WAVESHAPE

The configuration of the considered network is illustrated in Fig. 1. As already mentioned, the cable length has been considered of 100, 500 and 1000 m. Cable screen has been considered grounded at the sending end (overhead/cable transition junction) with impulse impedance of 30 Ω and at the receiving end (transformer side) with impulse impedance of 20 Ω. The transformer has been considered as a phase to ground lump capacity (for each phase) of 450 pF.

The overhead line is 2 km long, with the typical configuration illustrated in Fig. 6. The external conductors are assumed to be located at 10 m above ground and the central conductor at 10.8 m above ground. The distance between the external conductors is assumed equal to 1.3 m.

Fig. 6. Typical MV truss for 20 kV overhead line used in Italy.

We have applied the procedure described in Section II, for $n_{tot}$ equal to 40 000 events distributed over a 2 km large area $A$ along a side of the overhead line. By applying the line incidence electrogeometric model adopted in [14], the calculated number of indirect events $n_{ind}$ is equal to 39 612. All the direct events are assumed to cause flashovers along the over head line. Moreover, also some indirect events, namely 42 and 405 for the case of soil resistivity equal to 100 Ωm and 1000 Ωm respectively, are also expected to cause overhead line faults because their induced voltage amplitudes exceed the critical flashover assumed equal to 230 kV [38]. For the reasons already mentioned in the Introduction, all these events are not taken into account in the computation of conditional probability of cable breakdown.

The rise time probability distribution of the overvoltages stressing the cable insulation, calculated as described in Section II, well fits a Gaussian distribution with a mean value of about 9.2 μs and a standard deviation of about 4.4 μs. Fig. 7 plots two wave shapes relevant to one of the highest voltage values stressing the cable insulation for an indirect lightning overvoltage induced on the overhead line: in such a case the cable length is 100 m long with soil resistivity of 1000 Ωm. The two wave shapes represent the overvoltages at the receiving end of the three cable cores connected to the central and external phases of the overhead line (see also Fig. 7).

The wave shapes reported in Fig. 7 are both 21/30 μs and consequently the value of risk in this case is estimated taking into account the breakdown voltage distribution evaluated with the nearest wave shape among those stressing the cable insulation. Taking into account that the breakdown of the EPR insulation seems to be mainly sensitive to the front of the stressing voltage wave [28,29], the breakdown distribution $F_F(V)$ considered for the computation are selected in compliance with the closer rise time of those reported in Table I. Consequently for the breakdown behaviour of the cable insulation here considered, the wave shape with a rise time of 15 μs is assumed.

From Table I and equation (2) it is possible to estimate the value of risk of cable failure for such event: $7.6 \times 10^{-4}$ for the cable core connected to the central phase of the overhead line and $2.6 \times 10^{-4}$ for the cable cores connected to the external phases of the overhead line.

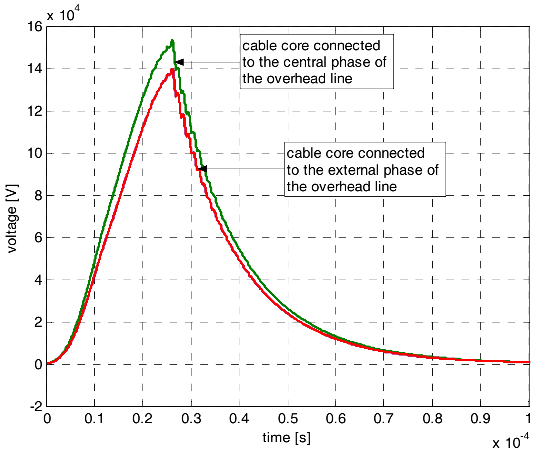

Fig. 7. Overvoltage wave shapes stressing the three cores cable insulation at the receiving end for an induced overvoltage on the overhead line. Cable length 100 m; soil resistivity 1000 Ωm.

## V. DISCUSSION OF THE RESULTS

Because of the symmetry of the conductor positions in the overhead line lay-out of Fig. 6, external phases have the same risk values and consequently of the expected number of failure per year $F_p$.

In Table II the values of the risk $R = \frac{1}{n_{tot}} \sum_{i=1}^{n'_{ind}} R_i$ for the cable phases connected to the external conductors and the central conductor of the overhead line, respectively are presented. As already mentioned, $n'_{ind}$ is the number of indirect lightning events that are expected not to cause overhead line flashovers. The results are calculated for two values of the soil resistivity, namely 100 Ωm and 1000 Ωm, and for the three considered cable lengths, namely 100 m, 500 m and 1000 m.

