VOLTAGE TRANSIENT MEASUREMENTS IN A DISTRIBUTION NETWORK AND SEQUENCE OF RELAY EVENTS ASSOCIATED TO LIGHTNING STROKES DETECTED BY LLS

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ABSTRACT

A two-year experimental campaign on lightning-originated disturbances carried out in an Italian rural region characterized by a high ground flash density (4 flashes/km²/yr) has provided a set of voltage transient measurements in a medium voltage (MV) feeder that are clearly correlated with both specific events detected by the Italian lightning location system (LLS) CESI-SIRF and sequences of relay operations. The paper describes the sequence of relay events, reports the data of the correlated LLS-detected stroke and presents the corresponding voltage transients recorded at three different busses of the MV feeder.

1 INTRODUCTION

An important issue for lightning protection/insulation coordination of overhead lines is the distinction between lightning caused faults from those due to other phenomena in general associated with thunderstorms, such as wind, rain, hail and trembling trees, which call for different countermeasures. Indeed, it is not uncommon that several outages and faults causing reclosing operations during thunderstorms are not really due to lightning, as Darveniza and Uman have observed in [1] as a result of a University of Florida’s research project carried out at the end of the 70s. That research project dealt with the correlation between ground flash data, obtained by several sources (flash counters, direction-finder based LLS, electric and magnetic fields recording systems, television lightning monitors), measurements of surge currents discharged through arresters [2] and distribution system records of circuit breaker operations. Other experimental projects have been carried out for the same purposes. For example, in the 80s, as a part of a an U.S. EPRI research project on the characteristics of lightning surges on distribution lines, an instrumentation called coincident lightning events detector (CLED) was developed and installed at some substations in Florida [3,4]. The CLED used a modified flash counter to sense when lightning occurs and a time-tagged information obtained from the distribution substation supervisory control and data acquisition (SCADA) system to determine if a subsequent circuit breaker operation was caused by lightning, taking into account that a distribution circuit breaker takes 4 to 6 cycles to trip after fault initiation. The modified flash counter used a 2-m antenna able to be triggered by the voltages induced by lightning events in the estimated range of 9.6 km, approximately the same size as the substation service area. As more sophisticated LLSs have been developed since the end of the 70s, their use has been proposed for the correlation between lightning events and faults in distribution networks [5-10].

However, due to the uncertainties associated with the data provided by LLS and the complexity of MV networks and their protections, the reliable correlation between faults and specific LLS-detected events is still an open issue and represents the motivation for the recent experimental campaign on lightning-originated disturbances in an Italian rural region characterized by a high ground flash density (4 flashes/km²/yr).

As described in [9,11-13], three measurement units able to record a-periodic voltage transients characterized by frequency content up to 4 MHz have been installed in one 20-km long MV feeder mainly composed by three-phase overhead lines. The compensated-neutral grounded feeder is protected by both overcurrent and zero-sequence relays. The relay operations are monitored by a sequence of events recorder with a 10-ms sampling time.

During a two-year (2007-2008) period, a set of voltage transient measurements, clearly correlated both with specific events detected by the Italian lightning location system (LLS) CESI-SIRF and with sequences of relay operations, have been collected.

The paper describes the sequence of relay events, reports the data of the correlated LLS-detected stroke and presents the corresponding voltage transients.
2 VOLTAGE TRANSIENTS MEASUREMENTS AND SEQUENCE OF RELAY INTERVENTIONS CORRELATED WITH LLS DETECTED STROKES

This section presents the analysis of the voltage transients and sequence of relay events due to the lightning strokes of 6 of the flashes detected by the LLS (indicated in the following with no. 15714, 62676, 64244, 4970, 1169, and 44074). Fig. 1 shows the LLS-estimated stroke locations with respect to the feeder and their 50% error ellipse.

In the following subsections, for each flash, we report the sequence of relays interventions as recorded by distribution data acquisition system and the voltage transients recorded by the three measurement units.

Fig. 1 LLS estimated stroke locations relevant to 6 flashes associated with relay sequence of events and the corresponding 50% error ellipses. The numbers in the x and y axes reports the coordinates using the cylindrical projection called Gauss-Boaga traditionally used in Italian maps.

