Direct Lightning Strikes to Test Power Distribution Lines—Part I: Experiment and Overall Results

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***Abstract*—The interaction of rocket-triggered lightning with two unenergized power distribution lines of about 800 m length was studied at the International Center for Lightning Research and Testing in Florida. A horizontally configured line was tested in 2000, and a vertically configured line in 2001, 2002, and 2003. The horizontally and vertically configured lines were equipped with six and four arrester stations, respectively, and, additionally, in 2003, the vertical line with a pole-mounted transformer. During the 2000, 2001, and 2002 experiments, arresters were frequently rendered inoperable by disconnector operation during triggered lightning strokes, but there was no disconnector operation during the 2003 experiment when the transformer was on the line. In all four years, there were commonly flashovers from the struck phase-conductor to the closest phase-conductor not subjected to direct lightning current injection. The self-consistency of measurements is assessed via comparison of the injected lightning current with: 1) the total current flowing to Earth through the multiple line groundings and 2) the total phase-to-neutral current flowing through the line arresters and line terminations. This paper is part one of two related papers.**

***Index Terms*—Arresters, grounding electrodes, lightning, power distribution lines, power transformers.**

I. Introduction

LIGHTNING commonly strikes power distribution lines and is particularly troublesome in areas exhibiting a high ground flash density, such as the southeastern U.S. Lightning arresters are often placed between the phase and neutral conductors of the power lines, both on the line proper and at so-called line weak points such as cable connections and pole-mounted transformers. The function of these arresters is to limit surge voltages in order to both protect equipment connected to the line and to prevent line flashovers and outages [1]. The design of lightning protection for distribution lines involves weighing the initial cost of the arresters and the replacement costs for damaged arresters against the benefits of protection for equipment and an expected reduction in line flashover and outage rates. Gapless metal–oxide varistors (MOVs) are the most widely used arresters for the protection of power lines. Arresters commonly contain disconnectors that serve to isolate from ground arresters that have failed in a short-circuit mode, so as to keep the line operational. Disconnectors are designed to withstand transient lightning currents during normal arrester operation. If the arrester fails, the thermal heating due to the 60 Hz fault current causes a detonation of a cartridge that separates the arrester ground lead from the base end of the arrester [2]. The present paper is the first of a sequence of two related papers. Presented in this paper is a description of experiments involving the interaction of rocket-triggered lightning with two unenergized test distribution lines, a verification of the validity of the experimental techniques used, and a performance assessment regarding the frequency of disconnector operation and line flashovers. The companion paper discusses various aspects of the lightning current division on the test lines and compares the measured lightning current division with model-predicted results. The interaction of rocket-triggered and natural lightning with power distribution and transmission lines has previously been investigated in studies conducted in the U.S. [3]–[6], Mexico [7], South Africa [8], and Japan [9]–[13].

The experiments discussed in this paper were performed at the International Center for Lightning Research and Testing (ICLRT), which is an outdoor facility occupying about 1 km^2 at the Camp Blanding Army National Guard Base, located in north-central Florida, approximately midway between Gainesville, home of the University of Florida, and Jacksonville. At the ICLRT, lightning is triggered (artificially initiated) from natural overhead thunderclouds for a variety of purposes using the rocket-and-wire technique [6], [14], [15]. Triggered lightning is typically composed of an initial stage involving a steady current of the order of 100 A with a duration of hundreds of milliseconds followed by one or more dart leader-return stroke sequences which are very similar to the strokes following the first stroke in natural lightning. An overview of the ICLRT is given in Fig. 1 including a depiction of both the horizontally configured and the vertically configured distribution lines on which experiments were performed. Also shown in Fig. 1 is the tower rocket-launching facility from which the triggered lightning current was directed to the distribution lines.

The rocket-triggered lightning experiments conducted from 2000 through 2003 were designed to study the direct lightning strike interaction with two different types of three-phase distribution lines and, if possible, to decide which line was better from the point of view of lightning immunity. The two distribution lines are: 1) a cross-arm horizontal line configuration with three spans between arrester stations studied during Summer 2000 and previously considered in [16] and 2) a vertical line configuration with four spans between arrester stations studied during Summers 2001, 2002, and 2003. The primary differences

Manuscript received January 24, 2006; revised November 21, 2006. This work was supported by the Florida Power and Light Company. Paper no. TPWRD-00032-2006.

