Comparison of Two Computational Programs for the Calculation of Lightning-Induced Voltages on Distribution Systems

M. Paolone, E. Perez, A. Borghetti, C.A. Nucci, F. Rachidi and H. Torres

Abstract—Lightning-induced voltages are important sources of power quality problems: indeed, they can cause short interruptions and voltages sags on distribution systems. The analysis of these disturbances induced on distribution networks by lightning electromagnetic pulses (LEMP) radiated by nearby lightning, requires the availability of accurate models and relevant computer programs of LEMP-illuminated lines. These should be able to reproduce the real and complex configuration of distribution systems including the presence of shielding wires and their groundings, as well as that of surge arresters and distribution transformers.

The paper is aimed at comparing two software tools for the calculation of lightning-induced voltages, namely the LIV-ATP and LIOV-EMTP programs.

Keywords: Lightning-induced voltages, EMTP, ATP, LIOV code, LIV code.

I. Introduction

THE calculation of lightning-induced transients on distribution power networks requires the availability of accurate models of LEMP-illuminated lines and their relevant implementation into software tools. Several contributions on this topic have been presented in the literature: analytical equations for an infinite wire above perfectly-conducting ground [1], approximate formulas for simple overhead lines [2][3] and, finally, sophisticated software tools [4-13] aimed at the calculation of the induced voltages on distribution networks having realistic topology and characteristics. The aim of the present paper is the comparison between the results, features and capabilities of two computation programs of this type namely: the LIV-ATP [4-7] and the LIOV-EMTP [8-11].

The comparison of the two programs is carried out discussing first the differences of the two theoretical approaches and then those between the implementations into the relevant computer programs. The paper also provides a comparison of simulation results obtained using LIOV-EMTP and LIV-ATP, for different line configurations, stroke locations and taking into account the finite conductivity of the ground. Finally, the case of complex distribution networks including the presence of branches and power system components (e.g. distribution transformers and surge arresters) is also analyzed.

II. Theoretical basis of the lightning-induced voltage calculation for the LIV-ATP and LIOV-EMTP programs

The LIV-ATP and LIOV-EMTP programs have been developed from various studies on the lightning-induced voltages made by the international scientific community. Although the theoretical bases of the two programs are similar, different methodologies and approximations are adopted and implemented, which will be briefly described in what follows.

A. The LIOV-EMTP program

The LIOV-EMTP program consists of the link between two distinct codes: the LIOV and the most popular EMTP one. The LIOV code has been developed in the framework of an international collaboration involving the University of Bologna (Department of Electrical Engineering), the Swiss Federal Institute of Technology (Power Systems Laboratory), and the University of Rome “La Sapienza” (Department of Electrical Engineering). The LIOV code is based on the field-to-transmission line coupling formulation of Agrawal et al. [14], suitably adapted for the case of a multiconductor overhead line above a lossy ground illuminated by an indirect lightning electromagnetic field. The return stroke electromagnetic field is calculated by assuming any of the available engineering return stroke model [15]. The vertical electric field is computed using well-known expressions derived in [16] assuming a perfectly-conducting ground. The horizontal electric field is computed using the Cooray-Rubinstein formula [17-19], therefore taking into account the presence of a lossy ground [8-10].

LIOV allows for the calculation of lightning-induced voltages along an overhead line as a function of current wave shape (amplitude, front steepness, duration), return stroke velocity, line geometry (height, length, number and position of conductors), stroke location with respect to the line, ground

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resistivity and relative permittivity, and value of termination impedances.

Concerning the effect of the ground resistivity in the calculation of the line parameters, Rachidi et al.'s expression for the ground transient resistance [20] is implemented into LIOV. This analytical expression corresponds to the general Sunde's expression for the ground impedance [21], and describes, within the limits of transmission line theory, both the early-time and late-time behavior of ground transient resistance in a more accurate way compared to the Timotin formula [22] (this corresponds to the Carson's expression for ground impedance [23]).

