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A Distributed Measurement System for Correlating Faults to Lightning in Distribution Networks

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Abstract. The paper describes a distributed measurement system developed for the monitoring of lightning-originated transients in distribution networks. The data obtained by means of the proposed system are intended to be integrated with those provided by the Italian lightning location system and with those recorded by a monitoring system of relay operations. The paper briefly illustrates the philosophy of the measurement system, its develop as well as its set-up in a distribution network, located in a high keraunic area, in the northern region of Italy.

1 INTRODUCTION

Overvoltages originated by nearby or direct lightning events may cause phase-to-ground and phase-to-phase flashovers in power distribution networks, which may need, for their removal, the operation of recloser breakers. These sequence of events produce voltage sags at customers' busses, which may cause serious malfunction of a large number of apparatus and represent a severe power quality limitation.

In electrical systems located in regions with high keraunic levels, lightning activity is responsible of more than 80% of the voltage sags that cause apparatus failures [1]-[4]. Consequently, the correlation between relay operations and lightning events is of crucial interest for the power quality improvement, especially in the presence of overhead lines [5]-[7]. Indeed, appropriate insulation coordination and protection measures can be selected only after the assessment of such a correlation.

Data from Lightning Location Systems (LLSs), which provide an estimations, for each lightning stroke, of both a lightning flash locations and return-stroke current amplitudes, can certainly be used to understand whether lightning is the real cause of relay operation during thunderstorms – which means, in turn, a voltage sag – or not. However, as it can be clearly seen, the information coming from LLS is, in general, not enough to infer the origin of voltage sags. It is indeed necessary to integrate these data with those obtained from other monitoring systems able to record protection maneuvers [6].

In general, the studies presented in the literature propose to perform such a correlation by means of time window and spatial distance criteria. Lightning is assumed to be the cause of a line fault if two events, namely the detected lightning and the relay operation, are recorded within a time window of a few seconds, and if the distance between the estimated stroke location and the line is lower than a chosen distance [5], [8].

It is worth mentioning that, in order to provide a more effective lightning-to-fault correlation assessment, it is also necessary to calculate the flashover probability associated to each lightning strike by means of appropriate simulation tools, able to reproduce the distribution system response to direct and indirect lightning events (e.g. [7] and discussions). Such a simulation tool can also take into account the uncertainty related to the estimation of lightning stroke location and current provided by LLSs (e.g. [9]).

Due to the complexity of the problem, additional information, capable of providing fundamental elements for validating such correlation procedures, can be gathered by distributed measurement systems (DMSs) for the measurement of lightning-originated transients in distribution power networks; as a matter of fact, the paper focuses on this aspect. In particular, the paper presents and discusses the performances of a developed DMS which represents a major evolution, extended to medium voltage networks, of the one for low voltage networks illustrated in [10]. The paper provides also some details on the setting-up of the developed DMS installed in a distribution network, located in a high keraunic area, in the northern region of Italy. The integration of the developed DMS with data coming from the Italian LLS (CESI-SIRF) [11], [12] and from the Italian monitoring system of relay operation (CESI-SAM) [6] is also presented.

The paper is structured as follows. Section 2 illustrates the structure and the functionalities of the developed DMS and, section 3 reports the details of the setting-up of the DMS. Additionally, Appendix illustrates some details relevant to the combined tools for lighting-to-faults correlation.

2 DISTRIBUTED MEASUREMENT SYSTEM FOR LIGHTNING-ORIGINATED TRANSIENTS

The typical architecture of a distributed measurement system (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 [13]-[15].

The proposed DMS represents an evolution of such a systems. 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. Fig. 1 shows the block diagram of a DMS unit.