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Digital Object Identifier 10.1109/TPWRD.2007.905378

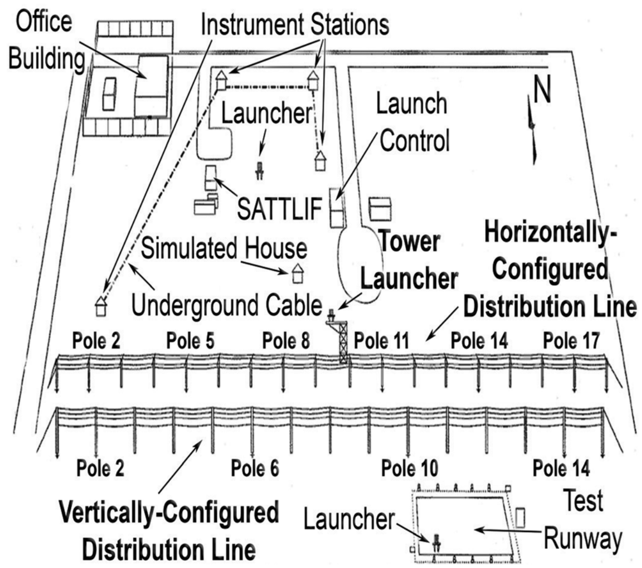

Fig. 1. ICLRT overview, 2000–2003. On the two test distribution lines, labeled poles indicate arrester stations.

TABLE I
EXPERIMENTAL CONFIGURATIONS USED IN 2000 THROUGH 2003 EXPERIMENTS. POLE NUMBERS ARE IDENTIFIED IN FIGS. 1 AND 2

	Horizontal Line	Vertical Line		
	2000	2001	2002	2003
Arrester stations	Poles 2, 5, 8, 11, 14, and 17	Poles 2, 6, 10, and 14		
Arrester types	"B" at poles 8 and 11, "A" at all other poles	"A" & "B" or "B" only	"A" only or "B" only	"B" only
Number of arresters	Single arrester at each phase		Struck phase: 2 arresters in parallel Other phases: single arrester	Single arrester at each phase
Transformer	No transformer			Transformer on struck phase at pole 2
ICC diverted from line	No		Yes	

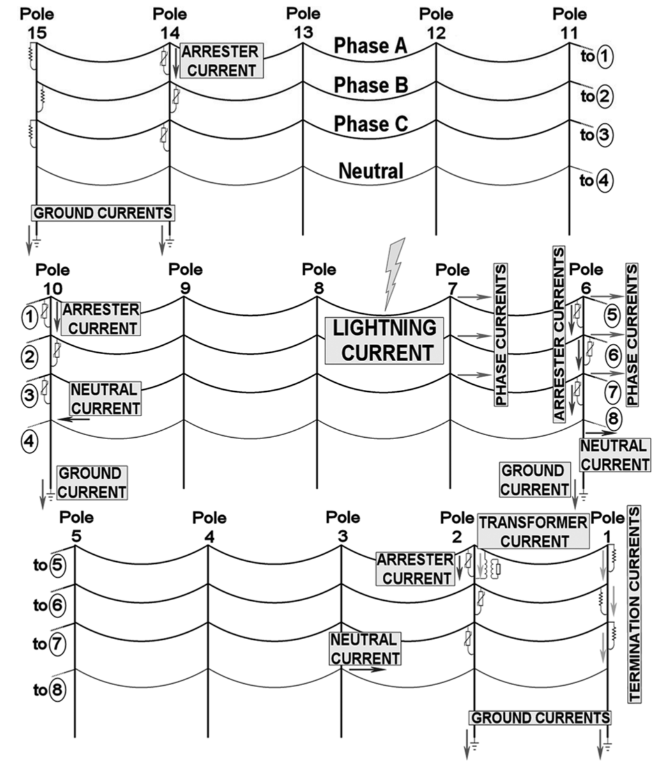

Fig. 2. Test distribution line having a vertical configuration (2001–2003) with measurement points and the location of lightning current injection identified. A transformer was connected to the phase A at pole 2 in 2003 only.

between the two test distribution lines and "real world" distribution lines are that 1) the test distribution lines are unenergized, 2) the test distribution lines are relatively short (about 800 m) and are terminated at the line ends in their characteristic impedances, and 3) a distribution transformer was present only on the line tested in 2003, and neither test line was connected to a zone substation transformer. A word of caution: One should not indiscriminately assume that all aspects of the experimental data acquired from the interaction of rocket-triggered lightning with the test distribution lines are directly applicable to the interaction of natural lightning with "real world" distribution lines, as we will discuss.