The field-to-transmission line coupling equations are solved in LIOV using a time domain approach. Indeed, most studies on lightning-induced voltages on overhead power lines use a direct time domain analysis because of its straightforwardness in dealing with insulation coordination problems, and its ability to handle non-linearities, which arise in presence of protective devices such as surge arresters or corona phenomenon. As a matter of fact, the LIOV code has been enlarged in order to take into account corona [24]. Also leader induction effects can be assessed, as in the LIOV code the leader model described in [25] has been implemented too [26].

One of the most popular approaches to solve the transmission line coupling equations in time domain is the finite difference time domain (FDTD) technique [27]. Such technique was used indeed by Agrawal et al. [14] when presenting their field-to-transmission line coupling equations. In [14], partial time and space derivatives were approximated using a 1^{st} order FDTD scheme. In [28] the use of a second order finite difference scheme is proposed based on the Lax-Wendroff algorithm [29] in order to improve the LIOV performances.

In principle, the LIOV code could be suitably modified, case by case, in order to take into account the presence of the specific type of termination, line-discontinuities (e.g. surge arresters across the line insulators along the line) and of complex system topologies. This procedure requires that the boundary conditions for the transmission-line coupling equations be properly re-written case by case, as discussed in [30]. However, it was found more convenient to link the LIOV code with the EMTP (similar approaches have been considered in [4-7,12,14]). In [11,30,31], the distribution system network is considered as consisting of a number of illuminated lines connected to each other through shunt admittances (see figure 1). This admittance represent the presence of surge arresters, of groundings of shielding wires, of distribution transformers or of other power components. Each section of the distribution system between two consecutive shunt admittances is modeled as a single line called 'LIOV-line'. The LIOV code has the task of calculating the response of the various lines connecting the two-ports while the EMTP has the task of solving the boundary condition and presents the advantage of making available a large library of power components.

Note that there are some differences between the LIOV-EMTP program described in [30] and the one described in [11,31], in particular this last version does not require any modification to the source code of the EMTP: the modified LIOV code is indeed contained in a dynamic link library (DLL), called within the EMTP-TACS environment. The data exchange between the LIOV code and EMTP is realized in the following way: the induced currents at the terminal nodes, computed by the modified LIOV code are input to the EMTP via current controlled generators, and the voltages calculated by the EMTP are input to the modified LIOV code via voltage sources.

The link between each LIOV-line termination and EMTP is realized by means of a short lossless Bergeron line.

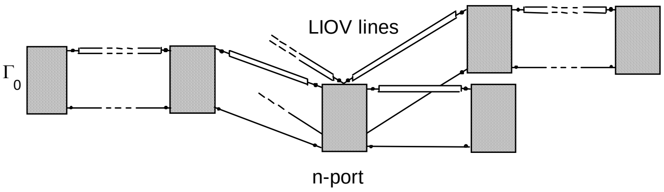


Fig. 1. Schematic representation of the electrical distribution system illuminated by LEMP in the LIOV-EMTP program. Adapted from [30].

B. *The LIV-ATP program*

The LIV-ATP program by Høidalen is proposed and described in [4-7]. It is based on the analytical solution of the lightning-electromagnetic field equations for a lossless ground using the approach proposed in [1] by Rusck. Assuming a lossless line and neglecting the transient ground resistance, the LIV-ATP program represents the LEMP-to-transmission line coupling by means of a modified Bergeron line which includes controlled generators representing the induced voltages (see figure 2).

The analytical calculation of the inducing terms is made assuming a step function to describe the channel base lightning current waveform. For other kind of channel base lightning current waveforms a convolution integral may be done.

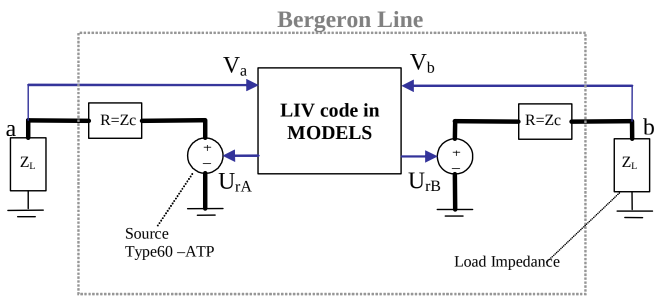


Fig. 2. Schematic representation of the interface of the LIV-ATP program for a single line. Adapted from [7].