2.1. Structure of a DMS-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). The DAQ board can operate, with simultaneous sampling, up to 100 MSa/s per channel. The EDB is specifically designed to detect voltage transients superimposed to the industrial frequency voltage waveform. As output, it provides a logic 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 manufacturer specifications of the above-mentioned components are reported in Table 1. Some additional details are provided in the following paragraphs.
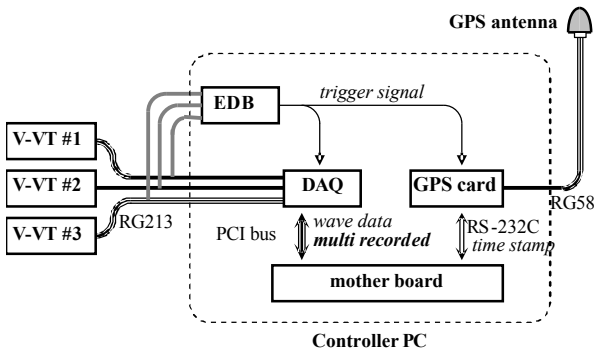

Fig. 1. Schematic block diagram of a DMS-unit.

Tab. 1. Manufacturer specifications of the DMS-unit shown in Fig. 1.

components	Specifications
V–VT VD305-A (Pearson Electronics, INC.)	*Critical Flashover Voltage (in air)*: 50 kV; *nominal dividing ratio*: 10000:1 *bandwidth*: 30Hz-4MHz (-3dB) *rise time*: 100ns *accuracy*: ±1%
GPS based device GPS168PCI (Meinberg Funkuhren GmbH & Co. KG.)	*time trigger resolution*: 100ns *output*: TTL signal *Interface to PC*: RS-232C
DAQ NI5112 (National Instruments Co.)	*Vertical resolution*: 8bit *number of channels*: 2ch *bandwidth*: 100MHz *sampling rate*: 100MS/s/ *on board memory*: 16MB/ch *multiple-record mode*: available

2.2. Voltage to-Voltage Transducer (V-VT)

In order to increase the Critical Flashover Voltage (CFO) of the V-VTs up to a value of 300 kV (i.e. a value larger than that of the monitored distribution overhead lines), an in oil-insulated container has been designed and built. Each container includes a V-VT. As the presence of such an oil-insulated container results in a modification of the V-VTs response, the experimental characterization of the relevant V-VT transfer function has been carried out. Fig. 2 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. 2 represent the mean values, whilst the vertical bars show the 95% confidence interval.
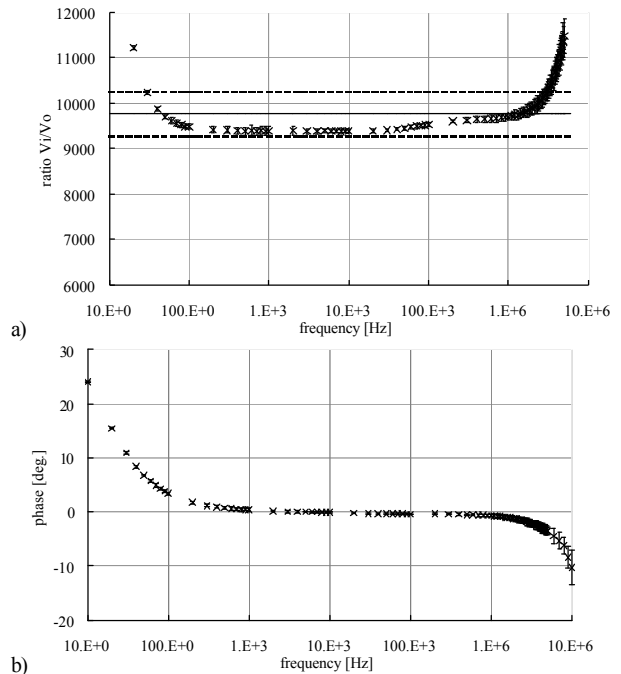

Fig. 2. Example of the experimentally determined V-VT transfer function: a) dividing ratio V_{in}/V_{out}; b) phase-shift.

The dividing ratio of each V-VT (illustrated by a solid horizontal line in 2a) 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. 2). As an example, the calculated dividing ratio relevant to the V-VT of Fig. 2 is equal to 9760 with an uncertainty of ±5%. Concerning the phase of the V-VT transfer function, it can be seen from Fig. 2b that, within the considered frequency range, namely 30 Hz ÷3 MHz, the phase shift is nearly zero.

