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VOLTAGE TRANSIENTS IN A DISTRIBUTION NETWORK CORRELATED WITH EVENTS IDENTIFIED BY A LIGHTNING LOCATION SYSTEM

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Abstract – Monitoring units for the measurement of high-frequency voltage transients have been in operation at three different busses of an Italian medium voltage (MV) distribution feeder, mainly composed by overhead lines, in March 2007 – August 2008. The feeder is located in a region characterized by a high ground flash density value (4 flashes/km^2/yr); many of the recorded voltage transients may be correlated with the lightning events detected for the same region by the Lightning Location System (LLS) CESI-SIRF. The paper presents some experimental results obtained using the monitoring units and their comparison with computer results obtained using a LIOV-EMTP model of the considered MV feeder. A procedure aimed at achieving the best fit between measurements and calculations, which takes into account the uncertainties associated with LLS data, is also presented.

1 INTRODUCTION

The correlation between faults and events detected by Lightning Location Systems (LLS) has been investigated in the literature taking into consideration both high voltage transmission lines (e.g. [1-8]) and medium voltage distribution networks (e.g. [9-11]). In these studies, data from LLSs are compared with those coming from fault-event recorders, such as monitoring system of relays operations. In the above mentioned studies the correlation is established, in general, by means of a time window and spatial distance criteria. In particular, a lightning event detected by a LLS is assumed to be the reason of a line fault if the following two conditions are satisfied: i) the two events, namely those recorded by LLS and relay operation ones, are recorded within a specific time window (in general of few seconds); ii) the distance between the estimated stroke location and the line is lower than a chosen distance, assumed to be ‘critical’.

As LLSs provide also a 50% error ellipse [2] for stroke location estimates, in the above mentioned studies the spatial correlation criterion is based, in general, on the identification of a positive intersection between the error ellipse and a corridor nearby the line.

In order to take into account all the uncertainties associated to the LLS estimates, [12,13] describe a procedure for the estimation of the probability distribution of the lightning-originated voltages along the power lines, associated to each specific LLS detected event. The procedure is based on the application of the Monte Carlo method and the use of the LIOV-EMTP code [14,15] for the accurate calculation of the induced voltages in the distribution network.

The conclusion of [14,15] was that even for those faults for which the correlation with lightning event was evident, the flashover probability due to the lightning was unexpectedly low. For this reason it appears of interest to further assess the reasons for possible disagreements between measurements and calculations which may depend both on the imperfect knowledge of the distribution system configuration and on the inherent uncertainty of the LLS data.

In this paper we first summarize the characteristics of a Distributed Monitoring System (DMS), able to measure a-periodic voltage transients characterized by a frequency content up to 4 MHz, which has been installed in March 2007 in three buses of a three-phase overhead feeder of an Italian medium voltage distribution network and that was first presented in [16].

We then present some significant experimental records relevant to one flash, obtained with the above mentioned DMS, along with procedure aimed at achieving the best fit between recorded voltage transients and computer results obtained by using a LIOV-EMTP model of the considered feeder, capable of taking into account the uncertainties associated with LLS data and the complex configuration of the distribution system.

2 LLS AND DMS EXPERIMENTAL DATA

2.1 LLS data

The lightning strokes of interest are selected within a rectangular area surrounding the distribution feeder, having a maximum distance of 2 km from the feeder extremities with a total area equal to 144 km^2. During the period from March 2007 to August 2008, CESI-SIRF [17,18] has detected 570 flashes and 851 strokes (778 negative and 73 positive) in the considered area.

Fig. 1 shows the feeder topology, the detected stroke locations and the position of measurement stations installed in correspondence of three secondary 20/0.4 kV substations (Torrate, Venus, and Maglio). The statistics of the estimated current peaks are reported in Table I.

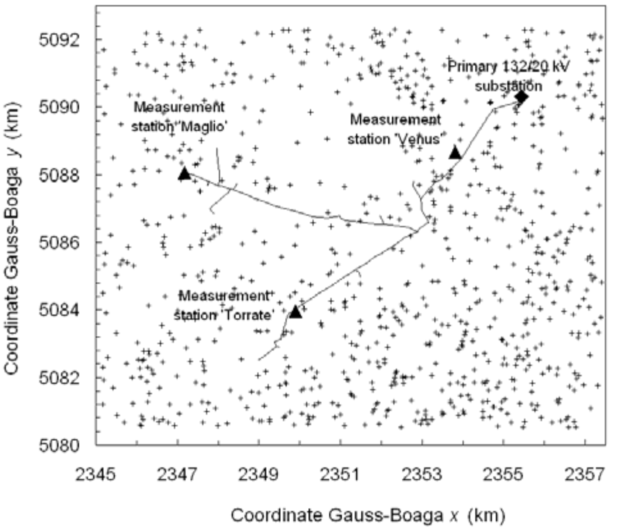


Fig. 1 – Considered distribution feeder, LLS-detected stroke locations during the period March 2007 – August 2008, position of measurement stations and of the primary substation.