The contribution due to the finite ground conductivity on lightning-induced voltages is taken into account by modifying the inducing term representing the induced voltages determined for the ideal ground case implementing a numerical approximation of the Cooray-Rubinstein formula [4-7].

The implementation of the LIV-ATP program is schematically described in figure 2: at each time step the LIV code calculates, in the ATP-MODELS environment, the total lightning-induced voltages at each illuminated line termination. For each line, such induced voltages corresponds to the inducing terms of the modified Bergeron line which are sent through a controlled source to the ATP. This last solves, by means of nodal analysis, the entire circuit model which includes the illuminated lines and their relevant boundary conditions. After this calculation, the determined total voltages are transmitted back to the illuminated line for the next time step calculation.

III. NUMERICAL COMPARISON BETWEEN LIV-ATP AND LIOV-EMTP PROGRAMS

The numerical comparison of the two programs is here presented for different cases of single-conductor straight line and complex distribution systems, considering different positions for the stroke location and different values for the ground conductivity. The geometry adopted for the single-conductor line above both ideal and lossy ground cases is represented in figure 3. The line is supposed to matched at its both ends. In order to perform a comparison between the two programs, the Transmission Line (TL) model has been adopted for the description of the return stroke current distribution. For the same reason, the triangular waveform of the channel base current has been adopted with an amplitude equal to 12 kA and a 1.2/50 μs waveform. The assumed return-stroke velocity is $1.3\cdot10^8$ m/s.

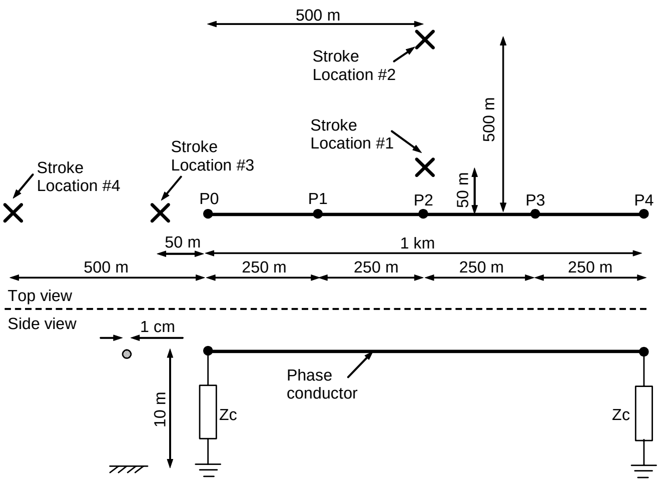
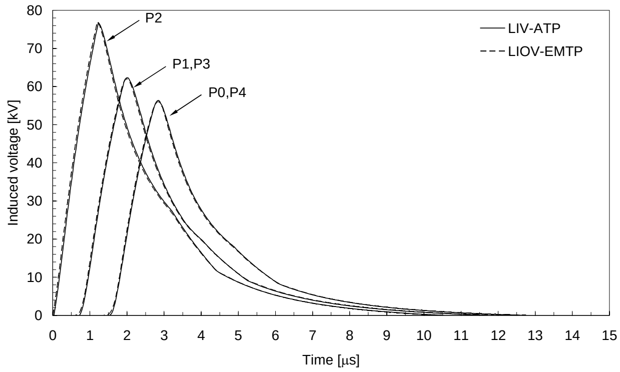


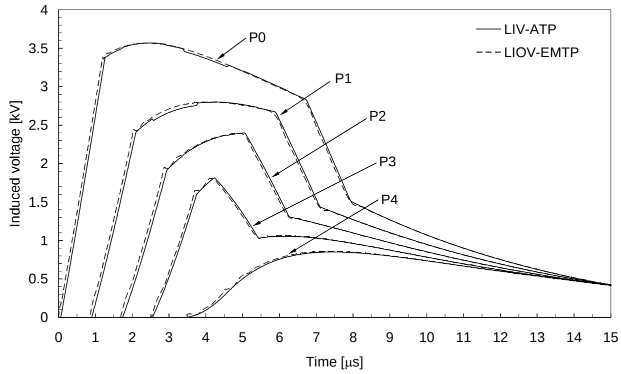
Fig. 3. Geometry adopted for the comparison between the LIOV-EMTP and LIV-ATP codes relevant to the single conductor straight line cases above ideal and lossy ground. The various stroke locations used for the simulations are shown in this figure.