2.3. Event Detection Block (EDB)

The 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 blocks in parallel (one per phase) as shown in Fig. 3. Each channel is composed by a buffer, a negative offset block, a low pass filter (LPF), and a comparator. The outputs of the 3 channels feed an AND gate that provides the input signal to a flip flop component (F/F). This last component has been used for preventing a possible "chattering" action of the EDB-output trigger signal.

As shown by Fig. 3, 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 that the LPF low-pass frequency value[1], produces a difference between the input waveforms of the comparator able to change its status.

Characteristic values of the EDB performance are the minimum operating voltage and the operation delay.
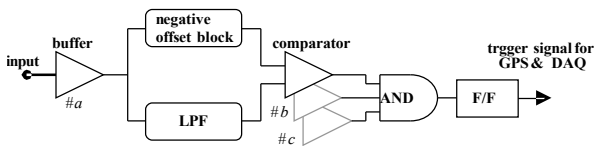

Fig. 3. Schematic block diagram of the Event Detection Board

A. EDB minimum operating voltage
Due to the structure of the EDB (see Fig. 3), the minimum amplitude of a transient able to produce the EDB trigger depends on the phase angle of the industrial frequency sinusoid wave at the transient occurrence.

In order to estimate the minimum operating voltage taking into account the phase-angle influence, we have

considered the DMS as connected to a 20 kV distribution network. For this case, the amplitude of the phase-to-ground voltage, measured by the considered V-VT, is 16.3 kV and, by assuming a theoretical V-VT dividing ratio of 10 000, the amplitude of the EDB input voltage is 1.63 V. We have therefore applied to the EDB a 50 Hz sinusoidal voltage with the above-mentioned amplitude and, superimposed, several pulses of various amplitudes, characterized by an 8-μs rise time.

The results are shown in Fig. 4. The circles correspond to the required minimum voltages for the correct operations of the EDB. The solid thin line represents the approximated envelope of such minimum required values for one phase and the solid thick line is the envelope of the values for the three phases.

Fig. 4 results show that the developed EDB is able to detect any transient characterized by an amplitude greater than 1.9 V (1.9 kV considering the V-VT) for each phase angle value of the industrial frequency sinusoid at the transient occurrence.
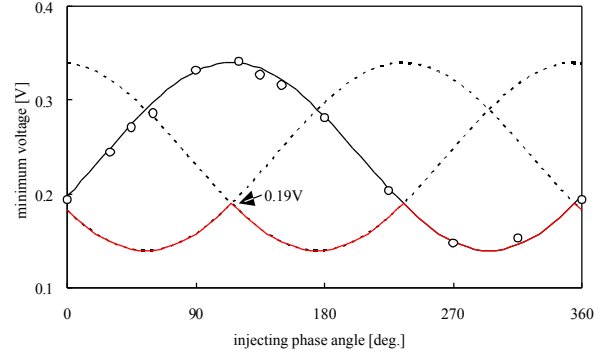

Fig. 4. Minimum required amplitude of transients capable of producing the EDB operation.

B. Operation delay of EDB
Fig. 5 plots refer to a triggering EDB operation obtained by means of a step waveform superimposed to a 50 Hz sinusoidal voltage. Fig. 5 shows, in solid lines, the EDB input and output plots and, in dotted lines, the waveforms of the outputs of the negative offset block and the LPF. By comparing the EDB transition time, the EDB operation time can be estimated as about 1 μs. Such an operation time can be adjusted by modifying the LPF 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 experimentally evaluated too. Such an evaluation has been performed by means of tests similar of those adopted for the previous assessment (results of Fig. 5).

Fig. 6 shows the experimentally determined curve of the EDB trigger delay as a function of the transient signal

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[1] The time constant of the low pass filter is set to 100 μs in order to reject all waveforms corresponding to slow transients.