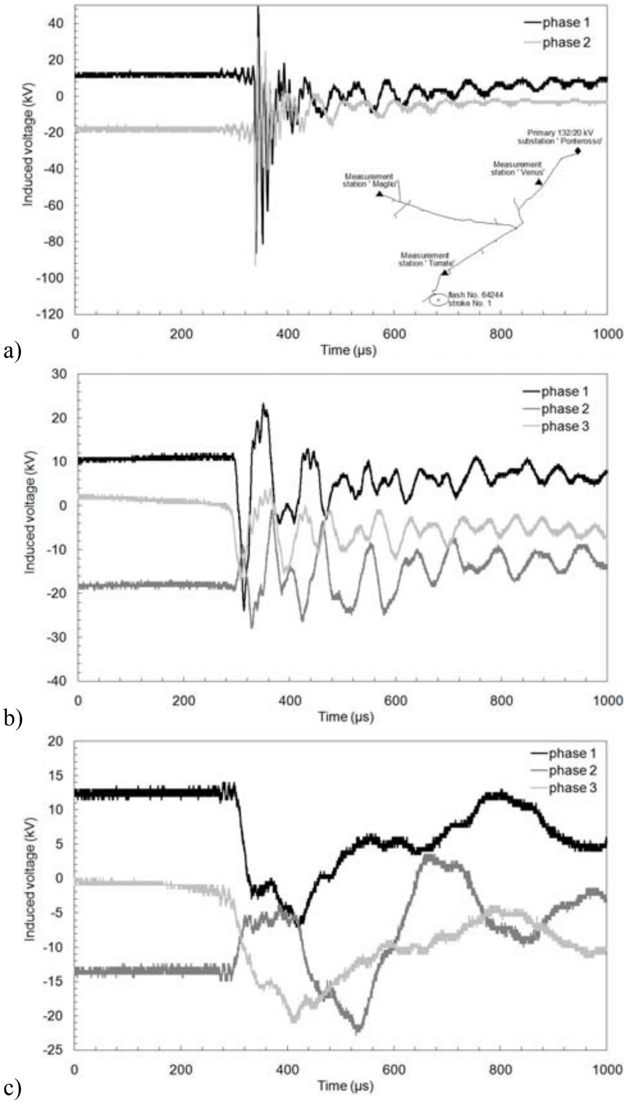
Table I: Statistical characteristics of the current peak values of the LLS-detected strokes in the area of interest.

Strokes	No.	Mean (kA)	Max (kA)	Min (kA)	Median (kA)	Std dev (kA)
Neg. first	498	16.4	141.1	2.5	12.2	15.8
Pos. first	72	47.5	250.7	8.6	32.9	44.8
Neg. subs	280	16.4	54.3	3.5	14.3	9.5
Pos. subs	1	10.6				

2.2 DMS data

Each DMS unit is able to record the transient waveform together with its UTC-GPS starting time. As described in [16], each phase-to-ground voltage is conditioned by means of a capacitive voltage divider (CVD) Pearson VD-305-A, with 300 kV insulation level, 10000 V/1 V nominal ratio, 30 Hz to 4 MHz (-3 dB) bandwidth, 100 ns rising time and ± 1% accuracy. The output signals of the three CVDs are the inputs of an event detection block specifically designed to detect the presence of transients superimposed to the supply voltage waveform. The output of this device is a TTL logic signal that acts as a pre-trigger for the data acquisition system and as a trigger for the GPS device (characterized by a nominal accuracy of ± 250 ns) in order to record the starting time of the transient. The data acquisition system is composed by two 8-bit digitizers working at the sampling frequency of 100 MSa/s with a nominal accuracy of ± 1% that allow an acquisition window of 1.5 ms for maximum 20 return strokes induced transients.

Until August 2008, each of the three DMS stations has recorded several voltage transients (about 2000). The feeder is located in an area characterized by a high ground flash density value (4 flashes/km^2/yr).



a)

b)

c)

Fig. 2 - Voltage transients time correlated to the first stroke of lighting flash #64244 measured at the three substations: a) Torrate (only phase 1 and phase 2 are available), b) Venus, and c) Maglio.

