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CORRELATING LIGHTNING WITH VOLTAGE DIPS AND FAULTS IN POWER DISTRIBUTION NETWORKS

Presentata da: FABIO NAPOLITANO

Coordinatore Dottorato Relatore

Prof. FRANCESCO NEGRINI Prof. CARLO ALBERTO NUCCI

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Chapter 1 - Introduction

Distribution networks located in areas with high keraunic level experience a large number of relay operation, and relevant voltage sags, and such a number shows a linear correlation with the ground flash density of the relevant geographical area [Gunther 1995].

The inference of the correlation between relay operations and lightning events is certainly of interest because can provide important information on the real cause of relay operations besides lightning induced voltages (e.g. tree-branch contacts, wind, etc.). Also, it can bring useful elements for improving the insulation coordination of the overhead lines composing the network and, in turns, its power quality.

For this reason, several studies dealing with power quality of distribution and transmission networks have focused on the source identification of voltage disturbances. Concerning disturbances originated by lightning, the relevant correlation algorithms presented in the literature are typically based on time-distance criteria, which assume a lightning event to be the source of a flashover if the first or both following conditions are satisfied:

1) the lightning event detect by a Lightning Location System (LLS) and the relay operation are recorded within a specified time window (typically a few seconds) [Parrish and Kvaltine 1989, Bernardi et al. 1998];

2) the distance between the estimated stroke location and the closest line of the network is lower than a critical value. Such a value can be a fixed (e.g. 1 km) or calculated as the maximum distance at which the recorded lightning current amplitude could produce an induced overvoltage larger than the basic insulation level (BIL) of the line [Bernardi et al. 1998]. Sometimes, this second condition takes into account, at least in part, the location uncertainty, namely a lightning event is a source of flashover when the 50% probability error ellipse related to the location uncertainty intersects a corridor limit that surrounds the overhead lines [Kappenman and Van House 1996, Cummins et al. 1998, Kosmač et al. 2006].
The use of condition 1) only is not acceptable because, in principle, also lightning strokes far away from the distribution network, and therefore unable to produce any significant overvoltage, would be selected as correlated. On the other hand, by using conditions 1) and 2) together, particular attention has to be taken in the calculation of the above mentioned critical distance value. As a matter of fact, a somewhat unexpected low number of correlated lightning events has been found by some authors [Bernardi et al. 1998]; in part as a result of the adoption of an oversimplified method for the calculation of lightning-induced overvoltages. Additionally, the deterministic approach, inherent to the above conditions, does not appear to be suitable for the problem of interest.

Therefore, in order to approach the problem in a more appropriate way, it is necessary: i) to take into account from a statistical point of view all the uncertainties introduced by LLSs, namely the lightning stroke location and the lightning current peak estimate, and ii) to perform the calculation of lightning-induced voltages, when necessary, using an accurate computational tool.

The goal of this thesis is the development of an advanced statistical procedure to infer the above mentioned correlation. The proposed procedure is based on the integrated use of:

- the data provided by LLSs;
- the data provided by the monitoring systems of protection manoeuvres;
- an advanced computational tool for the calculation of lightning-induced overvoltages.

The adequacy of the correlation procedure has been tuned by means of data from the voltage transients recorded by the distributed monitoring system installed at some secondary sub-stations in a medium-voltage network located in a high keraunic area in the northern region of Italy. The characteristics of such a measurement system are illustrated in Yamabuki et al. [2007].

The uncertainties introduced by LLSs are taken into account following a Monte Carlo-based approaches, standing on the one proposed in Borghetti et al. [2006].
The structure of the thesis is the following:

*Chapter 2.* A description of the approach followed to accomplish the correlation problem is given. The chapter is divided in six sections to treat the following items: a) literary review of the correlation issue; b) direct and indirect lightning: existing models for their discrimination based on prospective peak current and distance from power lines; c) lightning parameters of interest d) Italian LLS; e) Italian monitoring systems of protection manoeuvres; f) lightning overvoltages calculation; g) the proposed procedure for correlating lightning with voltage dips and faults in power lines.

*Chapter 3.* This chapter illustrates the application of the developed procedure to a real case and the analysis of the data collected during one year of observation.

*Chapter 4.* Chapter devoted to conclusions.
Chapter 2 – The approach chosen to solve correlation problem of interest

2.1 – Preliminary remarks
Increasing power quality requirements stimulated in the recent years several studies focused on the source identification of voltage disturbances occurring in transmission and distribution networks.

It is well known that power quality problems such as voltage transients and interruptions are more frequent during thunderstorms [Anderson 1985, Gunther 1995, Balijepalli 2005]. Nevertheless, lightning activity is not the only responsible for the occurrence of voltage dips related to the thunderstorms.

In fact, other natural causes associated with thunderstorms, such as wind, may cause short circuits. Consequently, the correlation between power quality problems and lightning events becomes of crucial interest for the assessment of the lightning performance of distribution systems, for the design of their appropriate insulation coordination and for maintenance planning.

Parrish and Kvaltine [1989] used a modified flash counter to differentiate between outages caused by lightning and those caused by other thunderstorm-related phenomena, such as trees, wind, rain. The flash counter was realized in order to cover an area approximately equal to a substation service area. The circuit breaker operations were tagged as lightning caused events if they took 4 or 6 cycles to trip after the event. The discrepancy between the detected and the predicted lightning faults, the latter calculated using Eriksson’s equation [Eriksson 1987b], was interpreted as due to the shielding effect of nearby structure, such as buildings, houses and trees, often taller than the lines.

Kappenman and Van House [1996] presented the improvement of the lightning performance of a transmission line achieved by means of local upgrades, instead of a more expensive upgrade of the complete line. The most fault susceptible areas, where the lightning mitigation upgrades were concentrated, were identified by means of data supplied by the United States National Lightning Detection Network (NLDN) and of accurate Global Positioning Systems (GPS) time-stamping of disturbances.
Bernardi et al. [1998] presented the results of a study on one year data coming from the “Sistema Italiano Rilevamento Fulmini” (SIRF) of “Comitato Elettrotecnico Sperimentale Italiano” (CESI), that is the Italian LLS, and the “Sistema Acquisizione Manovre” (SAM), that is the Italian system of acquisition of protection manoeuvres. In such a study, the time criteria, that is a lightning event is assumed correlated to a line fault if they happen within a specified time window, has given inhomogeneous results for the different areas analysed. Therefore both a time and distance criteria have been applied: the lightning event is assumed correlated to the fault if they happen within a time window (± 1 s) and if the distance between the estimated stroke location and the closest line of the network are lower then a given critical value. Such a value is the maximum distance at which the recorded lightning current amplitude could produce an induced overvoltage larger then the basic insulation level of the line. The overvoltages were estimated by means of the Rusck’s simplified formula [Rusck 1958]. The results of the time and spatial criteria, as far as better then those given by the time criteria alone, confirmed that a simple overvoltage model as the Rusck’s one appears to be inadequate to properly reproduce the line response against lightning electromagnetic pulses: it may result insufficient in case of overhead lines above a ground of finite conductivity, in presence of multi-conductor lines, when the line length is finite, when the line is equipped with protection devices like surge arresters and/or grounded wires and when power distribution transformers are connected to it. The inherent complexity of the problem calls therefore for the adoption of more accurate field-to-transmission-line coupling models and the use of adequate treatment of the boundary conditions for the analysis of complex line/systems configurations.

In Cummins et al. [1998] the main performance parameters of the NLDN are discussed and some applications are described. The importance of the location accuracy in lightning to line faults correlation is emphasized: to avoid false correlation the 50% probability error ellipses must be taken into account.

The study of Diendorfer [2001] has shown that most of the outages recorded in Austrian transmission lines are within ± 1 s since lightning events recorded by the Austrian Lightning Detection & Information System (ALDIS); about the 25% are correlated with lightning events located up to 5 km from the line; the remaining outages are assumed to
be caused by other weather related events or by lightning flashes not detected by the lightning location systems.

In the study of Chen et al. [2002], the correlation between line faults and lightning events was inferred to estimate detection efficiency and location accuracy of the Guandong lightning location system.

In Nucci et al. [2002] the same calculations performed in Bernardi et al. [1998] were repeated using a more accurate tool than the Rusck’s simplified formula: the LIOV-EMTP96 code (see section 2.4).

In Paolone et al. [2004] the main features of a distributed measurement system for power quality monitoring which could be used in coordination with an LLS in place of a system of acquisition of protection manoeuvres, are discussed.

Kosmač et al. [2006] used time and spatial correlation criteria to shorten fault location and power supply restoration.

In some of the above mentioned works (Kappenman and Van House [1996], Cummins et al. [1998], Kosmač et al. [2006]) the spatial criterion adopted to infer correlation is based on the position of the 50% error ellipse respect to a corridor nearby the line: if the ellipse is completely outside the corridor, the lightning event is assumed to be uncorrelated with respect the line fault event.

Such an approach is too simplified as the probability to have the actual stroke location inside the ellipse is only equal to 50%.

Borghetti et al. [2006] proposed a statistical approach, based on Monte Carlo method, aiming at improving the evaluation of the probability that a LLS-detected lightning discharge could be the cause of a fault on an overhead distribution line, taking into account the accuracy of both lightning location and current amplitude estimates. Such an approach represents the basis of the procedure developed in this thesis and will be illustrated in section 2.7.

As regards their origin, overvoltages due to lightning in overhead lines can be classified in direct stroke overvoltages (overvoltages due to direct strokes on the line or on structures close to these lines with consequence structure-to-line flashover) and induced overvoltages Typical distribution line surge impedances are in the range of 300-500 Ω, and the BIL of most distribution lines is only 100 to at most 500 kV [IEEE WG 1990].
As a consequence, a direct lightning on a distribution line can be expected to cause a flashover.

However, experience and observations show that many of the lightning-related outages of low-insulation lines are due to nearby lightning [IEEE Std 1410-2004]. Due to limited height, in fact, distribution lines are likely to be shielded by near tall object (trees and buildings).

It is worth mentioning that as overvoltages due to nearby lightning seldom exceed 200 kV [Cigré WG 1991] induced voltage are therefore of interest for distribution lines and not for transmission lines.

Nearby lightning can result in two types of transients on distribution networks.

If the induced overvoltages exceed the BIL, they cause phase-to-ground and/or phase-to-phase flashovers. Depending on the transformer’s connection to ground and/or presence of protection devices, flashovers can result in short circuits and their removal needs recloser breaker operation. A short-circuit followed by a recloser operation turns into what is usually referred to as a voltage sag (according to IEEE Std 1159-1995), or a voltage dip (European Standard EN 50160). Short circuits are perceived as supply interruptions by the customers connected to the line supplying the fault or as sags by the customers supplied by the other lines connected to the busbar of the same point of common coupling [Paolone et al. 2004].

It is worth reminding, in these preliminary remarks, the definitions of BIL and of CFO, often used as synonymous.

Basic lightning Impulse insulation Level (BIL) is the crest value of withstand voltage when insulation is subject to a standard lightning impulse, for dry conditions.

For self-restoring insulations, the BIL is statistical, namely the crest value of standard lightning impulse for which the insulation exhibits a 90% probability of withstand.

For non self-restoring insulations, the BIL is conventional, namely the crest value of standard lightning impulse for which the insulation withstands for a specific number of applications of the impulse.

The standard lightning impulse waveshape is $1,2/50 \mu s$, namely has time to crest equal to 1,2 $\mu s$ and time to half value equal to 50 $\mu s$. These times are evaluated constructing the linear characteristic passing through the times corresponding to 30% and 90% of the
crest value; the time corresponding to zero voltage on this characteristic is the virtual 
origin. The time to crest is the time interval between the virtual origin and the time 
corresponding to the crest voltage on the linear characteristic. The time to half value is 
the time interval between the virtual origin and the time at which the voltage decreases 
to 50% of the crest value.
The standard lightning impulse waveshape has been chosen in order to reproduce the 
short fronts and the relatively long tails of lightning surges, but above all because it may 
be easily produced in all laboratories.

Critical impulse FlashOver voltage (CFO) is the crest value of the standard lightning 
impulse wave that causes flashover through the surrounding medium on 50% of the 
applications.
For self-restoring insulations, an impulse having the standard waveshape and whose 
crest is equal to the BIL, the probability of a flashover or failure is 10%.
If a Gaussian distribution of flashover data is assumed, then any specific probability of 
withstand may be calculated from the CFO value and the standard deviation [Hileman 
1999].
The BIL is generally used in insulation coordination studies, while CFO is preferred in 
lightning performance estimations.
Dielectric strength of line insulators under lightning conditions depends on the impulse 
waveshape, magnitude and polarity. A lightning-impulse voltage, with a magnitude that 
exceeds the CFO, may still not last long enough to carry the streamers all the way to 
complete insulation breakdown. A plot of magnitude of the breakdown voltage versus 
the time to breakdown is called “volt-time curve”. The amount by which the voltage 
exceeds the CFO is referred as the “volt-time turn-up”. In IEEE Std 1410-2004 a 1.5 
factor is suggested to account the turn-up in the insulation volt-time curve for induced 
voltages.