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 between 0.1 to 10 μs. Assuming a V-VT dividing ratio equal to 10 000, we obtain a range of dV/dt between 0.02 to 100 V/μs and a consequent maximum trigger delay of 30μs.

a)

b)
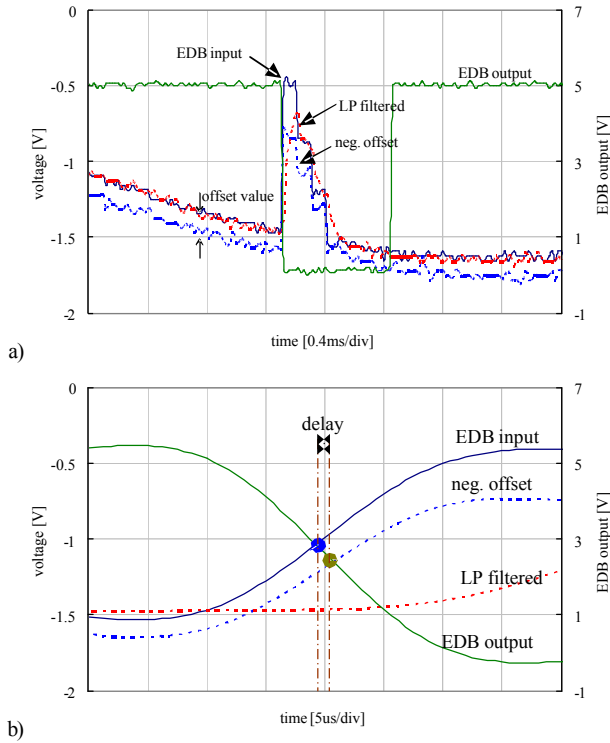
Fig. 5. Input and output waveforms during the EDB operation; a) observation time window of 3.2 ms, b) observation time window of 40 μs.
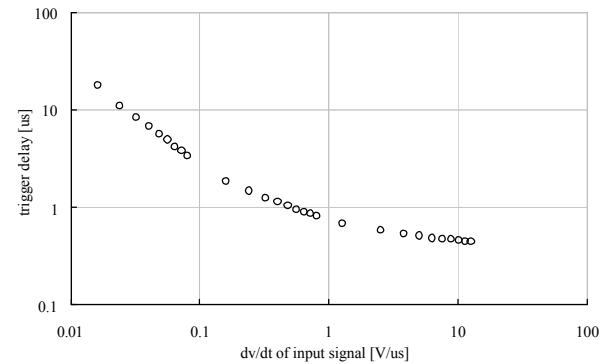

Fig. 6. Trigger delay dependence to the maximum time derivative of the transient.

2.4. Controller PC and general set-up of the DMS

Each unit of the DMS is controlled by an industrial PC characterized by the following characteristics: CPU: P-IV 2 GHz, memory: 1 GB, HDD: 40 GB. The software implemented in each PC is realized in LabVIEW environment. Table 2 provides the recording characteristics of the DMS DAQ hardware suitably controlled by the developed software. In particular, each DMS 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 DMS 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 DMS groups multi-recorded transients as belonging to the same flash if they occur within a time window of 5 s. Then, the DMS stores 3 phases wave-data, as well as the relevant GPS time stamps

Tab. 2. General settings of the DMS unit.

Setting item	variable
Time window for a stroke (*including pre-trigger 20%*)	1.5ms (*0.3ms*)
Sampling frequency	100 MSa/s
Number of sample for a flash	15000pts
Waiting time for a flash [= a group of sequential strokes]	5s
Maximum number of subsequent transients grouped within the same event	20
Vertical range of DAQ (*corresponding voltage considering the V-VT*)	±15V (*±150kV*)

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, we have chosen a pre-trigger corresponding to the 20% of the recording time window. The structure of the recording time window involves the possibility of leak parts of subsequent transients whether their occurrence time interval is less than 1.2ms (see Fig. 7). Additionally, if such a time interval lies within 1.2ms ÷ 1.5ms, the later transient can be entirely lost.

Making reference to the case of lightning-originated transients, the DMS distinguish sequential transients as belonging to different strokes if the time interval between subsequent return stroke is greater than 1.5 ms. However, considering that the median value of time interval between subsequent stroke is equal to 35ms [16], the presence of such a dead time will not influence the DMS performances.