2.1 Flash 15714 (May 15, 2007)

The event 15714-1 was detected by the LLS on May 15th, 2007 at 14:30:20.627983052 (standard time UTC) as a first positive stroke characterized by a 8.7 kA current peak value. As shown in Fig. 1, the major and minor axes of the 50% error ellipse are equal to 1200 m and 400 m, respectively.

Fig. 2 shows the voltage transients recorded at the three measurement units triggered with a delay equal to 9.8 µs (Unit 1), to 40.6 µs (Unit 2, the nearest to the estimated stroke location) and to 18.2 µs (Unit 3, Venus), after the LLS detected event. The relay monitoring system recorded the activation of the overcurrent relay 51 at 14:30:20.63, which was deactivated without tripping 110 ms after its activation.

2.2 Flash 62676 (June 15, 2007)

The event 62676-1 was detected by the LLS on June 15th, 2007 at 16:30:20.511131173 as a negative first stroke characterized by a 10.3 kA current peak value. As shown in Fig. 1, the major and minor axes of the 50% error ellipse are equal to 400 m and 300 m, respectively.

Fig. 3 shows the voltage transients recorded at the three measurement units triggered with a delay equal to 18.2 µs (Unit 1), to 2.8 µs (Unit 2, the nearest to the estimated stroke location) and to 18.2 µs (Unit 3, Venus), after the LLS detected event. The relay monitoring system recorded the activation of the overcurrent relay 51 at 16:30:20.54.
Almost 50 ms after the first event (at 16:30:20.566098022), the LLS detected a second negative stroke (Event 62676-2) of 11.5 kA current peak. The estimated stroke location and 50% error ellipse are also shown in Fig. 1 (both major and minor axes are equal to 300 m).

Fig. 4 shows the resulting voltage transients recorded by the three units triggered after a delay equal to 31.6 µs (Unit 1), to 3.6 µs (Unit 2) and to 15.7 µs (Unit 3). The transient recorded at Unit 2 clearly shows the fault in a phase and, indeed, the relay monitoring systems recorded the activation of AC directional overcurrent relay 67 at 16:30:20.57.

The relay trips after 90 ms and the ensuing circuit breaker opening at the substation caused the voltage transients recorded at Unit 3 (the nearest to the substation) and, also, at Unit 1, as shown in Fig. 5. After 470 ms the circuit breaker re-closing maneuver causes the recorded voltage transients shown in Fig. 6. The voltage transient recorded at Unit 3 shows that one of the circuit breaker poles re-closes with a delay of about 1/3 of ms after the others.
2.3 Flash 64244 (June 15, 2007)

The event 64244-1 was detected by the LLS on June 15th, 2007 at 16:41:49.626720476 as a first negative stroke characterized by a 11.2 kA current peak value. As shown in Fig. 1, the major and minor axes of the 50% error ellipse are equal to 400 m and 300 m, respectively.

Fig. 7 shows the voltage transients recorded at the three measurement units. Unit 1 and Unit 3 are triggered after a delay equal to 23.7 µs and 43.5 µs, respectively. Unit 2 triggered 0.6 µs before the time tag of the LLS event. The transient recorded at Unit 2 shows the induced voltages on faulted conductors.

With a delay of 43.9 ms after the first event, at 16:41:49.64 and at 16:41:49.65, respectively.

51 at 16:41:49.64 and at 16:41:49.65, respectively.

Fig. 8 shows the corresponding voltage transients recorded at the three measurement units: Unit 1 and Unit 3 triggered after a delay equal to 23.7 µs and 43.5 µs, respectively; whilst Unit 2 triggered 0.6 µs before the time tag of the LLS event. The transient recorded at Unit 2 shows the induced voltages on faulted conductors.
Fig. 8 Recorded voltage transients correlated with LLS event 64244-2: a) Unit 1, b) Unit 2, c) Unit 3. Phase 3 was not recorded at Unit 2. (Moving average in a 5 µs period except for the case of Unit 2)

After 59 ms, the directional relay eventually trips and the ensuing opening of the circuit breaker caused the voltage transients at Unit 3 (the nearest to the substation) shown in Fig. 9.