2.2 – Direct and indirect lightning
In the developed procedure to infer correlation between lightning and faults, a model to 
discriminate direct from indirect events is to be adopted. In literature, two main models
are available to solve such an issue: the ElectroGeometrical Model (EGM) and Leader Progression Model (LPM). The first is an empirical relationship based on the concept of the “striking distance”: the distance between the downward leader and an object on the earth, or the earth itself, at which the point of strike becomes determined. The latter are more physically oriented. The Dellera and Garbagnati’ [1990a, 1990b] LPM simulates step by step the development of the leader channels. LPMs may considered also Eriksson’s [1987a] and Rizk’s models [1990].

Lightning protection began in 1752 with Benjamin Franklin’s lightning rod. Franklin was the first to introduce in 1767 the concept of “striking distance” [Golde 1977]. The striking distance may be defined as the distance between the tip of a downward leader and an object on the earth, or the earth itself, at which the point that will be struck becomes determined.

The striking distance is not simply the distance at which a critical breakdown strength is reached, giving rise to the initiation of an upward leader, as it was initially conceived. In fact, to this first stage a second one follows. It is the so called final jump, that consists in the successful interception between downward and upward leaders, mainly determined by the local distribution of charges.

The EGM is a functional relationship between the striking distance to a horizontal conductor wire (or a vertical mast) and the prospective lightning stroke peak current

\[ r = A t^b \]  

(2.1)

The motivation for the first studies on EGM was the poor lightning performance of transmission lines equipped with overhead ground wires.

The foundations of the EGM are the theories developed by Golde, Wagner and Hileman, according to which critical electric fields for the last step of the lightning stroke may be related to the charge of the descending leader and, consequently, to the peak current of the stroke. The EGM was subjected to empirical calibration and adjustments, on the basis of field observations on the lightning performances of transmission lines. The EGM, therefore, may be considered an empirical model and is under continuous review, as it can be seen in Tab 2.1.
### Tab. 2.1 – Some expressions for the Striking Distance

<table>
<thead>
<tr>
<th>Source</th>
<th>A Striking distance to wire</th>
<th>A Striking distance to ground</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>derived from Golde’s data [Suzuchi et al 1981]</td>
<td>3.3</td>
<td>3.3</td>
<td>0.78</td>
</tr>
<tr>
<td>Wagner [1963]</td>
<td>14.2</td>
<td>14.2</td>
<td>0.42</td>
</tr>
<tr>
<td>derived from Wagner [Brown and Whitehead 1969]</td>
<td>10</td>
<td>10</td>
<td>0.51</td>
</tr>
<tr>
<td>Young, Clayton and Hileman [1963]</td>
<td>27 for h &lt; 18m</td>
<td>27</td>
<td>0.32</td>
</tr>
<tr>
<td>Wagner [1963]</td>
<td>14.2</td>
<td>14.2</td>
<td>0.42</td>
</tr>
<tr>
<td>derived from Wagner [Brown and Whitehead 1969]</td>
<td>10</td>
<td>10</td>
<td>0.51</td>
</tr>
<tr>
<td>Young, Clayton and Hileman [1963]</td>
<td>27 for h &lt; 18m</td>
<td>27</td>
<td>0.32</td>
</tr>
<tr>
<td>Armstron and Whitehead [1968]</td>
<td>6.7</td>
<td>6.0</td>
<td>0.8</td>
</tr>
<tr>
<td>Brown and Whitehead [1969]</td>
<td>7.1</td>
<td>6.4</td>
<td>0.75</td>
</tr>
<tr>
<td>Gilman and Whitehead [1973]*°</td>
<td>6.7</td>
<td>6.7</td>
<td>0.8</td>
</tr>
<tr>
<td>Love [1973]°</td>
<td>10</td>
<td>10</td>
<td>0.65</td>
</tr>
<tr>
<td>Whitehead [1974]*°</td>
<td>9.4</td>
<td>9.4</td>
<td>0.67</td>
</tr>
<tr>
<td>Anderson [1982]</td>
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<td>6.4 for UHV</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.0 for EHV</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 for others</td>
<td></td>
</tr>
<tr>
<td>IEEE WG [1985]</td>
<td>8</td>
<td>5.12 for UHV</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.4 for EHV</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8 for others</td>
<td></td>
</tr>
<tr>
<td>[Grant et al 1985]</td>
<td>8</td>
<td>176/h</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.8&lt;A&lt;7.2</td>
<td></td>
</tr>
<tr>
<td>Mousa [1988] (IEEE Std 998-1996)</td>
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<td>8</td>
<td>0.65</td>
</tr>
<tr>
<td>IEEE WG [1993] (IEEE Std 1243-1997)</td>
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<td>3.6+1.68ln(43-h) if h &lt; 40</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.6+1.68ln(43-40) if h &gt; 40</td>
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</tr>
<tr>
<td>IEEE Std 1410-2004</td>
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<td>0.9</td>
<td>0.65</td>
</tr>
</tbody>
</table>

* mean striking distance; for design of new lines the effective striking distance (the 90% of the mean striking distance) is recommended.

° with reference to the prospective current to earth \(I_0\), instead of to the conductor \(I, I_0 = 1.1I\).
The field data suggested the assumptions of different striking distance to the hearth and to the phase conductor, or shield wire (see Fig. 2.1). In certain instances, the ratio between the striking distance to the earth and the one to the line conductor is reduced as structure height increased. This is a consequence of the structure height effect that is not taken into account in the EGM explicitly, except made for Eriksson’s improved EGM [1987a, 1987b].

Eriksson distinguished the striking distance as the critical distance for the upward leader initiation and the “attractive radius” as the critical distance for the final jump. In the EGM giving both striking distance to the earth and to the wire, instead, no particular distinction is made between striking distance and attractive radius.

When the attractive (or exposure) area of a line or a structure is of interest, and the EGM considered provides a striking distance to ground, the difference between the attractive radius and the striking distance is to be intended as shown in Fig. 2.2, where the attractive radius is indicated with $d_l$, that stands for “lateral distance”. The lateral distance is given by

$$d_l = \sqrt{r_s^2 - (r_g - h)^2} \quad h < r_g$$  \hspace{1cm} (2.2)

$$d_l = r_s \quad h > r_g$$  \hspace{1cm} (2.3)

Eriksson developed an analytical model of the final jump using the concept of the “critical radius”. Carrara and Thione [1976] demonstrated, using laboratory tests on air
gaps energized with positive long-front impulses, that the breakdown voltage is nearly independent of the electrode size starting from very small dimensions up to the critical radius. This means that, to start the leader, it is necessary to reach the above critical size of corona sheath together with a proper critical electric field strength at the surface of the corona sheath itself. The use of the critical radius was made under the assumption of similarity of the leader inception phenomenon in laboratory and in nature.

![Diagram of direct and nearby strokes](image)

**Fig. 2.2 – Striking distance to a conductor \( r_c \) and to ground \( r_g \) and lateral attractive distance \( d_l \) of a line.**

Eriksson’s analytical model was based on the following assumptions (Eriksson 1987a):

- the structure is assumed free standing and represented by a cylindrical equivalent structure of the same height and radius equal to the “critical radius”;
- one major branch of a nearby approaching downward lightning leader is represented by a vertically descending linearly charged leader element;
- the prospective stroke peak current of the leader element is assumed related to the to the integrated leader charge, through Berger’s correlation factor between peak current and impulse charge;
- the electric field enhancement due to the protrusion of the structure is taken into account by means of a factor derived from the structure dimensional ratio (height in relation to cylindrical radius);
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- a critical field intensity over a critical corona radius over the structure extremity is assumed as criterion for the initiation of an upward leader;
- upward/downward leader velocity ratio equal to unity;
- stroke termination on the structure determined by the interception of the downward and upward leader.

By regression of the results of his simplified leader progression model, Eriksson obtained an analytical expression for the attractive radius of free standing vertical structure

\[ r = 0.84h^{0.6} I_a \]
\[ a = 0.7h^{0.02} \]

For horizontal conductors an 80% reduction is adopted

\[ r = 0.67h^{0.6} I_a \] (2.4)

From (2.4), substituting \( I = 35 \text{ kA} \) assumed as the median value of stroke-current peaks and \( a = 0.7 \), assumed as good approximation for the practical range of power lines structures heights (10 – 100 m), Eriksson obtained the following simplified analytical expression

\[ r = 12h^{0.6} \] (2.5)

In order to overcome the simplifications of the analytical model and the broad dispersion of the empirical data, Eriksson suggests a combination of (2.5) and the empirically derived expression (2.6)

\[ r = 16.6h^{0.55} \] (2.6)

obtaining

\[ r = 14h^{0.6} \] (2.7)

According to (2.7), the exposure area \( S \) (km²) corresponding to 100 km of line length is:

\[ S = \frac{2r + b}{10000} \times 100\text{km} = \frac{28h^{0.6} + b}{10} \] (2.8)

where \( b \) is the separation distance (m) of the overhead ground wires or, in absence of them, of the phase wires.

Multiplying the (2.8) for the ground flash density \( N_g \) (flashes/km²/year), the flash collection rate (flashes/100 km/year) is given

\[ N_s = N_g \left( \frac{28h^{0.6} + b}{10} \right) \] (2.9)
In [Eriksson 1987b] the average ground wire height is suggested for $h$, i.e. the tower height minus $2/3$ of the sag.

The (2.9) is the flash collection rate formula recommended by the IEEE Std 1410-2004.

A more detailed simulation of the lightning impact mechanism is the “Leader progression model”, developed since 1980. The Leader Progression Model (LPM) is a dynamic model of lightning, based in the similarity between lightning phenomena and discharges in large air gaps.

The calculation of the electrostatic field due to distributed charges is done by means of the charge simulation method [Singer et al 1974], in which distributed charges on the surface of conductors are approximated with a finite number of line charges inside the conductors, then the electric field in each point of interest is calculated by superposition.

The main steps of the process are [Cigré Task Force 33.01.03 Report 1997]:

- the model consider only the case of a full developing of the lightning, that is the natural extinction of the downward leader is not considered;
- each propagation step, some meters in length, of both upward and downward leader is added to the previous one; the direction is chosen for each step as the direction of the maximum field in front of the streamer zone;
- the streamer zone extension is characterized as an area in which the field strength is higher or equal to $3 \text{ kV/m}$;
- the cloud, 10 km in diameter, is simulated with four charge rings, equally spaced, with uniform charge density over all the cloud area;
- the charges used to simulate the ground structure and the terrain profile are: linear charge, spherical charge, conductor (infinite long line with a section radius charge);
- charge may be active or passive, depending on whether they could be a starting point for the leader inception or not; if they are active the radius is the critical one;
- the critical radius is the minimum radius at which the leader inception occurs, that is without the previous corona formation;
- the inception of the upward leader happens when the field in front of the active charges reaches the critical value.
Starting from the geometrical configuration of the earthed object and taking into account the orographic conditions, the model allows to evaluate the lateral distance as function of the lightning current amplitude.

By interpolation of the lateral distance vs height graphics obtained by the leader progression model, the following analytical expression was inferred [Borghetti et al. 2001]

$$d_l = 3h^{0.6} + 0.028hI$$

Another attractive radius expression containing explicit height dependence was inferred by Rizk. Rizk [1990] introduced a generalized leader inception model and applied it to several electrode configurations. In the following, only the application to lightning negative downward leader is summarized.

Rizk’s model gives a formula for the critical voltage, necessary for continuous positive upward leader inception from an object at the ground, as a function of the dimensions of the object. The basic idea in Rizk’s model is that in a generic gap configuration the positive leader inception takes place when the applied electric field exceeds the opposing field due to the streamer space charge by a critical value. The applied and the opposing field may be related to the applied voltage through constants depending on the gap geometry and on the type of gap.

The conclusion to be drawn from Rizk’s positive leader inception model is that the critical voltage for upward leader inception from a lightning rod or ground wire under the influence of a negative leader, and accordingly the critical radius of the grounded structure, is basically determined by its height above ground and not by the gap length.

An iterative procedure was used by Rizk [1990] to determine the lateral distances, as function of lightning peak current and of height of structure or conductor. The final jump model was based on the following assumptions:

- positive upward leader inception takes place when the induced potential reaches the critical value;
- the negative downward channel continues its downward motion unperturbed unless final jump takes place when the gradient between downward and upward leader exceeds 500 kV/m;
- the vector motion of the positive upward leader is such that at any instant it seeks the negative leader tip;
- the ratio of the speeds of the two leaders is taken equal to one;
- the tip potential of the downward leader is calculated from the leader space charge distribution, assuming Berger’s [1977] constant ratio between the linear charge density and the radius of the space charge channel.

A multiple regression of the obtained results for horizontal conductors yielded to the approximate expression for the lateral distance

\[ d_l = 1.57 h^{0.45} f^{0.69} \quad (2.11) \]

Leader inception models as the critical radius concept and Rizk’s generalized leader inception model neglect the effect of the propagation of the downward stepped leader. Becerra and Cooray [2006] showed that taking into account the time variation of the electric field produced by stepped leaders the striking distances result significantly larger.

### 2.3 – Lightning parameters of interest

The majority of lightning discharges, probably three-quarters [Rakov and Uman 2003], do not involve ground. The cloud to ground discharges are traditionally divided in four types according to the polarity of the charge effectively lowered to earth and the direction of propagation of the initial leader:

- (a) downward negative lightning;
- (b) upward negative lightning;
- (c) downward positive lightning;
- (d) upward positive lightning.