Fig. 2 shows the voltage transients time correlated to the first stroke of flash #64244 (June 15th, 2007 – 16:41:49.626720), with -11.2 kA estimated current amplitude. The flash is quite simultaneous also to the intervention of the 0-sequence relay operation of the primary substation. Fig. 2a also shows the stroke location 50% probability error ellipse (characterized by 400 m and 300 m semi-axes). The flashover affected phase 2, as the voltage transient waveforms relevant to that phase tend to zero.

Fig. 3 shows the voltage transients time correlated to the fourth stroke of flash #30260 (August 30th, 2007 – 11:23:36.307950), with -48.4 kA current peak estimate. The flash did not produce any line flashover. The semi-axes of the stroke location 50% probability error ellipse, shown in Fig. 3a, are equal to 600 m and 200 m.

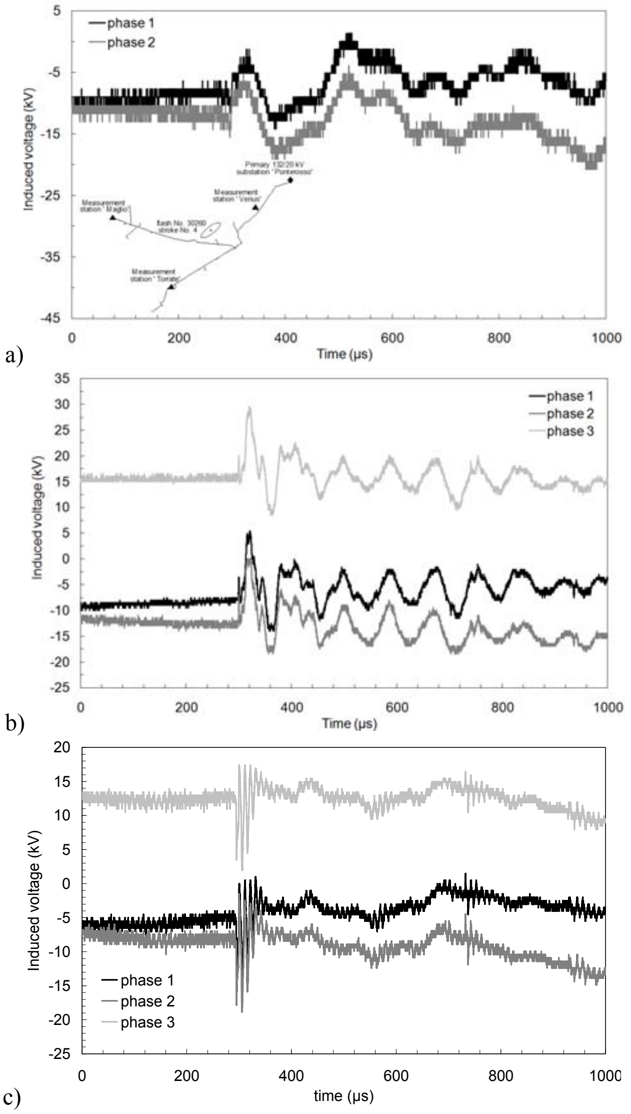


Fig. 3 - Voltage transients time correlated to the fourth stroke of lighting flash #30260 measured at the three substations: a) Torrate (only phase 1 and phase 2 are available), b) Venus, c) Maglio.

3 LIOV-EMTP MODEL OF THE DISTRIBUTION FEEDER

The distribution feeder shown in Fig. 1 has an overall length of 21.6 km and is composed manly by overhead lines (20.3 km), whilst the total length of shielded cable is 1.3 km.

As the finite-difference-time-domain (FTDT) solution of the Agrawal et al. coupling model [19], implemented in the LIOV-EMTP code, requires the calculation of the horizontal lightning electric at equally spaced points along each line, the coordinates of all these points have been obtained by an accurate graphical representation of all the overhead lines of the feeder.

The shielded cables have been modeled as non-illuminated lines by means of the FDQ-cable model of the Electromagnetic Transient Program [20].

The main assumptions adopted in the LIOV-EMTP calculations are:

- straight lightning channel perpendicular to the ground plane;
- return stroke speed equal to 1.5 10^8 m/s;
- spatial-time distribution of the return stroke current represented by the so-called transmission line (TL) model;
- ground conductivity value equal to 10 mS/m in both electromagnetic field calculation, based on the use of the Cooray-Rubinstein formula [21,22], and in the surge propagation [23];
- lightning current waveshape composed by two Heidler functions [24];
- power transformers at the MV line terminations represented by a phase-to-ground capacitances equal to 250 pF and protected by 20 kV rated-voltage surge arresters with the V-I characteristic reported in [25].