Subsequent strokes that occurs in the time interval from 1.5ms to 5s are grouped within the same flash (see Fig. 7) and an additional dead time is present due to the storage time require by the DMS unit to transfer data from the DAQ memory to the PC hard disk. Such a dead time depends on the number of recorded subsequent

strokes that, for the case of 20 subsequent transients (see Tab. 2) and the considered industrial PC, is equal to 310 ms (see Fig. 7).
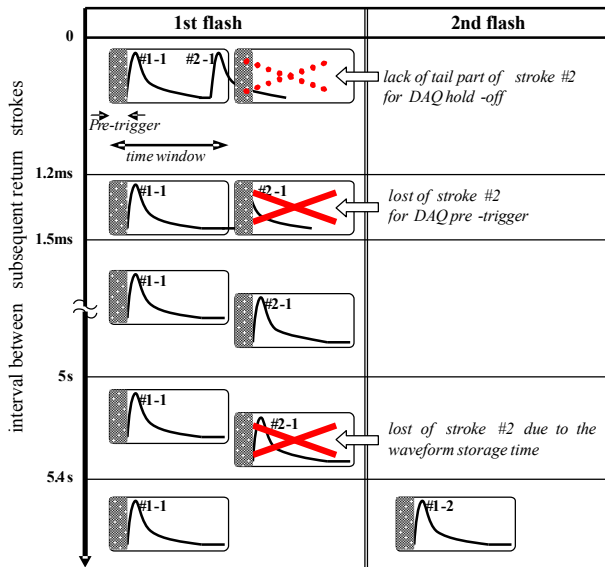

Fig. 7. Dead time of the DMS unit.

3 INSTALLATION OF THE DMS

The developed DMS has been installed in a distribution network located in the northern part of Italy. Fig. 8 shows the network topology, the position of the DMS units and the lightning stroke locations (599 strokes of 247 flashes) recorded by the Italian LLS CESI_SIRF during August 2006 (both network topology and stroke locations are reported in plane coordinates using the Gauss-Boaga projection). The considered lightning strokes are selected within a rectangular area surrounding the distribution network, having a maximum distance of 2 km from the lines extremities.
The setup of the DMS reported in Table 2, with particular reference to the selected resolution, has been chosen considering the CFO of the overhead lines that belongs to the considered distribution network that is of 125 kV.

4 CONCLUSION

The combined integration of (i) LLSs, (ii) monitoring system of relay operations, (iii) accurate models/computer codes for the calculation of overvoltages due to direct/indirect lightning and (iv) the proposed DMS, represent a powerful tool for power quality monitoring in distribution networks. Their coordinated use can provide an improved estimation of the correlation between lightning events and voltage sags.
The paper has described, in particular, the structure and peculiar characteristics of a DMS developed by the Authors for the measurement of lightning-originated

transients. The performances of the developed DMS have been determined experimentally and have been shown to be adequate for the purpose of interest.
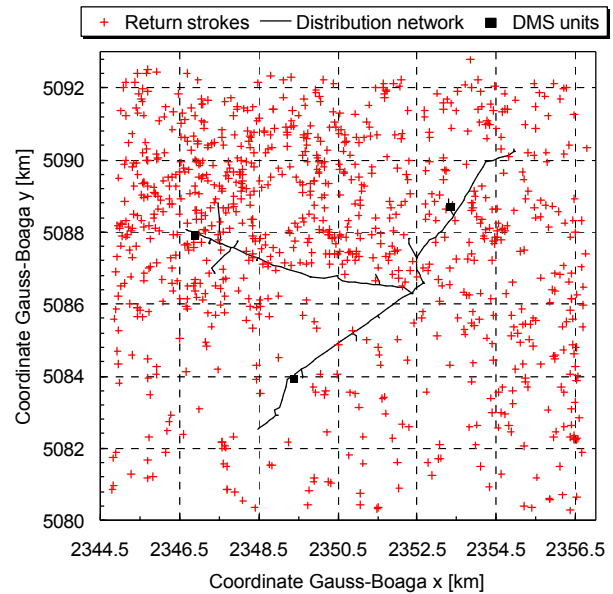

Fig. 8. Monitored distribution network and stroke locations recorded by the Italian LLS CESI-SIRF during the month of August, 2006.