This classification should be extended to include bipolar lightning flashes transporting to ground both negative and positive charges. Bipolar lightning is a poorly understood and often unrecognized phenomenon. Although positive lightning discharges account for 10% or less of global cloud-to-ground lightning activity, there are several situation that appear to conducive to the more frequent occurrence of positive lightning.
Upward lightning discharges are thought to occur only from tall objects (higher than 100 m or so) or from objects of moderate height located on mountain tops. Rocked-triggered lightning is similar in its phenomenology to the upward lightning initiated from tall objects.

The most common and most studied type of cloud-to-ground lightning is downward negative.

There are three modes of charge transfer in a negative downward lightning strike: a) leader-return stroke sequences; b) continuing currents; c) M-components.

(a) The leader creates a descending conductive path between the cloud and the earth. The following return stroke traverses that path moving from the earth and neutralizing the negative leader charge. For a subsequent return stroke, the leader is called “dart leader”;

(b) The lightning continuing current can be viewed as a quasi-stationary arc between the cloud charge source and earth. The current is relatively low but, due to the large charge transfer, is responsible to for the most serious lightning damage associated with thermal effects;

(c) M-components are perturbations (or surge) in the continuing current and in associated channel luminosity. The “M” stands for D.J. Malan, who was the first to study this process. In literature, different interpretations of this process are proposed, but all give a role to the development of in-cloud channels and to their interaction with the cloud-to-ground channel.
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Fig. 2.5 – Schematic representation of current versus height profiles for three modes of charges transfer to ground in negative lightning subsequent strokes: (a) dart leader-return stroke sequence; (b) continuing current; (c) M-component. The corresponding current versus time waveform represents the current at the ground (adapted from Rakov and Uman 2003).

The primary reference in the literature for lightning research is represented by the data collected on two instrumented television towers at Monte San Salvatore in Lugano, Switzerland. The majority of the lightning strikes collected was of the upward type, due to towers and mountain effect; only the data of downward flashes, believed more representative of natural lightning, were summarized by Berger et al. [1975]. The downward cloud to ground lightning flashes collected in 29 years, since 1943 to 1972, include:

- 101 first strokes;
- 136 negative subsequent strokes;
- 26 positive cloud-to-ground lightning flashes.

The cumulative distribution of some lightning parameters are reported in Berger et al. [1975], assuming the log-normal probability density function, already accepted at that time to provide a good fit for lightning parameters. The records of the measurements at Monte San Salvatore have been digitized and analysed by Anderson and Eriksson [1980] and the same parameters given in Berger et al. [1975] were re-evaluated, some new ones introduced. Some of the parameters given in Anderson and Eriksson [1980], relevant to the front of the lightning impulse are reported in Table 2.2.
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### Tab. 2.2 – Median values and standard deviation of front current parameters of negative downward lightning. Data taken from Anderson and Eriksson [1980].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>First strokes</th>
<th>Subsequent strokes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute peak $I_p$ (kA)</td>
<td>31.1</td>
<td>12.3</td>
</tr>
<tr>
<td>First peak $I_{p1}$ (kA)</td>
<td>27.7</td>
<td>11.8</td>
</tr>
<tr>
<td>Front duration $t_f$ (μs)</td>
<td>3.8</td>
<td>0.6</td>
</tr>
<tr>
<td>Maximum $dI/dt$ (kA/μs)</td>
<td>24.3</td>
<td>39.9</td>
</tr>
</tbody>
</table>

In Tab. 2.2, the front duration is derived from T-30, that is $t_f = T30/0.6$, where T-30 is the interval between the 10 percent and 90 percent intercepts on the front of the current waveshape (see Fig. 2.3). In Tab. 2.3 some correlation coefficients, that will be useful in the application of the procedure to infer correlation, as it will be cleared in section 2.6.

![Fig. 2.3 – Definition of front parameters for a lightning current impulse of negative polarity (adapted from Anderson and Eriksson [1980]).](image)

### Tab. 2.3 – Front parameter correlations of negative downward lightning assuming peak current as the independent variable ($I_p$ for the first strokes). Data taken from Anderson and Eriksson [1980].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>First strokes</th>
<th>Subsequent strokes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front duration $t_f$ (μs)</td>
<td>0.47</td>
<td>0</td>
</tr>
<tr>
<td>Maximum $dI/dt$ (kA/μs)</td>
<td>0.43</td>
<td>0.56</td>
</tr>
</tbody>
</table>
The main problems that arise in the use of statistics based on data collected by instrumented towers, are essentially related to the contamination due to tower effect. The primary problem is that stroke-current probability density functions are biased toward higher values as a consequence of the tower height. As the same EGM predicts, the striking distance increases with the height of the line or structure, so the tower ability to attract lightning flashes tends to increase for flashes with larger current.

The first to search for an equivalent current distribution for strokes to earth was Sargent [1972]. Sargent, by using an attractive-radius three-dimensional EGM model and on the basis of the lightning current amplitude experimental data available at that time, derived a so-called synthetic current amplitude distribution to ground level, which, as shown by Brown (1978), can be approximated by a lognormal distribution with $\mu_g = 13kA$ and $\sigma_g = 0.32$. Mousa and Srivastava [1989] have proposed a lognormal distribution of current amplitudes at ground level with $\mu_g = 24kA$ and $\sigma_g = 0.31$. Pettersson [1991] proposed an analytical formula that allows obtaining the statistical distribution of lightning peak current at ground starting from that obtained from elevated instrumented towers. A general procedure based on the Monte Carlo method is proposed in Borghetti et al. [2004]

The lightning current parameters are also affected by the influence of the reflections at the top and at the basis of the tower [Guerrieri et al. 1998, Rachidi et al. 2003, Bermudez et al. 2003, Baba and Rakov 2007]. In Krider et al. [2006] the effect of traveling-waves of current on the electromagnetic response of a tall Franklin rod considering various lightning return stroke models, is discussed.

The lightning parameters that may be considered of major interest in lightning performance studies are: peak current; front duration and return stroke velocity. Return-stroke speeds are usually measured using optical techniques. The value of speed that is needed for estimating the current peak from measured radiation field peak and distance, using simple return-stroke is lightning return-stroke speed within the bottom 100 m or so of the channel, that is, at the time when the initial peak of the channel-base current is formed. It is typically one-third to two-thirds of the speed of light [Rakov and Uman 2003].
2.4 – Italian lightning location system

The Italian lightning location system CESI-SIRF (‘Sistema Italiano Rilevamento Fulmini’), consists of 16 sensors located throughout Italian territory [Bernardi and Ferrari 2000]. In addition to that, data from Austrian, French and Swiss sensors located in the northern part of the network are made available to the system. CESI-SIRF provides stroke location coordinates in World Geodetic Coordinate System 1984 (WGS84). The CESI-SIRF system groups within a single flash all signals detected within one second and within a 10-km radius around the first detected stroke. For each lightning flash, the CESI-SIRF provides estimates the current peak and the location of each stroke of the flash. Concerning the estimated stroke location, a 50% probability error ellipse is provided by the LLSs as a confidence region in which there is a 50% probability that the actual stroke location lies within the area circumscribed by that ellipse, the center of the ellipse being the most probable stroke location [Cummins et al. 1998]. The electromagnetic field sensors of the Italian LLS allow to detect a stroke having a minimum current of about 2 kA. A single sensor measures the field in a so-called nominal range of 370 km. This ensures a stroke detection efficiency, for currents greater than 2 kA, of roughly 90% up to 200 km, which is also the mean baseline for the Italian sensors. This turns into a global flash detection efficiency of 90% over the Italian territory. Concerning the accuracy of the current peak estimates, it is provided by theoretical models and error analysis of the estimation process or by direct comparisons between LLS peak current estimations and the current measurements of the same lightning events at instrumented towers (e.g. Schulz and Diendorfer 2004]) or by means rocket-triggered lightning experiments (e.g. Jerauld et al. [2005]). It is worth noting that due to the high variability of key parameters such as the return-stroke speed, it is virtually impossible to determine the lightning current accurately from the remotely measured fields for a given event. However, it has been shown that a statistical estimation (e.g. in terms of mean values and standard deviations) is possible [Rachidi et al. 2004].
2.5 – Italian monitoring systems for protection manoeuvres

In order to infer the correlation between lightning and power line faults and dips, a monitoring system able to record all protection and circuit breaker status changes in the network of interest is required. The simplest procedure to correlate data coming from systems of acquisition of protection manoeuvres and data coming from lightning location systems, is time and spatial criteria as already discussed in section 2.1. Time correlation of such data requires a satisfactory synchronization. Clock drift and shifts among different clocks represented the main problem in some early works on correlation issue [Enel-Cesi working group 1994, Bernardi et al. 1994]. Such synchronization problems may be overcome if data coming from both systems have common time reference, i.e. GPS time-stamping.

A short sample time allows to recognize self-extinguishing faults.

In this research, data gathered by the Italian monitoring systems for protection manoeuvres SAM (‘Sistema Acquisizione Manovre’) have been used. A brief review of the main characteristics of SAM is reported; further details are given in Bernardi et al [1998].

SAM consists of a number of PC-based recording systems installed at some primary substations of the Italian MV power network, each receiving signals from the different protection devices of the lines connected to the given substation, namely: overcurrent, 0 sequence and breaker intervention relays. The system, having a 10-ms sampling time, is provided with an internal clock synchronized with the UTC time, which gives the required synchronization between lightning CESI-SIRF data and MV network data, and records any status change for each protection device in an ASCII file that can be post-processed.

2.6 – Indirect lightning-induced overvoltages calculation

In this research, the LIOV code [Nucci and Rachidi, 2003] has been used for lightning induced overvoltages calculations. The LIOV (Lightning Induced Over-Voltages) is a computer program allows for the evaluation of lightning-induced voltages on a multiconductor overhead line above a lossy ground (see Nucci et al. [1993], Rachidi et
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al. [1996] for the theoretical background). LIOV has been developed in the framework of an international collaboration involving the University of Bologna, the Swiss Federal Institute of Technology and the University of Rome. The code is based on the field-to-transmission line coupling formulation of Agrawal et al. [1980], suitably adapted for the calculation of induced overvoltages when lightning strikes near a horizontal overhead transmission line. In the LIOV code, the electromagnetic field radiated by the lightning channel is calculated using the field equations in the form given by Uman et al. [1975], with the extension to the case of lossy ground introduced by Cooray [1994] and Rubinstein [1996]. The forcing functions in the Agrawal et al. coupling model are expressed in terms of the vertical and horizontal electric field components. The vertical electric field radiated by the lightning channel is calculated assuming the ground as a perfectly conducting plane, since such a field component is not affected significantly by the soil resistivity in the frequency and distance range of interest.

Among the improvements of the LIOV, it is worthy mentioning the implementation of the version of Cooray-Rubinstein formula [Cooray, 1998], that takes into account remarks by Wait [1997], and the adoption of the second order point-centred finite-difference method to solve field-to-transmission line coupling equations of the Agrawal model [Paolone 2001a, 2001b].

The accuracy of the LIOV code has been verified by comparison with experimental data, both using reduced scale models [Piantini et al. 2007, Nucci et al. 1998, Paolone et al. 2004b] and full-scale setup [Paolone et al. 2004c].

The estimation of lightning-induced overvoltages requires the solution of two problems:
- the evaluation of the electromagnetic field change along the considered line;
- the coupling between the external electromagnetic field and the line;

The research activity has yielded additional improvement of LIOV on both issues. In this section only these original contributions will be highlighted.

2.6.1 – Lightning Electromagnetic field calculation

The most important event in a lightning flash, for lightning protection applications, is the return stroke. Indeed, only for lightning very close to the lines (i.e. 30 m), a significant overvoltage is induced by the leader [Rubinstein et al. 1995].
Different lightning return-stroke models are proposed in literature. “Engineering” models are return-stroke models that aim at predicting the temporal and spatial characteristics of return stroke current and the electromagnetic field at different distances. Other return-stroke models are the electromagnetic models, usually based on the approximation of the lightning channel as a thin wire antenna; distributed-circuit models and gas dynamic models.

Some engineering models assume the return stroke as a current pulse originating at ground level and propagating from earth to cloud along the leader channel. Other engineering models assume each point of the leader channel as a current source, turned on by the arrival of the return stroke front. The distributed current sources allow to model the injection of charge from the corona sheath of the leader to the return stroke channel. Some others use both concepts portrayed by the previous mentioned model.

A comprehensive review of the various models proposed is beyond the scope of this thesis, as the only model used in the proposed procedure is the Transmission line model (TL) [Uman and McLain, 1969]. According to which it is assumed that the current wave at the ground travels undistorted and unattenuated up the lightning channel at a constant speed \( v \).

Mathematically

\[
\begin{align*}
    i(z,t) &= i \left(0, t - \frac{z}{v}\right) & \text{if } 0 \leq vt \\
    i(z,t) &= 0 & \text{if } z > vt
\end{align*}
\]  

Given the spatial and temporal distribution of the source current (that is given the current at the base of the lightning channel and adopted an engineering return stroke model), the electric and magnetic field generated by the lightning return stroke may be calculated using the so-called “dipole technique”, that is the method used in this thesis. Another method is the so-called “monopole technique”, which requires the knowledge of both the current and the charge density as a function of time and space. The two methods are equivalent [Rubinstein and Uman 1989].