A. *Single conductor straight line above a lossless ground*

This section is focused on the comparison of the two codes for an ideal (lossless) ground. Figure 4 shows the induced voltages at the line terminations for two different stroke locations (#1 and #4 of figure 3). It can be seen that LIOV-EMTP and LIV-ATP provide nearly identical results for these cases.



a)



b)

Fig. 4. Lightning induced voltages along the line (points P0 through P4 are defined in figure 3; a)stroke location #1, b)stroke location #4. The ground is assumed to be perfectly conducting.

B. *Single conductor straight line above a lossy ground*

This section is focused on the comparison of the two codes for the case of lossy ground. The adopted ground conductivity in all the presented simulations is of 0.001 S/m.
Considering that the effect of the finite ground conductivity is taken into account in the LIV-ATP only in the field computation and not in the surge propagation, a first comparison is shown in figure 5 for the configuration of figure 3. It can be seen that the two programs provide very similar results.

Figure 6 presents similar results but considering a 5-km long line and a stroke location 50 m from left line termination. For this case, it can be observed that the LIV-ATP program results in an overestimation of the lightning-induced voltages. It can be seen that at the line far-end, such overestimation is about 100%. As discussed in [9], this overestimation is due to the absence of the transient ground resistance in LIV-ATP.

C. *Complex distribution networks*

The comparison of the two computer programs is here presented by making reference to the case of a LEMP-illuminated power distribution network. The network is composed by a 1.5-km long main feeder and by two laterals of 0.7-km and 0.5-km long respectively. Each line termination is connected to a power transformer protected by means of a surge arrester.