APPENDIX: COMBINED TOOLS FOR LIGHTNING-TO-FAULTS CORRELATION

The correlation algorithm is based on the procedure proposed in [9] conceived to correlate lightning strokes detected by the Italian LLS CESI-SIRF, with fault events detected by the Italian monitoring system for relay operation CESI-SAM. This is accomplished with the additional support of a specific calculation tool (LIOV-EMTP) and the proposed DMS.
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 stroke 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 CESI-SIRF 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;

5. for the case of both direct and indirect events, the lightning overvoltages along the lines are calculated using the LIOV-EMTP code and compared with the overhead line insulation withstanding characteristics, i.e., the CFO value, which makes it possible to estimate the probability that the detected lightning stroke is a cause of fault events.

6. comparison of the flashover probability of each stroke event with the lightning-induced voltages measured by the DMS.

A.1. Italian LLS

The Italian LLS CESI-SIRF ('Sistema Italiano Rilevamento Fulmini'), consists of 16 sensors located throughout Italian territory. 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. The sensors can detect strokes characterized by minimum current values in the order of 2 kA [11], [12] within an area of 370 km of radius. These characteristics, associated with the sensors position, allow for a theoretical flash-detection efficiency of 90% over the entire Italian territory. CESI-SIRF provides spatial-temporal information relevant to cloud-to-ground lightning, namely the estimation of the stroke location (using the World Geodetic Coordinate System 1984, WGS84), the absolute time referred to the UTC-GPS time and the peak current. Such an information is provided for each single stroke in a flash. The accuracy of the estimates is in the order of 500 m for the location and of 120 ns for the absolute time [13]. Additionally, for each detected stroke, CESI-SIRF provides a probability error ellipse 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 [5].

A.2. CESI-SAM

The adopted relay operation monitoring system CESI-SAM ('Sistema Acquisizione Manovre') is a PC-based recording system installed at some primary substations of Italian MV distribution networks. Each system receives signals from different protection devices of the lines connected to the substation, e.g. over current, 0-sequence, and breaker intervention relays. The system, having a 10-ms sampling time, is provided with an internal clock synchronized with the UTC-GPS time, which gives the required synchronization between LLS data and relay operation data [6]. Fig. A1 shows the typical configuration of the Italian distribution network feeder including the relays monitored by the CESI-SAM.

A.3. LIOV-EMTP

The LIOV-EMTP code is the result of the merging of the LIOV code [17], [18] and the Electromagnetic Transient program, EMTP [19], [20].

Starting from the waveform of the lightning current at the channel base, the LIOV code implements a return-stroke model [21] to determine the temporal and spatial distribution of the current along the channel; then, the lightning electromagnetic pulse (LEMP) is calculated by using the Master and Uman equations [22] and the Cooray-Rubinstein formula [23]-[25] to take into account the effect of the ground finite conductivity on the propagating field. The Agrawal et al. model [26], extended to the case of a lossy ground [27], is then used to represent the coupling between LEMP and the multiconductor overhead line, which finally allows the evaluation of the induced voltages along the line. The accuracy of the LIOV code has been verified by comparison with experimental data obtained using reduced scale models [28] and full scale set-up illuminated by triggered lightning electromagnetic fields [29].
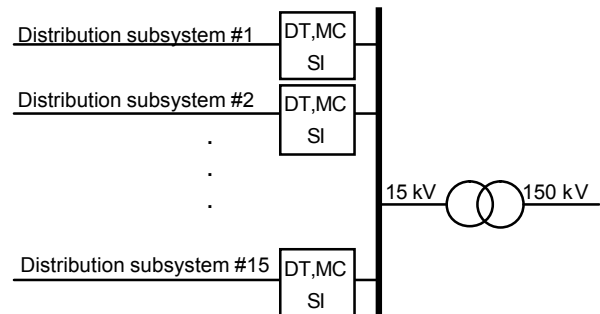
Overhead line relays:
DT: 0-sequence directional relay
MC: overcurrent relay
SI: breaker tripping relay

Fig. A1: Protection system relays installed in a typical substation of an Italian MV distribution system.

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