In the dipole technique the electromagnetic field due to a current distribution is calculated considering the current path made up of a large number of small current elements. By continuity, equal and opposite time-varying charges must exist on the two ends of the current element, so the element is frequently called small dipole or Hertzian.
dipole. The frequency domain solution of the small dipole is reported in many textbooks (i.e. Ramo and Whinnery [1964]). The time domain solution of the problem in spherical coordinates may be found in Uman et al. [1975]; in rectangular coordinates in Price et al. [1980]; in cylindrical coordinates in Master and Uman [1983].

In this thesis, the equations in cylindrical coordinates are used

\[
dE_\rho (\rho, z, t) = \frac{1}{4\pi \varepsilon} \frac{d\varepsilon}{dt} \left[ \frac{3}{c^2 r^3} i \left( z', t - \frac{r}{c} \right) + \frac{1}{c^2 r^3} \frac{\partial}{\partial t} i \left( z', t - \frac{r}{c} \right) + \frac{3}{r^2} \int i \left( z', t - \frac{r}{c} \right) dt \right] \tag{2.13}
\]

\[
dE_z (\rho, z, t) = \frac{1}{4\pi \varepsilon} \frac{d\varepsilon}{dt} \left[ \frac{2z'^2 - \rho^2}{c^2 r^4} i \left( z', t - \frac{r}{c} \right) - \frac{\rho^2}{c^2 r^3} \frac{\partial}{\partial t} i \left( z', t - \frac{r}{c} \right) + \frac{2z'^2 - \rho^2}{r^5} \int i \left( z', t - \frac{r}{c} \right) dt \right] \tag{2.14}
\]

\[dE_\phi = 0\]

\[dH_\rho = 0\]

\[dH_z = 0\]

\[
dH_\phi = -\frac{1}{4\pi} \frac{d\varepsilon}{dt} \frac{1}{r^2} \left[ i \left( z', t - \frac{r}{c} \right) - \frac{\partial}{\partial t} i \left( z', t - \frac{r}{c} \right) \right] \tag{2.15}
\]

where \(z'\) is the coordinate of the small current; \(\rho\) and \(z\) are cylindrical coordinates, in the system having the small current at the origin, of the point at which the field is desired to be calculated, \(r\) is the distance between the point and the small current (see Fig. 2.4).
In order to calculate the electric and magnetic field generated by the return stroke, the (2.13)-(2.15) need to be integrated along the channel. As the (2.13)-(2.15) are valid only for small currents at the origin of the coordinate system, a suitable change of system of coordinates is necessary. In the case of vertical channel, $z$ must be substituted by $z - z'$ in the right side of (2.13)-(2.15); $r$ is given by

$$r = \sqrt{\rho^2 + (z - z')^2}$$

The extremes of integration are zero and the coordinate $z_{\text{max}}$ of the last dipole turned on. The generic dipole at coordinate $z'$, gives a contribute to the field in $P(\rho,z)$ if enough time is passed so that the current front reached the height $z'$ and the field propagated from $z'$ to $P(\rho,z)$. Mathematically:

$$t \geq \frac{z'}{v} + \frac{\sqrt{\rho^2 + (z - z')^2}}{c}$$

that gives

$$z' \leq \left( \frac{t - z}{c^2} \right) - \sqrt{\left( \frac{t - z}{c^2} \right)^2 - \left( \frac{1}{c} - \frac{1}{v} \right)^2 \left( t^2 - \rho^2 + z^2 \right)} \left( \frac{1}{c} - \frac{1}{v} \right) \left( \frac{1}{c^2} - \frac{1}{v^2} \right)$$

(2.16)
The upper limit given by (2.16) is $z_{\text{max}}$.

In literature, the integrals of (2.13)-(2.15) are reported for the case of positive step function of current propagating along the channel according to the TL model [Rubinstein and Uman 1991].

In the case of more complex channel base current functions or return stroke models, a numerical evaluation of the integrals is needed, using suitable subroutine. Such numerical evaluations implies long computational times for statistical studies as the procedure used in this thesis. On the other hand, a square current represents a too simplified assumption, as it does not allow to take into account the shape of the wavefront of the return stroke current, that plays an important role in indirect-lightning induced overvoltage calculations [Borghetti et al. 2001].

One of the major contributes of this thesis is the analytical solution of the integrals of the electric and magnetic field for a current surge propagating along a vertical channel in the case of “trapezoidal” current, that is linearly rising current linearly rising with flat top, and TL return stroke model.

Mathematically, the linearly rising currents with flat top may be expressed as:

$$i(0,t) = \begin{cases} \frac{I_p}{t_f} t, & t \leq t_f \\ I_p, & t > t_f \end{cases}$$

(2.17)

where:

$I_p$ is the maximum current amplitude;

$t_f$ is the front duration;

Assuming the TL model, it is easy to obtain

$$i(z',t) = \begin{cases} I_p, & z' < v(t - t_f) \\ I_p \left( t - \frac{z'}{v} \right), & v(t - t_f) < z' < vt \end{cases}$$

(2.18)

$$i(z',t) = 0 \quad z' > vt$$

$$\frac{\partial}{\partial t} i(z',t) = 0 \quad z' < v(t - t_f)$$

(2.19)

$$\frac{\partial}{\partial t} i(z',t) = \frac{I_p}{t_f} \quad v(t - t_f) < z' < vt$$
\[ \int_0^t i(z', t) = I_p \left( t - \frac{t_f - z'}{v} \right) \quad z' < v(t - t_f) \]  
\[ \int_0^t i(z', t) = \frac{I_p}{2t_f} \left( t - \frac{z'}{v} \right)^2 \quad v(t - t_f) < z' < vt \]

Be:

\( z_f \) the coordinate of the dipole at which the current starts to have constant value;

\( t_f \) is the rise time of the current front.

Analogously to \( z_{\text{max}} \), \( z_f \) is obtained by the condition

\[ t - t_f > \frac{z'}{v} + \sqrt{\frac{\rho^2 + (z - z_f)^2}{c^2}} \]

that gives

\[ z' < \frac{\left( \frac{t - t_f}{v} - \frac{z}{c^2} \right) - \sqrt{\left( \frac{t - t_f}{v} - \frac{z}{c^2} \right)^2 - \left( \frac{1}{v^2} - \frac{1}{c^2} \right) \left( t - t_f \right)^2 - \frac{\rho^2 + z_f^2}{c^2}}}{\left( \frac{1}{v^2} - \frac{1}{c^2} \right)} \]  
\[ (2.21) \]

The upper limit given by (2.21) is \( z_f \).

In the case of TL model and “trapezoidal” current, the integrals of (2.13)-(2.15) have been calculated taking into account the contribute of the front and of the constant tail separately. The final solution is

\[ E_p(\rho, z, t) = \frac{1}{4\pi\varepsilon_0} \int_\rho^t \frac{1}{\sqrt{\rho^2 + (z - z_f)^2}} \left[ \frac{t - \frac{t_f}{2} - \frac{z}{v}}{v\rho^2 \left( z - z_f \right)^3} - \frac{t - \frac{t_f}{2} - \frac{z}{v}}{v \rho^2 z^3} \right] \]

\[ - \frac{2}{v\rho^2} \left( t - \frac{z}{v} \right) \left( z - z_{\text{max}} \right)^3 + \frac{3}{v^2} - \frac{1}{c^2} \left( z - z_{\text{max}} \right)^2 + \left( t - \frac{z}{v} \right)^2 + \rho^2 \left( \frac{2}{v^2} - \frac{1}{c^2} \right) \]

\[ 2t_f \sqrt{\rho^2 + (z - z_{\text{max}})^2} \]

\[ - \frac{2}{v\rho^2} \left( t - \frac{z}{v} \right) \left( z - z_f \right)^3 + \frac{3}{v^2} - \frac{1}{c^2} \left( z - z_f \right)^2 + \left( t - \frac{z}{v} \right)^2 + \rho^2 \left( \frac{2}{v^2} - \frac{1}{c^2} \right) \]

\[ 2t_f \sqrt{\rho^2 + (z - z_f)^2} \]

\[ (2.22) \]
The vertical electric field is given by

\[
E_z(\rho, z, t) = \frac{1}{4\pi c} \int \frac{2(z'-z)}{v} \left[ \left( t' - \frac{t}{v} \right) \left( z' - \frac{z}{v} \right) + \frac{\rho^2}{v^2} \left( \frac{z}{v} + \frac{\rho^2}{v^2} \right) \right] \left( \frac{1}{\sqrt{\rho^2 + (z-z')^2}} \right) \frac{dz'}{\sqrt{\rho^2 + (z-z')^2}}
\]

\[
+ \frac{1}{t_f} \left( \frac{1}{v^2} - \frac{1}{c^2} \right) \ln \frac{\rho^2 + (z-z_{\text{max}})^2 - (z-z_{\text{max}})}{\rho^2 + (z-z_{\text{max}})^2 - (z-z_{\text{max}})}
\]

\[
\frac{3}{v^2 - c^2} \left( z - z_{\text{max}} \right)^3 + \frac{4}{v} \left( t - \frac{z}{v} \right) \left( z - z_{\text{max}} \right)^2 + \left[ \left( t - \frac{z}{v} \right)^2 + \rho \left( \frac{2}{v^2 - c^2} \right) \left( z - z_{\text{max}} \right) + \frac{2\rho^2}{v} \left( t - \frac{z}{v} \right) \right] \frac{dz'}{\sqrt{\rho^2 + (z-z')^2}}
\]

(2.23)

The magnetic field is given by

\[
H_\phi(\rho, z, t) = \frac{I_p}{2\pi} \left[ \frac{z - z_f}{\rho \sqrt{\rho^2 + (z-z_f)^2}} + \frac{z}{\rho \sqrt{\rho^2 + z^2}} \right] \frac{dz}{\sqrt{\rho^2 + (z-z_f)^2}}
\]

\[
\frac{\rho - \frac{1}{v} \left( t - \frac{z}{v} \right) \left( z - z_{\text{max}} \right)}{t_f \sqrt{\rho^2 + (z-z_{\text{max}})^2}} - \frac{\rho - \frac{1}{v} \left( t - \frac{z}{v} \right) \left( z - z_f \right)}{t_f \sqrt{\rho^2 + (z-z_f)^2}}
\]

(2.24)

### 2.6.2 – Field-to-transmission line coupling

The problem of the field-to-transmission line coupling may be solved by means of antenna theory, that is the general approach based on Maxwell’s equations [Tesche et al. 1997]. However, due to the length of overhead lines, the use such a theory for the calculation of the lightning-induced overvoltages implies long computation time. If the cross dimensions of the line are electrically small (smaller than one tenth of the minimum significant wavelength of the electromagnetic field), the waves along the
propagation mode of the waves along the lines may be assumes as Transverse Electromagnetic (TEM). The properties of TEM waves are:

- no electric field or magnetic field in direction of propagation
- electric field normal to magnetic field
- direction of propagation given by the direction of $\vec{E} \times \vec{H}$
- energy stored in electric field per unit volume at any instant and any point equal to energy stored in magnetic field per unit volume at that instant and that point
- electric field is gradient of a scalar potential in so far as variations in the transverse plane are concerned.

If the dielectric has conductivity, the TEM mode may exist, but if the current-carrying conductors of the transmission line have finite conductivity there must be at least some small component of electric field in the direction of propagation to force current through the conductors.

If the losses of the lines are small, it may be still assumed that the propagation still occurs only along the line axis (quasi-TEM) and the line can be represented by a distributed-parameter structure along the its axis.

Different field-to-transmission line coupling models have been developed based on TEM assumption, among them:

- Rusck model [1958];
- Taylor, Satterwhite and Harrison model [1965];
- Chowduri and Gross model [1967]
- Agrawal, Price and Gurbaxani model [1980];
- Rachidi model [1993];

Cooray [1994] and Nucci et al. [1995] demonstrated that the Agrawal et al. model, Taylor et al., and Rachidi models are equivalent, and the only that can be considered as rigorous within the limits of the transmission line approximation. The Rusck’s model becomes equivalent to the Agrawal et al. model in the case of an electromagnetic field originated by a straight vertical channel.

It is worth reminding the simplified analytical Rusck formula [Rusck, 1958], which applies to the case of an infinitely long single conductor line above a perfectly conductor ground. This formula gives the maximum value of the induced overvoltages at the point of the line nearest the stroke location.
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\[
V_{\text{max}} = 30 \frac{Ih}{y} \left( 1 + \frac{1}{\sqrt{2}} \frac{v}{v_0} \left( 1 - \frac{1}{2} \left( \frac{v}{v_0} \right)^2 \right) \right)
\]

(2.25)

where

in which

\(I\) is the amplitude of the lightning-peak current assumed to have a step function waveshape;

\(h\) is the average height of the line over the ground level;

\(y\) is the closest distance between the lightning strike and the line;

\(v\) is the return stroke velocity;

\(v_0\) is the velocity of the light in free space.

Note that this formula includes not only the coupling model between the electromagnetic field and the line, but also the return stroke model for the calculation of the electromagnetic field radiated by the lightning current.

In what follows, only the Agrawal et al field-to-transmission line coupling equations are reported as they are the one adopted in the LIOV code, that has been used in this research.