TABLE II
RISK OF CABLE LINE FAILURE FOR LIGHTNING-INDUCED OVERVOLTAGES DETECTED FROM THE OVERHEAD LINE.

| Soil resistivity [Ωm] | Cable length [m] | R on external phases | R on central phase |
|---|---|---|---|
| 100 | 100 | $2.8 \times 10^{-8}$ | $8.0 \times 10^{-8}$ |
|  | 500 | $1.3 \times 10^{-11}$ | $3.8 \times 10^{-11}$ |
|  | 1000 | $9.2 \times 10^{-14}$ | $2.6 \times 10^{-13}$ |
| 1000 | 100 | $2.1 \times 10^{-7}$ | $6.1 \times 10^{-7}$ |
|  | 500 | $7.5 \times 10^{-11}$ | $2.0 \times 10^{-10}$ |
|  | 1000 | $7.1 \times 10^{-13}$ | $2.0 \times 10^{-12}$ |

From the risk values $R$ reported in this table we note that:

- as expected, the highest values of the risk $R$ are obtained for a cable length equal to 100 m , but, in any case, very small values are estimated in respect to the case of direct lightning events to the overhead line [11];
- the risk value changes over three order of magnitude, by increasing the cable length from 100 m to 500 m and over two order of magnitude from 500 m to 1 km;
- the variation of soil resistivity from 100 Ωm to 1000 Ωm gives rise to a risk increase of an order of magnitude.

In Table III the values of expected number of annual insulation flashovers $F_p$ and allowed number of failures per year $F_{pA}$ are reported, for the case of $N_g = 1$ km$^{-2}$ yr$^{-1}$. The number of allowed failure per year here is assumed 0.2 per 100 km of cable line. This is the typical value accepted from the utilities. As in Table II, the results of Table III are calculated for soil resistivity values of 100 Ωm and 1000 Ωm and for three different cable lengths.

TABLE III
NUMBER OF EXPECTED ($F_P$) AND ALLOWABLE ($F_{PA}$) FAILURE EVENTS PER YEAR FOR THE CABLE LINE FOR LIGHTNING-INDUCED OVERVOLTAGES DETECTED FROM THE OVERHEAD LINE.

| Soil resistivity [Ωm] | Cable length [m] | $F_p$ on external phases | $F_p$ on central phase | $F_{pA}$ |
|---|---|---|---|---|
| 100 | 100 | $3.3 \times 10^{-7}$ | $9.5 \times 10^{-7}$ | $2.0 \times 10^{-4}$ |
|  | 500 | $1.6 \times 10^{-10}$ | $4.5 \times 10^{-10}$ | $1.0 \times 10^{-3}$ |
|  | 1000 | $1.1 \times 10^{-12}$ | $3.1 \times 10^{-12}$ | $2.0 \times 10^{-3}$ |
| 1000 | 100 | $2.5 \times 10^{-6}$ | $7.2 \times 10^{-6}$ | $2.0 \times 10^{-4}$ |
|  | 500 | $8.9 \times 10^{-10}$ | $2.4 \times 10^{-9}$ | $1.0 \times 10^{-3}$ |
|  | 1000 | $8.4 \times 10^{-12}$ | $2.2 \times 10^{-11}$ | $2.0 \times 10^{-3}$ |

We note that:

- the highest value of expected number of failure per year is two order of magnitude lower than the allowed number;
- the worst condition occurs for the cable length of 100 m. In this case the ratio of the number of expected and the number of allowed failure events is $3.6 \times 10^{-2}$ for a soil resistivity of 1000 Ωm in respect to $4.8 \times 10^{-3}$ of the case with a soil resistivity of 100 Ωm.

## VI. CONCLUSIONS

In this paper we have assessed the conditional probability of the cable breakdown in absence of line flashovers for the case of overvoltages induced by nearby lightning on a distribution system composed by overhead lines and cables. For the case of very short length of cable lines and high values of soil resistivity, the largest value of risk of failure and the largest value of expected number of failures per year due to induced overvoltage are about two orders of magnitude lower than the allowed number of failure per year.

Consequently, within the limits of the assumptions, the insulation coordination of cable lines that are part of overhead/cable composite MV systems as to be accomplished basically taking into account the overvoltages stressing the cable in correspondence of flashover events along the overhead line.

Further investigation is needed, however, to evaluate the effects on the cable insulation on the coupling between the LEMP and buried cables.

## VII. ACKNOWLEDGMENT

This work was supported in part by the Italian Ministry for University Scientific and Technological Research.

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