4 COMPARISON AND BEST FIT BETWEEN VOLTAGE TRANSIENT MEASUREMENTS AND SIMULATION RESULTS

We make reference to the event of Fig. 3, which has not produced a line flashover.

For the comparison shown here below (Fig. 4 and Fig. 5), being the measured transients synchronized by the UTC-GPS time stamps, the calculated waveforms are superimposed with the measured ones by choosing a unique zero reference for the time axis so that we obtain the same instant in which the -4 kV value is reached at phase 2 of the Maglio substation.

Fig. 4 shows the comparison between measured and calculated voltage transients obtained by assuming the stroke location coordinates to the center of the 50% error ellipse of the LLS stroke location estimation and by assuming the parameters of the Heidler functions equal to I_{01} = 43.5 kA, τ_{11} = 0.25 μs, τ_{21} = 2.5 μs, n_1 = 2, I_{02} = 26.4 kA, τ_{12} = 2.1 μs, τ_{22} = 230 ms, n_2 = 2, being amplitudes I_{01} and I_{02} chosen to obtain a lightning current peak value equal to the LLS estimation of 48.4 kA.

Fig. 5 shows the analogous comparison accomplished using the earlier mentioned best fitting procedure, which is described here:

1) a set of some one hundred random stroke locations is generated, by using the bi-variate normal distribution "centered" on the estimated location, with a 50% probability to be inside the 50% probability error ellipse [26];

2) for each of the generated stroke location, the parameters I_{01} and I_{02} are suitably scaled (by using the `lsqnonlin` Matlab function) in order to minimize the least square error between measured and calculated induced voltages at the three measurement stations.

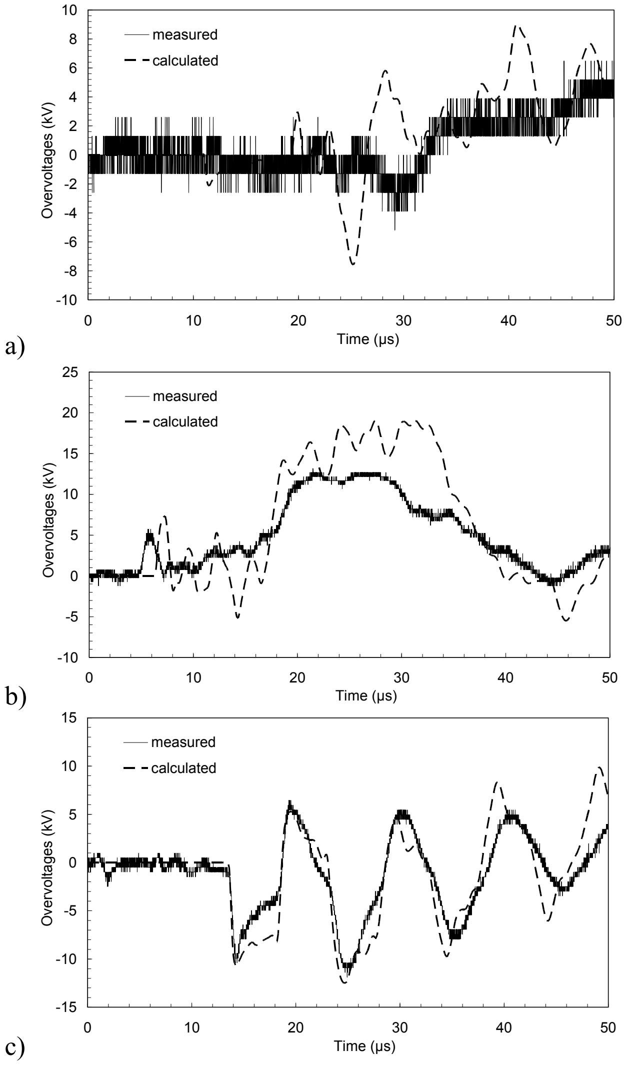


Fig. 4 – Comparison between measured and calculated overvoltages in phase 2 at the three substations: a) Torrate, b) Venus, c) Maglio, for stroke 30260-4. Stroke location at the centre of the error ellipse and current peak amplitude equal to the LLS estimation.