The Agrawal et al field-to-transmission line coupling equations for a multiconductor line along the x axis above a lossy ground can be written as [Rachidi et al. 1999]

\[
\frac{\partial}{\partial x} [v_i'(x,t)] + [L_{ij}'] \frac{\partial}{\partial t} [i_j(x,t)] + [\mathcal{S}_{ji}] \frac{\partial}{\partial t} [i_j(x,t)] = [E_i^e(x,h_j,t)]
\]

(2.26)

\[
\frac{\partial}{\partial x} [i_j(x,t)] + [C_{ij}'] \frac{\partial}{\partial t} [v_i'(x,t)] = [0]
\]

(2.27)

where

\([v_i'(x,t)]\) and \([i_j(x,t)]\) are time-domain vectors of the scattered voltages and the current along the line;

\([E_i^e(x,h_j,t)]\) is the vector of the exciting electric field tangential to the line conductor;

\([L_{ij}']\) and \([C_{ij}']\) are the matrices of the per-unit-length line inductance and capacitance, respectively;
\[ \left[ \xi_{gi} \right] \text{ is the “transient ground resistance” matrix, that is the inverse Fourier transform of the matrix of ground impedance;} \]

\[ \odot \text{ denotes convolution product.} \]

Note that, in the proposed procedure to infer correlation between lightning and voltage dips and faults in distribution systems, the transient ground resistance is neglected, as it introduces little modifications of the results in front of a large increase of the computational time due to the convolution.

The transmission line coupling equations in time domain may be solved by means of the finite difference time domain (FDTD) technique. Such a technique was used indeed by Agrawal et al. [1980] when presenting their field-to-transmission line coupling equations. In the above publication, partial time and space derivatives were approximated using the 1st order FDTD scheme. In [Paolone et al. 1997], the use of a 2nd order FDTD scheme based on the Lax-Wendroff algorithm has been proposed [Lax and Wendroff 1960, Omick and Castillo 1993].

By expanding the line current and the scattered voltage using Taylor’s series applied to the time variable until the second order term yields

\[
\begin{align*}
[v'_i(x,t)] &= [v'_i(x,t_0)] + \Delta t \frac{\partial}{\partial t}[v'_i(x,t)] + \frac{\Delta t^2}{2} \frac{\partial^2}{\partial t^2}[v'_i(x,t)] + [O(\Delta t^3)] \\
[i(x,t)] &= [i(x,t_0)] + \Delta t \frac{\partial}{\partial t}[i(x,t)] + \frac{\Delta t^2}{2} \frac{\partial^2}{\partial t^2}[i(x,t)] + [O(\Delta t^3)]
\end{align*}
\] (2.28) (2.29)

where \( O(\Delta t^3) \) is the remainder term, which approaches zero as the third power of the temporal increment.

By substituting the time derivatives in (2.28) and (2.29) with the corresponding equations (2.26) and (2.27) and the derived ones obtained by differentiating (2.26) and (2.27) with respect to the \( x \) and \( t \) variables, we obtain the following second order differential equations

\[
\begin{align*}
[v'_i(x,t)] &= [v'_i(x,t_0)] - \frac{\Delta t}{[C']} \frac{\partial}{\partial x}[i(x,t)] \\
- \frac{\Delta t^2}{2[L'][C']^2} \left( \frac{\partial}{\partial x}[E'_e(x,h,t)] - \frac{\partial^2}{\partial x^2}[v'_i(x,t)] \right) + [O(\Delta t^3)]
\end{align*}
\] (2.30)
\[ [i(x,t)] = [i(x,t_0)] - \frac{\Delta t}{L} \left( \frac{\partial}{\partial x} \left[ v^i(x,t) - [E^i(x,h,t)] \right] \right) \]

\[ + \frac{\Delta t^2}{2L'[C']} \left( \frac{\partial^2}{\partial x^2} [i(x,t)] + [C'] \frac{\partial}{\partial t} [E^i(x,h,t)] \right) \text{[O(\Delta t^3)]]} \]  

(2.31)

Note that

\[ [L'[C']] = [C'][L'] = \frac{1}{u} I \]

where:

\( u \) is the propagation speed of the electromagnetic transients along the line;
\( I \) is the identity matrix.

In order to represent equations (2.30) and (2.31) within the FDTD integration scheme, we will proceed with the discretization of time and space as follows

\[ v^i(x,t) = v^i(k\Delta x, n\Delta t) = v^n_{ik} \]  

(2.32)

\[ i(x,t) = i(k\Delta x, n\Delta t) = i^n_{ik} \]  

(2.33)

\[ E^e(x,h,t) = E^e(k\Delta x, h, n\Delta t) = E^n_{hk} \]  

(2.34)

where

- \( \Delta x \) is the spatial integration step;
- \( \Delta t \) is time integration step;
- \( k = 0, 1, 2, \ldots, k_{\text{max}} \) is the spatial discretization index \((k_{\text{max}} = L/\Delta x + 1, \text{ where } L \text{ is the line length});
- \( n = 0, 1, 2, \ldots, n_{\text{max}} \) is the time discretization index.

In the integration scheme, the scattered voltage and current at time step \( n \) are assumed as known for all spatial nodes. Therefore equations (2.30) and (2.31) allow the scattered voltages and currents to be calculated at the time step \( n + 1 \).

The discrete spatial derivatives of the scattered voltages, line currents, and horizontal electric fields can be written respectively as follows

\[ \frac{\partial v^i(x,t)}{\partial x} \bigg|_{n\Delta t} \approx \frac{v^n_{ik+1} - v^n_{ik-1}}{2\Delta x} \]  

(2.35)

\[ \frac{\partial i(x,t)}{\partial x} \bigg|_{n\Delta t} \approx \frac{i^n_{ik+1} - i^n_{ik-1}}{2\Delta x} \]  

(2.36)
\[ \frac{\partial E^x_i(x, h_i, t)}{\partial x} \bigg|_{i=n\Delta x} \approx \frac{Eh^n_{i,k+1} - Eh^n_{i,k-1}}{2\Delta x} \]  
(2.37)

On the other hand, the discrete time derivatives of the horizontal electric field read

\[ \frac{\partial E^x_i(x, h_i, t)}{\partial t} \bigg|_{i=n\Delta t} \approx \frac{Eh^n_{i,k} - Eh^{n-1}_{i,k}}{2\Delta t} \]  
(2.38)

The discrete second order spatial derivatives can be written as

\[ \frac{\partial^2 v^x_i(x, t)}{\partial x^2} \bigg|_{i=n\Delta x} \approx \frac{v^n_{i,k+1} + v^n_{i,k-1} - 2v^n_{i,k}}{\Delta x^2} \]  
(2.39)

\[ \frac{\partial^2 i^x_i(x, t)}{\partial x^2} \bigg|_{i=n\Delta x} \approx \frac{i^n_{i,k+1} + i^n_{i,k-1} - 2i^n_{i,k}}{\Delta x^2} \]  
(2.40)

By including equations (2.32)-(2.40) into (2.30) and (2.31), the equations of the 2nd order FDTD integration scheme are obtained for the internal nodes, namely \( k = 1, 2, \ldots, k_{max}-1 \):

\[ [v^n_{i,k+1}] = [v^n_{i,k}] - \Delta t[C']^{-1}\left(\frac{[i^n_{i,k+1}] - [i^n_{i,k-1}]}{2\Delta x}\right) \]
\[ - \frac{u^2 \Delta t^2}{2} \left(\frac{[Eh^n_{i,k+1}] - [Eh^n_{i,k-1}]}{2\Delta x} - \frac{[v^n_{i,k+1}] + [v^n_{i,k-1}] - 2[v^n_{i,k}]}{\Delta x^2}\right) \]  
(2.41)

\[ [i^{n+1}_{i,k}] = [i^n_{i,k}] - \Delta t[L']^{-1}\left(\frac{[v^n_{i,k+1}] - [v^n_{i,k-1}]}{2\Delta x} - [Eh^n_{i,k}]\right) \]
\[ + \frac{u^2 \Delta t^2}{2} \left(\frac{[i^n_{i,k+1}] + [i^n_{i,k-1}] - 2[i^n_{i,k}]}{\Delta x^2} + [C']\frac{[Eh^{n+1}_{i,k}] - [Eh^{n-1}_{i,k}]}{2\Delta t}\right) \]  
(2.42)

A complex issue, in the solution of the transmission line coupling equations, is the treatment of the boundary conditions that links the voltages and currents in correspondence of the terminal FDTD nodes, namely \( i^n_{i,k} \bigg|_{k=0,k_{max}}, v^n_{i,k} \bigg|_{k=0,k_{max}} \).

For linear or non-linear line terminations, the boundary conditions can be written as

\[ v^n_{i_0} = -\Gamma_0(i^n_{i_0}) + \int_0^{h_i} E^z_0(0,0,t)dz \]  
(2.43)

\[ v^n_{i_{k_{max}}} = \Gamma_{k_{max}}(i^n_{i_{k_{max}}}) + \int_0^{h_i} E^z_0(L,0,t)dz \]  
(2.44)
In application to realistic power networks, the presence of complex power component (i.e. transformers and surge arresters) make difficult to explicit in a closed numerical form the boundary conditions.

To deal with the problem of lightning-induced voltages on complex systems, the LIOV has been previously interfaced [Nucci et al. 1994, Borghetti et al. 2004] with EMTP (ElectroMagnetic Transient Program).

Other proposed models for the evaluation of the LEMP (Lightning ElectroMagnetic Pulse) response of distribution networks are the one proposed by Orzan et al. [1996, 1998] and Høidalen [1997, 1999, 2003a, 2003b].

In the model proposed by Orzan et al., for each illuminated line the coupling between the external incident field and the phase conductors is reproduced, in the distribution network model, by means of equivalent current generators whose value is pre-calculated by solving the Agrawal et al. transmission line coupling model. The current generators are then inserted in an EMTP simulation where traditional lines models replace illuminated lines. Such an approach cannot take into account non-linear local phenomena, like a variation in the line-capacitance with space, as necessary for instance when taking into account the presence of corona phenomenon.

In the model proposed by Høidalen, the analysis of the response of the illuminated distribution system uses the same concepts adopted in the model developed by Orzan et al., namely each illuminated line response is reproduced by means of equivalent voltage generators. The evaluation of the coupling between the external incident field and each illuminated line is solved using an analytical approach valid only within the following assumptions: i) lightning channel-base current represented by means of a step function, ii) a TL return stroke model, iii) transient ground impedance neglected in the coupling equations.

In the recent version of the LIOV-EMTP code [Napolitano et al. 2008], based on EMTP-RV (ElectroMagnetic Transient Program Revisited Version) some improvements in the interface scheme has been introduced.

The interface between LIOV and EMTP-RV is based on the same concepts of the previous LIOV-EMTP96, that is the link between voltages and currents in correspondence of ideal line terminations is realized with the numerical treatment of the
travelling wave solution known as the Bergeron method or the method of characteristics [Bergeron 1949].

In the previous versions, the use of fictitious lossless Bergeron lines at line terminations introduces a small time shift introduced between each illuminated LIOV-line and the boundary solution provided by the EMTP-RV.

In the Perez model [Perez 2006], based on the same formulation of LIOV, such a difficulty has been solved in a way similar to the one proposed by Napolitano et al. [2008], by extending the use of Bergeron lines in order to take into account the presence of the exciting LEMP, so removing the need of adding these short lines outside the line of interest. The solution proposed by Perez differs from the proposed interface in the solution of voltages and currents at the nodes adjacent to the Bergeron lines.

In Napolitano et al. the space and time integration steps are correlated by means of the following equation that provides the so-called magic integration steps [Paul 1994] and satisfy the Courant stability condition

$$\frac{\Delta x}{\Delta t} = u \quad (2.45)$$

where the propagation speed $u$ is assumed to be frequency independent.

The (2.45) allows the Bergeron lines to substitute the first and last spatial discretization of the LIOV line characterized by line length equal to $u\Delta t$, so no linear interpolation is needed.

With the assumption of (2.45), the (2.41) and (2.42) simplify as follows

$$[v_{ik}^{n+1}] = -\frac{u}{2}[L^n][(i_{ik+1}^n - [i_{ik-1}^n]) + \frac{1}{2}([v_{ik+1}^n] + [v_{ik-1}^n]) - \frac{\Delta x}{4}([Eh_{ik+1}^n] - [Eh_{ik-1}^n]) \quad (2.46)$$

$$[i_{ik}^{n+1}] = -\frac{1}{2u}[L']^{-1}([v_{ik+1}^n] - [v_{ik-1}^n]) + \frac{1}{2}([i_{ik+1}^n] + [i_{ik-1}^n]) + \frac{\Delta t}{4}[L']^{-1}(4[Eh_{ik}^n] + [Eh_{ik}^{n+1}] - [Eh_{ik}^{n-1}]) \quad (2.47)$$

The Bergeron equations that describes the travelling waves in absence of external exciting LEMP are:

$$[v_j(0,t)] - [Z][i_j(0,t)] = [v_j(u\Delta t, t - \Delta t)] - [Z][i_j(u\Delta t, t - \Delta t)] \quad (2.48)$$

$$[v_j(L,t)] + [Z][i_j(L,t)] = [v_j(L - u\Delta t, t - \Delta t)] + [Z][i_j(L - u\Delta t, t - \Delta t)] \quad (2.49)$$

where
[\mathbf{v}_i(0,t)] and [\mathbf{i}_i(0,t)] are the vectors of the voltages and currents at the beginning of the line;  
[\mathbf{v}_i(L,t)] and [\mathbf{i}_i(L,t)] are the vectors of the voltages and currents at the end of the line;  
\[ Z \] is the matrix of surge impedances of the line.