After 410 ms the circuit breaker re-closing maneuver causes the recorded voltage transients shown in Fig. 10.
2.4 Flash 4970 (August 9, 2007)

The event 4970-1 has been detected by the LLS on August 9th, 2007 at 02:31:49.484531417 as a first negative stroke characterized by a 15.9 kA current peak value. As shown in Fig. 1, the stroke location is close to Unit 1 and the major and minor axes of the 50% error ellipse are equal to 400 m and 300 m, respectively.

Fig. 11 shows the voltage transients recorded at the three measurement units. Unit 2 and Unit 3 were triggered after a delay with respect to the LLS event equal to 68.5 µs and 50.0 µs, respectively. Unit 1 was triggered 89.5 µs before the time in which the event was detected by the LLS. The transient recorded at Unit 2 shows line-to-ground overvoltages well above 60 kV (at which value the data acquisition board saturated) that caused a fault. Indeed, the relay monitoring system recorded the activation of both the overcurrent relay 51 and the directional overcurrent relay 67 at 02:31:49.49 and at 02:31:49.51, respectively. The consequential opening of the circuit breaker cleared the fault and Fig. 12 shows the recorded voltage transients associated with the circuit breaker re-closure triggered at 02:31:50.981.

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Fig. 10 Recorded voltage transients correlated to the circuit breaker reclosure after the trip of Fig. 9: a) Unit 1, b) Unit 2, c) Unit 3. Phase 3 was not recorded at Unit 2 (moving average in a 5 µs period).

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Fig. 11 Recorded voltage transients correlated with LLS event 4970-1: a) Unit 1, b) Unit 2, c) Unit 3. Phase 3 was not recorded at Unit 2 (moving average in a 5 µs period except for the case of Unit 1).

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Fig. 12 Recorded voltage transients associated with circuit breaker re-closure triggered at 02:31:50.981.
2.5 Flash 1169 (May 23, 2008)

The event 1169-1 was detected by the LLS on May 23rd, 2008 at 04:54:04.831727601 as a first positive stroke characterized by a 33.8 kA current peak value. Fig. 1 shows the stroke location estimated by the LLS together with the 50% error ellipse (major and minor axes are equal to 300 m).

Fig. 13 shows the voltage transients recorded at the three measurement units, triggered with a delay equal to 19.80 µs (Unit 1), 101.9 µs (Unit 2) and 39.0 µs (Unit 3). Due to the stroke location, the highest overvoltages are recorded by Unit 1 and Unit 2. The relays detect a fault in the feeder. Fig. 14 shows the voltage transients at Unit 3 associated to the opening of the circuit breaker triggered at 06:54:05.082 and to the re-closure triggered at 06:54:05.431.

2.6 Flash 44074 (June 11, 2008)

The event 44074-1 was detected by the LLS on June 11th, 2008 at 15:32:56.060838753 as a first positive stroke characterized by a 81.2 kA current peak value. The stroke location estimated by the LLS is shown in Fig. 1 together with the 50% error ellipse (major and minor axes are equal to 400 m and 300 m, respectively).

Fig. 15 shows the voltage transients recorded at Unit 2 and Unit 3, triggered with a delay equal to 35.4 µs and 14.2 µs, respectively. As expected, the largest overvoltages are recorded by Unit 3. The relay monitoring system recorded the activation of the overcurrent relay 51 at 15:32:56.08, which is deactivated.
without tripping after 30 ms.

The stroke originated transients recorded by the measurement unit nearest to the stroke location appear to show the effects of the leader propagation and are mainly characterized by the effects of the faults. The earliest part of the transients recorded at distant point with respect to the stroke location shows, instead, the typical characteristics of induced voltage waveforms. During the on-going campaign, the distributed measurement units have recorded around 2000 voltage transients that are not associated with relay operation (i.e. have not caused a flashover). Many of them are clearly due to daily capacitor bank switching and other operation maneuvers. There are also other transients (chiefly the common-mode ones) that, although not all clearly time-correlated with one of the 569 LLS detected flashes, may be ascribed to lightning events. A Monte Carlo procedure has been proposed in [14] for the assessment of the statistical distribution of the expected overvoltages in the network due to a lightning event, based on the use of the LIOV-EMTP code [15] for the accurate calculation of the lightning induced effects. The set of the data collected during the experimental campaign appears to be useful also in order to validate and improve the proposed procedure, taking into account the uncertainties associated with the LLS data and the complexity of the distribution network.

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REFERENCES