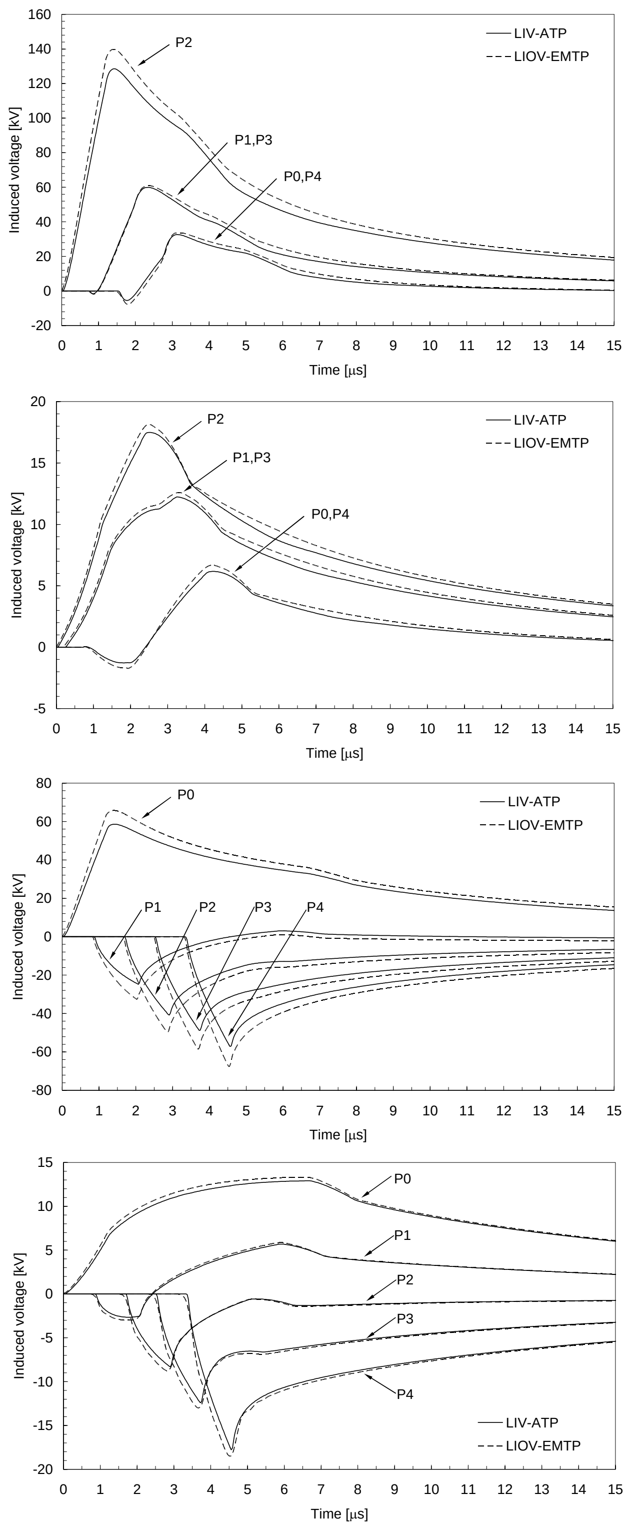


Fig. 5. Lightning induced voltages along the line (points P0 through P4 are defined in figure 3; a)stroke location #1, b)stroke location #2, c)stroke location #3, d)stroke location #4. Ground conductivity 0.001 S/m, relative permittivity 10.

The comparison between the lightning-induced voltages on conductor #1 computed by the two computer programs is shown in figures 8 and 9 relevant to the two considered stroke locations.

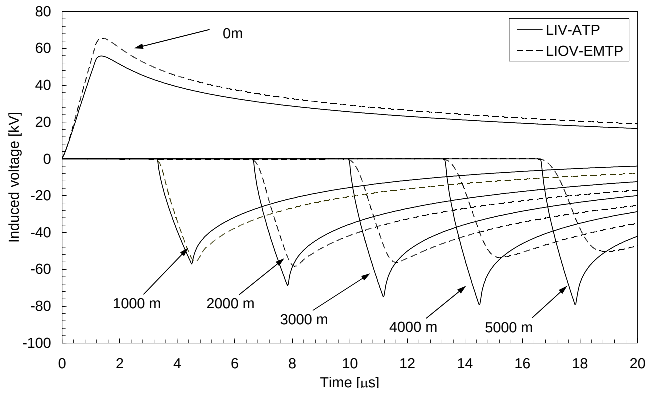
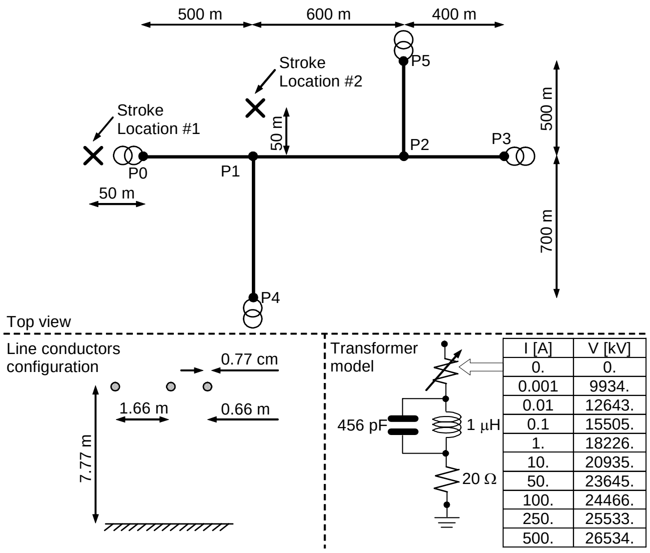


Fig. 6. Comparison between LIV-ATP and LIOV-EMTP codes for a 5 km overhead single conductor line; stroke location 50 m from left line termination, observation point placed each 1 km. Ground conductivity 0.001 S/m, relative permittivity 10. Stroke location # 3.