In presence of an exciting LEMP field and using the Agrawal et al. coupling model, (2.48) and (2.49) read

\[
[v'_i(0,t)] - [Z][i'_i(0,t)] = [v'_i(u\Delta t, t - \Delta t)] - [Z][i'_i(u\Delta t, t - \Delta t)] - \int_0^{\Delta t} E'_s(x, h_i, t) dx \tag{2.50}
\]

\[
[v'_i(L,t)] + [Z][i'_i(L,t)] = [v'_i(L - u\Delta t, t - \Delta t)] + [Z][i(L - u\Delta t, t - \Delta t)] + \int_{L-u\Delta t}^{\Delta t} E'_s(x, h_i, t) dx \tag{2.51}
\]

By applying the FDTD method the (2.50) and (2.51) become

\[
[v^n_{i_0}] - [Z][i^n_{i_0}] = [v^n_i] - [Z][i^n_i] - \frac{\Delta x}{2} ([E_{h^n_{i_0}}] + [E_{h^n_i}]) \tag{2.52}
\]

\[
[v^n_{i_{k_{\text{max}}}}] + [Z][i^n_{i_{k_{\text{max}}}}] = [v^n_{i_{k_{\text{max}}-1}}] + [Z][i^n_{i_{k_{\text{max}}-1}}] + \frac{\Delta x}{2} ([E_{h^n_{i_{k_{\text{max}}}}}] + [E_{h^n_{i_{k_{\text{max}}-1}}}]) \tag{2.53}
\]

These equations provide the link between the LIOV and the EMTP-RV as illustrated in Fig. 2.5.

---

Fig. 2.5 – Numerical solution of the illuminated line boundary conditions and the relevant link with EMTP-RV.
In Fig. 2.5 the terms \((Ez_n^{n+1} \cdot h)\) and \((Ez_{k_{\text{max}}}^{n+1} \cdot h)\) are the numerical representation of
\[
\int_0^h E_z^e(0,0,t)\,dz \quad \text{and} \quad \int_0^h E_z^e(L,0,t)\,dz
\]
respectively, being the vertical component of the exciting electric field assumed constant along the \(z\) axis, as generally accepted for overhead distribution lines [Agrawal et al. 1980].

The values of two voltages sources \(G_0\) and \(G_{k_{\text{max}}}\) are calculated as
\[
G_0 = v_1^n - Zi^n \quad \text{(2.54)}
\]
\[
G_{k_{\text{max}}} = v_{k_{\text{max}}}^n + Zi_{k_{\text{max}}-1}^n \quad \text{(2.55)}
\]

Equations (2.54) and (2.55) are calculated at each time step by means of dynamic link library (DLL) called within the EMTP-RV environment.

While in the LIOV-EMTP96 code the interface was made by means of the so called TACS (Transient Analysis of Control Systems), in LIOV-EMTP-RV the voltage sources \(G_0\) and \(G_{k_{\text{max}}}\) are defined in the solution provided by the augmented nodal analysis formulation [Mahseredjian et al. 1993, 2003, 2005]. In particular, each voltage source is defined by adding one row to the augmented nodal admittance matrix and, in the added row, the unknown quantity is the current of the added voltage source, while the known voltage is inserted in the known coefficients column, namely the column of the history currents sources. Together with the additional row, an auxiliary column is also added, where a coefficient equal to one is suitably inserted in order to satisfy the Kirchoff’s laws in the loop containing the voltage source.

At the end of each time step, the current of each line termination, that corresponds to the unknown current of the voltage generators \(G_0\) and \(G_{k_{\text{max}}}\), are calculated as a solution of the EMTP-RV augmented nodal analysis. Therefore, the scattered voltage can be calculated using the known values of current, source voltage, surge impedance and components of the exciting incident field.

In what follows the advantage of the new interface is analyzed.
Fig. 2.7 refers to the simple line configuration reported in Fig. 2.6, considered placed above an ideal ground and illuminated by a LEMP produced by a lightning current characterized by a 12 kA amplitude and 40 kA/μs of maximum time derivative, return stroke speed equal to 1.3·10^8 m/s and return stroke time-space distribution represented with the MTLE model. In particular, the results make reference to cases in which the line is segmented in one and five sections and with space and time integration steps equal to: a) Δx = 5 m, Δt = 1.66·10^{-8} s, b) Δx = 10 m, Δt = 3.33·10^{-8} s, c) Δx = 20 m, Δt = 6.66·10^{-8}.

Fig. 2.7 shows that for the case of a line simulated by means of a single illuminated section, the two versions of the interface provide the same results irrespective the chosen space and time integration steps. On the other hand, the results relevant to the segmentation of the illuminated line in five parts results in an enhancement of the errors produced by the presence of the time-delay associated to the short external Bergeron’s line used in the previous version of the interface. In particular, the appropriate use of the previous version of the interface was relying on the choice of sufficiently small space and time integration steps, whilst the new version of the interface provides simulation results that are substantially independent from the width of the chosen space and time integration steps (provided they are consistent with the frequency content of the simulated transients). This last result allows the adoption of large integration steps.
resulting in an important decrease of computational time of particular importance in statistical studies as the one dealt in this thesis.

Fig. 2.7 – Comparison between results provided by LIOV-EMTP96 and LIOV-EMTP-RV relevant to the line geometry of Fig. 2.6: a) line segmented in one section simulated by LIOV-EMTP96, b) line segmented in one section simulated by LIOV-EMTP-RV, c) line segmented in five sections simulated by LIOV-EMTP96, d) line segmented in five sections simulated by LIOV-EMTP-RV.

Another important advantage of the new interface lies in the possibility of simulating correctly multiconductor lines with terminations matched with both self and mutual surge impedance, as a consequence of the implementation of the Bergeron lines with the entire matrix of surge impedances $Z$, instead of the only surge impedances, that is the solution generally adopted in the models available in literature.
Chapter 2 – The approach chosen to solve correlation problem of interest

Fig. 2.8 – Line configuration adopted for the analysis of matched multiconductor line response
(adapted from Rachidi et al. 1997)

Fig. 2.9 – Response of multiconductor lines: a) lines matched terminated on self surge impedance;
b) lines matched terminated on self and mutual surge impedances.

Assuming the same assumption of the previous case study, except for the line configuration that is the one portrayed in Fig. 2.8 (without ground wire), with conductor radius 9.14 mm, the responses of multiconductor lines for different line termination is reported in Fig. 2.9. It may be noted that if the lines are terminated on resistances equal to the characteristic impedance determined in absence of the other conductors, a reflected wave is visible. Such a reflected wave disappear if the line is terminated on the matrix of self and mutual resistances equal to the self and mutual surge impedances of the line.
Chapter 2 – The approach chosen to solve correlation problem of interest

The LIOV-EMTP-RV has been validated using experimental data obtained by means of reduced scale models and trigger lightning technique (see Napolitano et al. 2008).

2.7 - The correlation algorithm

The correlation algorithm (see [Borghetti et al. 2006] for additional details) is conceived to correlate lightning strokes detected by CESI-SIRF, with fault events detected by CESI-SAM. In particular, the correlation algorithm is composed by the following steps:
1. a set of potential events is selected by means of a time correlation criterion, namely each lightning event is considered potentially correlated to a fault event if it occurred within ± 1 s (GPS time) from the fault event occurrence;
2. for each stroke candidate, a set of 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 error ellipse provided by the LLS;
3. a set of current values is also generated from the available distribution of peak current estimation errors;
4. in order to distinguish between direct and indirect strokes, a suitable model of the lightning incidence to the distribution lines is applied to each event (see section 2.2);
5. for the case of both direct and indirect events, the lightning overvoltages along the lines are calculated and compared with the overhead line insulation withstanding characteristics, which makes it possible to estimate the probability that the detected lightning flash is a cause of fault events.

As for the step 2, the generation of the random stroke locations need the knowledge of the standard deviations of the location error along the directions of the maximum and minimum errors. These standard deviations may be obtained by dividing by 1.177 the semi-axis of the 50% error ellipse provided by the LLS. Indeed, the probability of the stroke location to be inside the ellipse with axis equal to above mentioned standard deviations is equal to 39.35%, and 1.177 is the scaling factor used to increase the error to a more meaningful error probability of 50% [Schulz 1997].
As for the step 3, in order to obtain a realistic flashover probability estimation, at least a trapezoidal waveshape is needed for the currents, that is two parameters are needed: current peak $I_p$ and time to peak $t_f$. For the generation of the set of current peaks a distribution of current peak errors has to be assumed. Regarding to $t_f$, which is not provided by the LLS, the random value of $t_f$ may be generated assuming a median value $\mu_{\text{ln}t_f}$, a standard deviation $\sigma_{\text{ln}t_f}$, a correlation coefficient $\rho$ with $I_p$ and that a conditional probability density function of log-normal type is followed. The log-normal conditional probability density function of $t_f$ given $I_p$ is [Brown 1969]

$$f(t_f | I_p) = \frac{1}{t_f \sigma_{\text{ln}t_f} \sqrt{1 - \rho^2} \sqrt{2\pi}} \exp \left( -\frac{1}{2} \left( \frac{\ln t_f - \ln \mu_{\text{ln}t_f}}{\sigma_{\text{ln}t_f} \sqrt{1 - \rho^2}} \right)^2 \right)$$

where

$$\mu_{\text{ln}t_f} = \mu_{\text{ln}t_f} + \rho \frac{\sigma_{\text{ln}t_f}}{\sigma_{\ln I_p}} (\ln I_p - \mu_{\ln I_p})$$
Chapter 3 – Application to a real case

3.1 – The Distributed measurement system

In this section, the distributed measurement system (DMS) developed for the monitoring of lightning-originated transients in distribution networks is described. The developed DMS, which philosophy has been described in [Yamabuki et al 2007], represents a major evolution, extended to medium voltage networks, of the one for low voltage networks illustrated in [Peretto et al 2004].

The typical architecture of a DMS for power quality monitoring in distribution power networks consists of a number of units connected at some buses of the monitored network. Each unit, typically linked to a central server by means of local or wide area communication networks (LANs or WANs), acquires measurements of phase currents and phase-to-ground voltages, and performs the designed signal processing functions [Paolone et al 2004a, Cristaldi et al 2002, Bucci et al 2003].

The proposed DMS represents an evolution of such a system. Indeed, it preserves the distributed architecture, but includes additional features such as an event detection block for the trigger of a-periodic disturbances and the availability of wide-band high voltage probes, as it was specifically designed for the measurement and analysis of lightning-originated transients.

![Schematic block diagram of a DMS-unit.](image-url)
3.1.1 – Structure of a distributed measurement system unit

Each line voltage transient is measured by means of a voltage-to-voltage transducer (V-VT) whose output is sent both to an event detection block (EDB) and to an acquisition and A/D conversion board (DAQ). Fig. 3.1 shows the block diagram of a DMS unit. The DAQ board can operate, with simultaneous sampling, up to 100 MSamples/s per channel. The EDB is specifically designed to detect voltage transients superimposed to the industrial frequency voltage waveform. As output, it provides a logical TTL signal that, in correspondence of a transient, acts as a trigger for both the DAQ board and the GPS device. The latter device is included in the DMS unit in order to record the time of arrival of the lightning-originated transient at the unit location.

The manufacture specifications of the above mentioned components are reported in Tab. 3.1. Some additional details are provided in the following paragraphs.

| Tab. 3.1 – Manufacturer specifications of the distributed measurement system unit |
|---------------------------------|--------------------------------|
| component                      | specifications               |
| **V-VT**                       |                              |
| VD305-A                        | critical flashover voltage (in air): 50 kV |
| Pearson Electronics, Inc.      | nominal dividing ratio: 10000:1 |
|                                 | bandwidth: 30 Hz-4MHz (-3dB)  |
|                                 | rise time: 100ns              |
|                                 | accuracy: ± 1%                |
| **GPS based device**           |                              |
| GPS 168PCI                     | time trigger resolution: 100 ns |
| Meinberg Funkuhren GmbH % Co.KG.| output TTL: signal            |
|                                 | Interface to PC: RS-232C      |
| **DAQ**                        |                              |
| NI5112                         | vertical resolution: 8 bit |
| National Instruments Co.        | number of channels: 2        |
|                                 | bandwidth: 100 MHz           |
|                                 | sampling rate: 100 MS/s      |
|                                 | on board memory: 16 MB/ch    |
|                                 | multiple-record mode: available |

3.1.2 – Voltage-to-voltage transducer

In order to increase the Critical Flashover Voltage (CFO) of the voltage-to-voltage transducers (V-VT) up to a value of 300 kV (i.e. a value larger than that of the monitored distribution overhead lines), an oil-insulated container has been designed and built (see Fig. 3.2).
Chapter 3 – Application to a real case

Fig. 3.2 – Oil-insulated container designed and built to increase the Critical Flashover Voltage of the voltage-to-voltage transducer.