For the considered event, the procedure selected a current peak equal to 30.1 kA (Heidler function parameters $I_{01} = 27.1$ kA, $I_{02} = 16.4$ kA) and the stroke location close to the 50% error ellipse shown in Fig. 6.

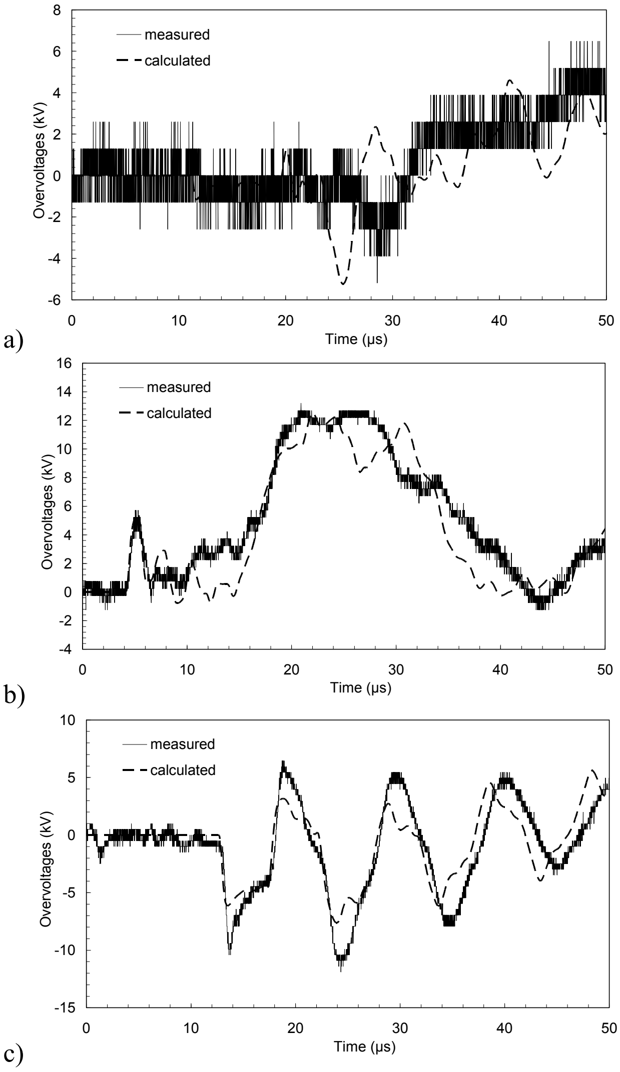


Fig. 5 – Comparison between measured and calculated overvoltages in phase 2 at the three substations: a) Torrate, b) Venus, c) Maglio, for stroke 30260-4. Stroke location and current peak amplitude using the best matching procedure.

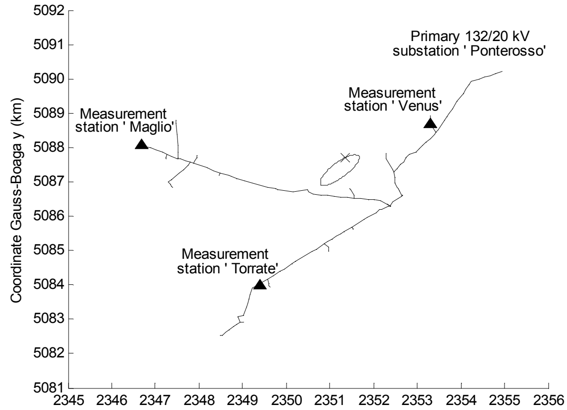


Fig. 6 – Stroke location selected by the best-matching procedure.

The larger accuracy of the stroke location estimation selected by the best-fitting procedure is clear if one observe the early time portion of the waveshapes at the substation Venus.

5 CONCLUSIONS

The satisfactory fit between recorded lightning induced voltage transients and computer simulations obtained by using a model of the response of a distribution network illuminated by a lightning electromagnetic pulse is inherently complex due to both the configuration of distribution systems – that largely differs from the straight overhead line sometimes assumed in studies on the subject – and to the uncertainties and incompleteness associated with the LLS estimates. The procedure – aimed at achieving the best fit between measurements and calculations – takes into account the information provided by the 50% error ellipse of the stroke location estimation and adjusts the current peak value estimation by using a least square optimization procedure, being the error associated with a specific current amplitude LLS estimate not available. Additional tests are being carried out in order to understand how far the deviations of the computer results from the measured ones depend on the imperfect knowledge of the distribution system or to the inherent uncertainty of the LLS data.

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