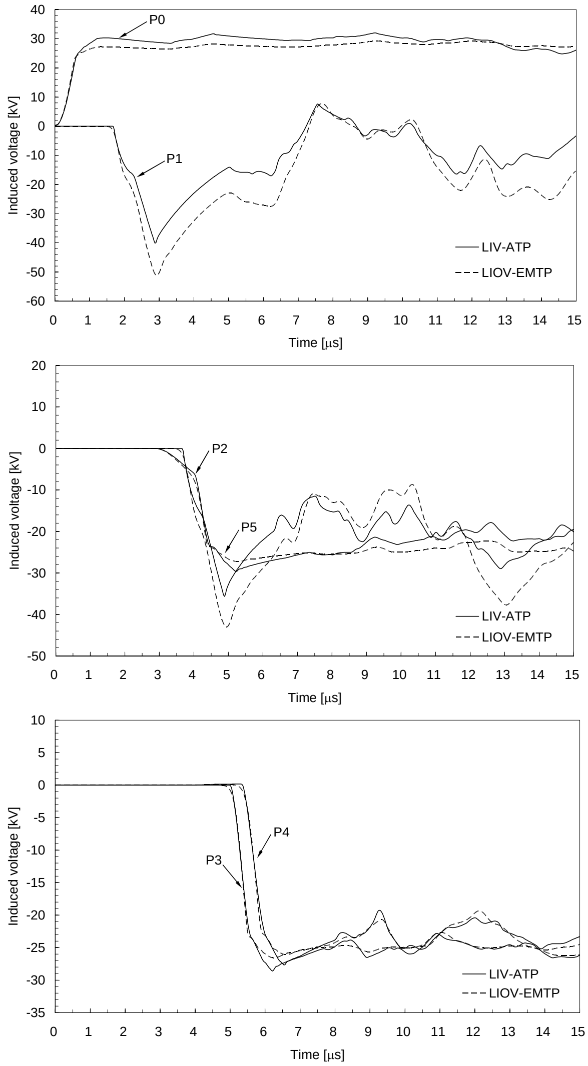


I [A]	V [kV]
0.	0.
0.001	9934.
0.01	12643.
0.1	15505.
1.	18226.
10.	20935.
50.	23645.
100.	24466.
250.	25533.
500.	26534.

Fig. 7. Geometry adopted for the comparison between the LIOV-EMTP and LIV-ATP codes relevant to the complex distribution network case.

IV. Discussion on the Simulation Results

In general, it can be concluded that for the case of a perfectly-conducting ground, LIV-ATP and LIOV-EMTP produce nearly the same results. When the finite ground conductivity is considered, LIV-ATP results are still in reasonable agreement with the LIOV-EMTP program, especially concerning the waveform of the induced voltages. For the case of short lines for which surge propagation along the line is not significantly affected by ground losses, LIV-ATP results show slightly smaller peak values compared to those predicted by LIOV-EMTP; the greater differences are found when the lightning strike is near to the line end, in any case lower than about 10%. These differences can be attributed to different numerical methods used in the two approaches. On the other hand, for longer lines, the omission of ground transient resistance in LIV-ATP can result, in some cases, in an overestimation of lightning-induced voltage peaks.

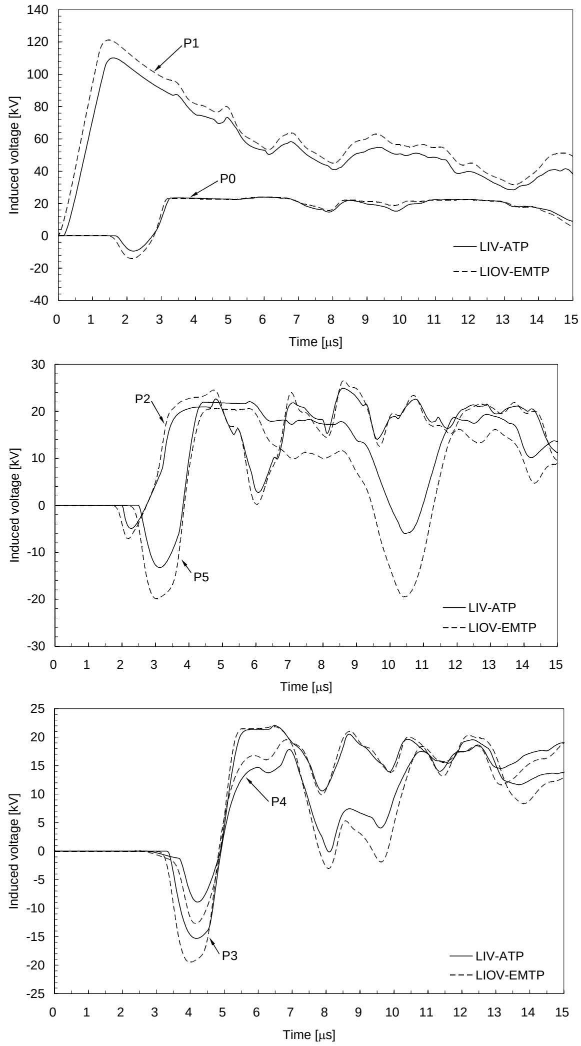


a)
b)
c)