Each container includes a V-VT. As the presence of such an oil-insulated container results in a modification of the response of the V-VT, the experimental characterization of the relevant transfer function has been carried out. Fig. 3.3 shows the results of the experimental determined V-VT transfer function (dividing ratio and the phase shift) in the frequency range between 10 Hz ÷ 10 MHz. For each analyzed frequency, 50 measurements have been performed: the cross marks of Fig. 3.3 represent the mean values, whilst the vertical bars show the 95 % confidence interval. The dividing ratio of each V-VT (illustrated by a solid horizontal line in Fig. 3.3a) is estimated as the mean of the maximum and minimum values of the transfer function confidence intervals within 30 Hz ÷ 3 MHz (dotted horizontal lines in Fig. 3.3). As an example, the calculated dividing ratio relevant to the V-VT of Fig. 3.3 is equal to 9760 with an uncertainty of ± 5 %. Concerning the phase of the V-VT transfer function, it can be seen from Fig. 3.3b) that, within the considered frequency range, namely 30 Hz ÷ 3 MHz, the phase shift is nearly zero.
Chapter 3 – Application to a real case

3.1.3 – Event Detection Block

The event detection block (EDB) is one of the most important components of the DMS. It receives the input of the 3 V-VTs and provides, as output, a TTL pulse (negative logic) whenever it detects the presence of a transient superimposed to the industrial frequency waveform. The EDB is composed by 3 EDB blocks in parallel as shown in Fig. 3.4.

Fig. 3.3 – Example of the experimentally determined voltage-to-voltage transducer transfer function: a) dividing ratio $V_{in}/V_{out}$; b) phase-shift.
As shown in Fig. 3.4, the EDB performs an analog subtraction between the negative-offset input waveform and the low-pass-filtered input waveform. In absence of a transient wave superimposed to the industrial-frequency waveform, the input and the low-pass-filtered signals are almost identical and the comparator status does not change. Conversely, the presence of a transient, characterized by frequency contents greater than the low-pass frequency value, produces a difference between the input waveforms of the comparator able to change its status. The time constant of the low-pass filter is set to 100 μs in order to reject all waveforms corresponding to slow transients.

In order to estimate the minimum operating voltage taking into account the phase-angle influence, the EDB has been tested by applying a 50 Hz sinusoidal voltage with amplitude 1.63 V and, superimposed, several pulses of various amplitudes characterized by an 8 μs rise time. The value 1.63 V corresponds, assuming a theoretical V-VT dividing ratio of 10000:1, to the phase to ground voltage of a 20 kV distribution network. The results are shown in Fig. 3.5. The circles correspond to the required minimum voltages for the correct operations of the EDB. The solid thin line represents the approximated envelop of such minimum required values for one phase and the solid thick line is the envelope of the values for the three phases.

Fig. 3.5 results show that the enveloped EDB is able to detect any transient characterized by an amplitude greater than 0.19 V (1.9 kV considering the V-VT) for each phase angle value of the industrial frequency sinusoid at the transient occurrence.
Fig. 3.5 – Minimum required amplitude of transients capable of producing the event detection block operation.

Fig. 3.6 refers to a triggering EDB operation obtained by means of a step waveform superimposed to a 50 Hz sinusoidal voltage. Fig. 3.6 shows, in solid lines, the EDB input and output plots and, in dotted lines, the waveforms of the output of the negative offset block and the low-pass filter. By comparison, the EDB operation time can be estimated as about 1 μs. Such an operation time can be adjusted by modifying the low-pass filter time constant and the offset value of the negative offset block. The offset value has a major influence on the EDB operation time. There is, however, a minimum offset value of 250 mV that has been experimentally determined in order to avoid false triggers due to the voltage-waveform noise distortion.

The influence on the EDB operation delay of the transient signal rise-time has been performed by means of tests similar of those adopted for the previous assessment.
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Fig. 3.6 – Input and output waveforms during the EDB operation: a) observation time window of 3.2 ms; b) observation time window of 100 μs.

Fig. 3.7 shows the experimentally determined curve of the EDB trigger delay as a function of the transient signal maximum time derivative dV/dt. The curve shows a tendency to a monotone decrease with a threshold of a few hundred nanoseconds for high dV/dt values.

In order to provide an estimation of the trigger delay dependence to transient rise time, let consider lightning-originated transients characterized by amplitudes in the range between 2 to 100 kV and rise times in the range 0.1 to 10 μs. Assuming a V-VT dividing ratio equal to 10000:1, a range of dV/dt between 0.02 to 100 V/μs is obtained, that corresponds to a consequent maximum trigger delay of 30 μs.
Each unit of the distributed measurement system is controlled by an industrial computer characterized by the following characteristic:
- Central Processing Unit: P-IV 2 GHz
- Memory: 1 GB;
- Hard Disk Drive: 40 GB.

The software implemented in each computer is realized in LabVIEW environment.

Tab. 3.2 provides the recording characteristics of the distributed measurement system DAQ hardware suitably controlled by the developed software.

**Tab. 3.2 – General settings of the distributed measurement system unit**

<table>
<thead>
<tr>
<th>setting item</th>
<th>variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>time window for a stroke (including pre-trigger 20%)</td>
<td>1.5 ms</td>
</tr>
<tr>
<td>sampling frequency</td>
<td>100 MSa/s</td>
</tr>
<tr>
<td>number of samples for a flash</td>
<td>15000</td>
</tr>
<tr>
<td>waiting time for a flash (time interval grouping sequential strokes)</td>
<td>5 s</td>
</tr>
<tr>
<td>maximum number of subsequent transients grouped within the same event</td>
<td>20</td>
</tr>
<tr>
<td>Vertical range of DAQ (taking into account the V-VT)</td>
<td>± 150 kV</td>
</tr>
</tbody>
</table>
In particular, each distributed measurement system unit allocates a 1.5 ms time window to record transients corresponding to a single lightning stroke with a sampling frequency of 100 MSA/s. The distributed measurement system unit is capable to perform a multi-record of maximum 20 subsequent transients corresponding to the strokes within a flash. The time delay between two subsequent multi-record time windows corresponds to the sampling time ($10^{-8}$ s). The distributed measurement system groups multi-recorded transients as belonging to the same flash if they occur within a time window of 5 s. Then the distributed measurement system stores 3 phases wave-data, as well as the relevant GPS time stamps.

The chosen recording time window of 1.5 ms, allocated in the DAQ board buffer, is composed of a pre-trigger period and an observation one. In view of the above determined trigger delay, a pre-trigger corresponding to the 20% of the recording time window has been chosen. The structure of the recording time window involves the possibility of leak parts of subsequent transients whether their occurrence time interval is less then than 1.2 ms, see Fig. 3.8. Additionally, if such a time interval lies within 1.2 ms ÷ 1.5 ms, the later transient can be entirely lost.

![Fig. 3.8 – Dead times of the distributed measurements system.](image-url)
Making reference to the case of lightning-originated transients, the DMS distinguish sequential transients as belonging to different strokes if the time interval between strokes is greater than 1.5 ms. However, as the median value of time interval between subsequent stroke is equal to 35 ms (Cigré WG 33.01 1991) the presence of such a dead time will not influence the DMS performance.

Subsequent strokes that occur in the time interval 1.5 ÷ 5 ms are grouped in the same flash (see Fig. 3.8) and an additional dead time is present due to the storage time required by the DMS unit to transfer data from DAQ memory to the hard disk. Such a dead time depends on the number of recorded subsequent strokes that, for the case of 20 subsequent transients (see Tab. 3.2) and the considered industrial computer, is equal to 310 ms (see Fig. 3.8).

3.2 – Characteristics of the analyzed distribution network

The developed DMS has been installed in a distribution network located in the northern part of Italy, in a region characterized by a relatively high ground flash density that ranges between 1 ÷ 4 flashes/km²/year (see Fig. 3.9).

In particular, one of the 13 feeders that start from the common primary 132/20 kV substation “Ponterosso” is analyzed. The considered feeder is composed of three-phase overhead lines of overall length equal to 21.9 km, without the presence of cable lines. The overhead lines consist of three conductors (without a shield wire), located at 10 m, 10.8 m and 10 m above ground, respectively. The ground conductivity is estimated to be equal to 1 mS/m. The BIL of the overhead line is equal to 125 kV. The feeder is composed of three branches, each 7-km long, arranged in a Y shape configuration (see alto the top view shown in Fig. 3.12).

The feeder is protected at the feeding station of Ponterosso with one circuit breaker equipped with a three-level overcurrent relay (for multi-phase faults) and a three-level zero-sequence relay (for line-to ground-faults).
Fig. 3.9 – Ground flash density provided by CESI-SIRF in the area where the distribution network object of the study (framed within the Area of interest) is located.

Secondary 20/0.4 kV substations, protected – a part from one – by MV surge arresters, are located at several points along the lines and at the end of the branches. The distributed measurement units described in the previous section have been installed at three of these substations, namely “Maglio”, “Venus” and “Torrate”. Fig. 3.10 shows the network topology and the position of the three measurement stations (designated by a black triangle), in plane coordinates using the Gauss-Boaga reference system.

In the considered feeder, a monitoring system for protection manoeuvres is also present (see section 2.5). Fig. 3.11 is an inside view of one of the three substations equipped with a DMS unit; in which it is possible to note the voltage-to-voltage transducers connected in parallel to the three phase wires.
Fig. 3.10 – Monitored distribution network and positions of the measurement stations and of the primary substation.

Fig. 3.11 – An inside view of one of the three substations equipped with a DMS unit.
3.3 – Analysis of the collected lightning data

The lightning strokes of interest are selected within a rectangular area surrounding the distribution network, having a maximum distance of 2 km from the feeder extremities with a total area equal to 144 km².

In 2007, CESI-SIRF has detected 375 flashes and 752 strokes in the considered area. Therefore, the average number of strokes per flash is about 2. Out of the 375 flashes, 205 (54.7%) have only one stroke, whilst 170 flashes (45.3%) have more than one stroke. The maximum number of strokes in a single flash was 14 (the system considers a maximum of 15 stroke per flash). We assume that all of them are downward lightning events.

CESI-SIRF provided the location and current peak estimates of 582 strokes: 542 negative strokes (93.1%) and 40 positive strokes (6.9%). All the strokes attributed to the same flash show the same polarity: 339 are flashes with strokes of negative polarity (170 with a single stroke) and 36 flashes have strokes with positive polarity (35 with a single stroke). Out of 375 flashes, 53 have a subsequent stroke with a current value larger than the first stroke (all of negative polarity). The statistics of the estimated current peaks are reported in Tab. 3.3.

<table>
<thead>
<tr>
<th>No.</th>
<th>Mean current value (kA)</th>
<th>Maximum current value (kA)</th>
<th>Minimum current value (kA)</th>
<th>Median current value (kA)</th>
<th>Standard deviation (kA)</th>
<th>Standard deviation of log(I) (base 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negative first strokes</td>
<td>301</td>
<td>15.6</td>
<td>141.2</td>
<td>2.5</td>
<td>11.8</td>
<td>14.9</td>
</tr>
<tr>
<td>Positive first strokes</td>
<td>39</td>
<td>51.5</td>
<td>250.7</td>
<td>8.6</td>
<td>32.9</td>
<td>55.0</td>
</tr>
<tr>
<td>Negative subsequent strokes</td>
<td>241</td>
<td>16.4</td>
<td>48.4</td>
<td>3.5</td>
<td>14.2</td>
<td>8.6</td>
</tr>
<tr>
<td>Positive subsequent strokes</td>
<td>1</td>
<td>10.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3.12 shows the network topology and the 582 lightning stroke locations provided by CESI-SIRF during the year 2007 (in plane coordinates using the Gauss-Boaga reference system).
The DMS has been installed in early January 2007 and has recorded overall 3,444 transients due to both lightning events and other events, such as the transients associated to the energization of network components (e.g., lines, transformers, capacitor banks etc). Concerning the lightning-originated events, the DMS has collected most of the transients associated to the strokes detected by CESI-SIRF shown in Fig. 3.12. Only few strokes have induced a lightning overvoltage lower than the threshold of DMS unit trigger. The trigger threshold is set to 2 kV for all the three measurement units.
3.4 – Calculation of the lightning-induced transients in the analyzed network

The calculation of the lightning-induced transients has been performed by means of the LIOV-EMTP code (see par. 2.5). The main assumptions adopted are:

- constant value of ground conductivity assumed equal to 1 mS/m according to the Italian average ground conductivity map;
- stroke location identical to the one determined by CESI-SIRF;
- lightning current waveform of trapezoidal waveshape;
- straight lightning channel perpendicular to the ground plane;
- for the return stroke current, the so-called TL model has been used for the calculation of the lightning electromagnetic pulse;
- return stroke speed assumed equal to 1.5\times10^8 \text{ m/s};
- power transformers installed in secondary substations, located in correspondence of the line terminations, have been modelled by means of a $\Pi$ circuit of capacitances assumed to be a valid model if only the reflected surges at the medium voltage side of the transformers are of interest (Borghetti et al. 2009). The adopted value of capacitance is 250 pF, inferred by means of measurements performed on a typical Italian distribution transformers;
- the power transformers installed in the considered network are assumed to be protected by means of 20 kV rated surge arresters having the $V$-$I$ characteristic of Fig. 3.13, obtained by making reference to a standard 8/20 $\mu$s pulse.

The TL model has been adopted even if more accurate models are available in literature (i.e. Nucci et al. 1988, 1990). The TL model has to be preferred for convenience in time consumption (see par. 2.5).