Fig. 8. Comparison between lightning-induced voltages on conductor #1 computed with LIV-ATP and LIOV-EMTP codes for the power distribution network of figure 7, stroke location #1; a) observation points P0 and P1; b) observation points P2 and P5; c) observation points P3 and P4.

Note, additionally, that a small time shift introduced between each illuminated LIOV-line and the boundary solution of the EMTP is introduced in the LIOV-EMTP program. This delay is due to the structure of the link between the LIOV code and EMTP which adds, at each line termination, a non-illuminated line segment (Bergeron line). The length of such a line segment depends on the value of the adopted integration time step used to solve the transmission line equations (for the presented simulations, the time step is 10 ns). The effect of this time delay becomes more evident when a large number of nodes is considered in complex distribution systems. Typical values of integration time step which produce negligible effects of such a time delay are of the order of 10^{-8} s [1]. Concerning the calculation run time, it has been found that LIV-ATP is generally faster than LIOV-EMTP. This result is due to the analytical solution of the problem as implemented in LIV-ATP compared to the numerical one, used in LIOV-EMTP. As the calculation time of the LIV-ATP is not affected by the length of each line segment, the above difference is more evident when increasing of the length of the line segments that compose the illuminated system.

A comparison between the two codes, summarizing the main features of each of them is presented in table I.



a)
b)
c)

Fig. 9. Comparison between lightning-induced voltages on conductor #1 computed with LIV-ATP and LIOV-EMTP codes for the power distribution network of figure 7, stroke location #2; a)observation points P0 and P1; b)observation points P2 and P5; c)observation points P3 and P4.

[1] It is worth noting, however, that the introduction of a non-illuminated line at the ends of each line segment does not represent, in principle, a limitation of the program. As a matter of fact, the introduction of a non-illuminated line at each end of the line, with length equal to the line height, is needed in case one wants to take into account in a more accurate way the coupling phenomena at the line terminations, as shown in [32].

V. CONCLUSIONS

In this paper, we presented a comparison between two computer programs for the calculation of lightning-induced voltages namely: LIV-ATP and LIOV-EMTP.

The comparison has been carried out presenting first the theoretical approaches and computational models on which the two programs are based. Then, a comparison of simulations results obtained using the two programs has been presented, considering simple and complex configurations, different stroke locations, and, taking into account the finite ground conductivity.

The observed differences in the results obtained using LIV-ATP and LIOV-EMTP have been discussed, and their features and capabilities summarized.

TABLE I
SUMMARY OF THE PRINCIPLE FEATURES OF LIV-ATP AND LIOV-EMTP SOFTWARE TOOLS

	LIV-ATP	LIOV-EMTP
Channel-base current representation	Step function. Any analytical waveform is possible, what requires a convolution integral	Any waveform is possible
Return-Stroke Model and leader induction effects	Transmission Line (TL) model for return stroke	Any available engineering model (TL, BG, TCS, MTLL, MTLE, DU) for return stroke. Schonland [25] model for the leader phase.
Vertical Electric Field Computation	Analytical solution assuming a perfectly conducting ground	Assuming a perfectly-conducting ground
Horizontal Electric Field Computation	Cooray-Rubinstein Formula [17,18]	Cooray-Rubinstein Formula [17-19]
Field-to-Transmission Line Coupling Model	Agrawal et al. model [14]	Agrawal et al. model [14]
Ground Transient Resistance	Neglected	Rachidi et al. [20]
Non linearities along the line, such as corona effect.	Non treated	yes
Implementation	ATP-MODELS environment	FDTD solutions of field-to-line coupling equations, interfaced with EMTP for boundary conditions

VI. ACKNOWLEDGMENTS

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