The entire monitored network has been implemented in EMTP, in order to be able to obtain over-voltages estimations of any of the three measurement stations.

The implementation of the topology of transmission lines networks in LIOV is subjected to the bond of lengths of lines multiple of the spatial step chosen for the finite-difference-time-domain solution of the field-to-transmission lines coupling equations. Moreover, due to the large extension and to the irregular shape of the
network topology, the implementation of the network model requires a suitable expedient.

![Diagram of V-I characteristic](image)

**Fig. 3.13 – The assumed V-I characteristic of the 20 kV surge arrester connected in parallel with power distribution transformer in the secondary substations of the monitored network.**

Two solutions have been experienced. The first is the approximation of the real lines with straight line having appropriate lengths, chosen in order to minimize the discrepancy between the orientations of the real lines and the implemented ones. The rationale of such an approach lies in the great sensibility of the line response to the angle of incidence of the external field. The second approach consists of mapping sampled points of the real network lines. The network topology is specified as input data to the dynamic library that calculates the electromagnetic field inside the EMTP environment by means of:

- in the first approach, the coordinates of the starting points, the lengths and the orientation of the lines;
- in the second approach, the coordinates of the points and the cosine directors of the line to which the points belong.

Some results obtained using the first approach are reported in [Borghetti et al 2008].
The second approach has been adopted to obtain the results illustrated in the next section, which cover also the events studied in [Borghetti et al 2008]. The results obtained by means of the two approaches are very close. The second approach is portrayed in Fig. 3.14 for one portion of the monitored distribution network, near the measurement station “Maglio”. In the figure, the lines have been sampled at spatial step of 30 m, in order to give a clearer representation. The adopted spatial step in over-voltages calculation is, indeed, 10 m. The coordinates in Fig. 3.14 have the primary station as zero reference.

![Fig. 3.14 – Discretization of the real topology, used for LIOV calculation, of one portion of the monitored distribution network near the measurement station “Maglio”.](image)

In order to appropriately compare the DMS-measured and simulated lightning-induced voltages, we have selected events that do not produce a line flashover. Such a criterion is justified because: a) flashover position along the lines is unknown and b) the superimposition of the lightning-originated transients and the travelling waves associated to the flashover itself makes it the comparison complex. Fig. 3.15 reports the location of the second stroke of the flash 43735 detected by CESI SIRF on August 20, 2007. The stroke is characterized by an estimated current peak of 29.1 kA and, considering that such an event is a subsequent stroke, a 2 μs time-to-peak has been assumed [Anderson and Eriksson 1980]. In order to assess the adequacy of both the DMS and of the calculation code for the problem of interest, the lightning-
induced voltages recorded by the DMS relevant to the above event have been compared with those calculated by means of the LIOV-EMTP code. Fig. 3.16 shows such a comparison, which, within the limits of the simplifying assumptions that have been adopted for this study, can be considered satisfactory.

![Diagram showing location and measurement stations]

Fig. 3.15 – Location of the second stroke of the 3-stroke flash number 43735 of recorded by CESI-SIRF on Aug. 20, 2007. Estimated current amplitude: 29.1 kA, negative polarity.
Fig. 3.16 – Comparison between measured and simulated induced overvoltage, for the event reported in Fig. 3.15 and the measurement station “Maglio”.

### 3.5 – Calculation of the flashover probability

In 2007, 15 relay interventions have been recorded for the analyzed feeder. Among these, 3 relay interventions are correlated to lightning flashes detected by CESI-SIRF using the time correlation criterion mentioned in the introduction, namely: the detected lightning stroke and relay intervention are correlated when they are recorded within a time window of 1 second. All the lightning correlated relay interventions refer to the trigger of the second threshold-level of the zero-sequence relay which means that the flashovers are of phase-to-ground type.

Tab. 3.4 reports the data relevant to the 5 strokes of the 3 correlated flashes. Fig. 3.17 shows the relevant stroke locations.

The overvoltage cumulative distributions of the voltage peak amplitudes due to the LLS detected lightning events of Tab. 3.3, time-correlated with relay operations, have been calculated by applying the statistical procedure described in section 2.7.
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Tab. 3.4 – Current data of the strokes of the flashes time-correlated with relay operations.

<table>
<thead>
<tr>
<th>Correlated stroke name</th>
<th>Sequential No. of the flash in the day</th>
<th>dd-mm-yyyy hh:mm:ss.ms</th>
<th>No. stroke</th>
<th>Current peak (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>62676</td>
<td>15-06-07 16:30:20.511</td>
<td>1</td>
<td>-10.3</td>
</tr>
<tr>
<td>A2</td>
<td>62676</td>
<td>15-06-07 16:30:20.566</td>
<td>2</td>
<td>-11.5</td>
</tr>
<tr>
<td>B1</td>
<td>64244</td>
<td>15-06-07 16:41:49.627</td>
<td>1</td>
<td>-11.2</td>
</tr>
<tr>
<td>B2</td>
<td>64244</td>
<td>15-06-07 16:41:49.671</td>
<td>2</td>
<td>-10.4</td>
</tr>
<tr>
<td>C1</td>
<td>4970</td>
<td>09-08-07 02:31:49.484</td>
<td>1</td>
<td>-15.9</td>
</tr>
</tbody>
</table>

Fig. 3.17 – Locations of the 5 strokes of Tab. 3.4 relevant to the 3 flashes time-correlated with a relay intervention.

As already mentioned, the cumulative distributions are calculated using a Monte Carlo procedure that takes into account the uncertainties related to the estimation of lightning stroke location and current peak provided by the LLS, namely the 50% error ellipse and the distribution of the errors relevant to the current peak amplitude estimates.

The current peak values are generated from the available distribution of peak current estimation errors with a median error value of -18% inferred by means of rocket triggered lightning [Jerauld et al 2005] (see Fig. 3.18).
Fig. 3.18 – Histograms of the National Lightning Detection Network peak current estimation errors given as a percentage of the directly measured Camp Blanding current, for 70 negative strokes in 22 flashes triggered during 2001-2003. Corresponding statistics are given below the histogram (adapted from Jerauld et al 2005).

The time to peak values are generated assuming median value equal to 3.8 $\mu$s, standard deviation of the logarithm (to base e) equal to 0.553 and a coefficient of correlation $\rho$ equal to 0.47 between the probability distributions of $t_f$ and $I_p$ [Anderson and Eriksson 1980, Cigré 1991].

In the following, for each of the lightning events time-correlated with faults recorded by SAM, reported in Tab. 3.4, the results of the proposed procedure are reported together with the relevant voltage transients measured at the three substations equipped with DMS. Note that for the period in which the strokes of Tab. 3.4 occurred, the measurements of the voltage of one phase at the sub-station “Torrate” are not available, due to the outage of the corresponding voltage-to-voltage transducer.

The voltage transient waveforms recorded at the three measurement stations show the phase affected by flashover, that is the one which voltage tends to decreases to zero. Such a transient behaviour is particularly evident in the measurement station closest to the stroke location. At the far measurement stations, the voltage transients are mainly due to the travelling waves generated by the flashover, and the lightning-induced voltages are characterized by lower amplitude with higher frequency content.
Fig. 3.19 – Measured voltage transients correlated to the indirect stroke A1 of Tab. 3.4: a) measurement station “Maglio”, b) measurement station “Venus”, c) measurement station “Torrate”.

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Fig. 3.20 – Top view of the randomly generated stroke locations for the calculation of the flashover cumulative distribution relevant to the stroke A1 of Tab. 3.4. The crosses indicate the direct strokes. The figure also shows the 50% error ellipse of LLS estimated location.

Fig. 3.21 – Probability of having flashover versus CFO for the stroke A1 of Tab. 3.4.
Fig. 3.22 – Measured voltage transients correlated to the indirect stroke A2 of Tab. 3.4: a) measurement station “Maglio”, b) measurement station “Venus”, c) measurement station “Torrate”.
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Fig. 3.23 – Top view of the randomly generated stroke locations for the calculation of the flashover cumulative distribution relevant to the stroke A2 of Tab. 3.4. The crosses indicate the direct strokes. The figure also shows the 50% error ellipse of LLS estimated location.

Fig. 3.24 – Probability of having flashover versus CFO for the stroke A2 of Tab. 3.4.
Fig. 3.25 – Measured voltage transients correlated to the indirect stroke B1 of Tab. 3.4: a) measurement station “Maglio”, b) measurement station “Venus”, c) measurement station “Torrate”.

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Fig. 3.26 – Top view of the randomly generated stroke locations for the calculation of the flashover cumulative distribution relevant to the stroke B1 of Tab. 3.4. The crosses indicate the direct strokes. The figure also shows the 50% error ellipse of LLS estimated location.

Fig. 3.27 – Probability of having flashover versus CFO for the stroke B1 of Tab. 3.4.
Fig. 3.28 – Measured voltage transients correlated to the indirect stroke B2 of Tab. 3.4: a) measurement station “Maglio”, b) measurement station “Venus”, c) measurement station “Torrate”.
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Fig. 3.29 – Top view of the randomly generated stroke locations for the calculation of the flashover cumulative distribution relevant to the stroke B2 of Tab. 3.4. The crosses indicate the direct strokes. The figure also shows the 50% error ellipse of LLS estimated location.

Fig. 3.30 – Probability of having flashover versus CFO for the stroke B2 of Tab. 3.4.
Fig. 3.31 – Measured voltage transients correlated to the indirect stroke C of Tab. 3.4: a) measurement station “Maglio”, b) measurement station “Venus”, c) measurement station “Torrate”.
Fig. 3.32 – Top view of the randomly generated stroke locations for the calculation of the flashover cumulative distribution relevant to the stroke C of Tab. 3.4. The crosses indicate the direct strokes. The figure also shows the 50% error ellipse of LLS estimated location.

Fig. 3.33 – Probability of having flashover versus CFO for the stroke C of Tab. 3.4.
Chapter 4 – Conclusions

In this thesis the problem of inferring the correlation between voltage dips and faults and lightning events has been addressed. A procedure, standing on the initial work by Borghetti et al. [2006] has been developed, which allows one to estimate the probability that lightning location systems detected strokes can cause voltage dips or faults in a given distribution network. It is based on the integrated use of:

- data provided by lightning locations systems;
- data provide by the monitoring systems of protection manoeuvres;
- an advanced computational tool for the calculation of lightning-induced overvoltages (LIOV-EMTP).

The problem has been approached from a statistical perspective, because data from lightning location systems relevant to stroke locations and lightning current amplitudes are given with their error probability.

The stroke location and the lightning current amplitude along with their uncertainty are input to the early mentioned computer program, which provides, by means of appropriate integration of a Monte Carlo routine, the cumulative distribution of lightning-overvoltage amplitudes. The discrimination between voltage dips and faults is made on the basis of the records made available by monitoring systems of protection manoeuvres.

The procedure has been applied to the data collected over the year 2007 by (a) the monitoring system of protection manoeuvres located at the substation “Ponterosso” (nearby San Vito al Tagliamento, North-Italy) and (b) the data provided by the Italian lightning location system, SIRF, within the 144 km² area around the part of distribution network of interest. Both data are GPS synchronised. Five faults/dips that are certainly correlated with lightning, as inferred by the analysis of the relevant experimental data acquired by the distributed measurement system developed within the framework of this thesis and by the SAM, have been selected to apply the proposed procedure. These five events are clearly compatible with the mentioned time criterion, which means that the two events (SIRF-detected lightning and SAM-detected relay operation) happened
within a time window of ± 1 s. The flashover probabilities for these five events have been calculated and plotted as a function of the line insulation level, making distinction between direct or indirect lightning events, as the protection against direct events calls for different mitigation techniques than that against indirect events. The low flashover probability in correspondence of the line insulation level can be interpreted as an hint that lightning location systems still need to improve their performance when used to infer the correlation of interest concerning distribution networks. Also, the accurate knowledge of the network geometry and topology as well as the adequacy of the computational tools for the evaluation of lightning-originate voltages is a crucial point. In this respect, it is worth mentioning that the used computational tool, consisting of the LIOV code, suitably interfaced with EMTP, has been improved throughout the development of this thesis. In particular, the analytical formulation of the electric field generated by a “trapezoidal” return stroke current (that is current with linear front and flat top), and the interface of the LIOV code with the most recent version of EMTP (EMTP-RV), are the two most important contributions in this respect. Among the engineers, indeed, the use of models not suitable to realistic configurations is still in use due to their straightforwardness and computational speed, a limitation that this thesis was in part aimed at overcome.
References


Bernardi M., Ferrari D., The Italian lightning detection system (CESI-SIRF): main statistical results on the first five years of collected data and a first evaluation of the improved system behaviour due to a major network upgrade”, 25th International Conference on Lightning Protection, Rhodos, Greece, September 2000.


Cigré Task Force 33.01.03 Report, Lightning Exposure of structures and interception efficiency of air terminals, October 1997.


Rusck, S., Induced lightning overvoltages on power transmission lines with special reference to the overvoltage protection of low voltage network, Transactions of the Royal Institute of Technology, Stockholm, no. 120, 1958.


Schulz W. and Diendorfer G., Lightning peak currents measured on tall towers and measured with lightning location systems, 18th International Lightning Detection Conference, Helsinki, Finland, June 7-9, 2004.


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