II. EXPERIMENT

An overview of all experimental configurations considered is found in Table I. The table includes information about the location of the three-phase arrester stations, arrester types (manufacturer "A" or "B"), number of arresters on the line, the presence of a transformer on the line, and the use of a diversion technique for the initial-stage current, often referred to as initial continuous current (ICC).

The configuration of the horizontal line experiment has been described in detail in [16] and [17]. The horizontal line had three horizontally-arranged phase conductors and one neutral conductor located about 1.5 m below the phase conductors, a length of about 856 m with 18 poles (average span length: 50 m), and arrester stations at poles 2, 5, 8, 11, 14, and 17. Lightning currents were injected into phase C between poles 9 and 10 at midspan. The distance between the struck phase (phase C) and the next closest conductor (phase B) was 70 cm. The test line neutral was grounded at each arrester station and at the line terminations. Currents on the horizontal line were measured with current transformers or shunts. Additionally, phase-to-neutral and phase-to-phase voltages were measured at pole 8 and pole 11 with magnetic-flux-compensated voltage dividers. The voltage dividers were designed to minimize voltages due to the time-varying magnetic flux produced by the arrester current and coupled to the voltage divider loop.

The vertical line shown in Fig. 2 had four vertically arranged conductors—three phase conductors and one neutral conductor below the phase conductors (see also [18] and [19]). It had a length of about 812 m with 15 wooden poles (average span length: 58 m) and arrester stations at poles 2, 6, 10, and 14 where gapless MOV 18 kV arresters manufactured by manufacturer "A" or manufacturer "B" were installed on all three phases. Tests with the manufacturer "B" arresters according to IEEE Standard C62.11 [20] show that the time to disconnector

TABLE II
ARRESTERS VI-CHARACTERISTICS

	Manufacturer "A"	Manufacturer "B"
Current [kA]	Voltage [kV]	Voltage [kV]
1.5	48.5	49
3	51.6	52
5	53.9	55
10	58.8	60
20	65.0	70
40	73.2	82

operation is about 1000, 300, 200, and 30 ms for 60 Hz fault currents of 20, 80, 200, and 800 A rms, respectively. The manufacturer-provided VI-characteristics of the two arrester types in response to an 8/20 μs current pulse are found in Table II.

At each end of the vertical line, a 500 Ω terminator was installed between each phase and the neutral conductor to simulate, as far as microsecond-scale transients are concerned, infinitely long lines by matching the characteristic impedances of the lines. A drawing of the vertical line showing all current measurement points in 2003 is given in Fig. 2. No voltages were measured on the vertical line. A 50 kVA transformer without service drop was present in 2003 at pole 2 and connected to the top phase conductor (phase A). The center-tapped secondary of the transformer was terminated in resistive loads of 4 Ω and 6 Ω. Current in the transformer primary was measured. The 2001 and 2002 measurement points were similar to those in 2003 except for the additional measurement at the transformer primary in 2003. There were two other differences between the experiments: 1) each of the four arrester stations had two arresters in parallel[1] on phase A in 2002 and only one arrester in 2001 and 2003, and 2) phase A insulators in 2003 had higher insulation strength than in 2001 and 2002. A detailed description of the 2001 and 2002 experiments is found in [21]. The vertical test line neutral was grounded at each arrester station and at the line terminations (Fig. 2). The low-frequency, low-current grounding resistances measured using a clamp-on meter were 24, 20, 18, 18, 28, and 24 Ω for poles 1, 2, 6, 10, 14, and 15, respectively. Note that the precise resistance values may vary with level of rainfall or lack of same. During 2001, 2002, and 2003, currents from 99 triggered-lightning return strokes were injected into phase A of the vertical line at midspan between poles 7 and 8 (Fig. 2). The distance between the struck phase (phase A) and the next closest conductor (phase B) was 80 cm. The rocket launcher, shown in Fig. 3, was mounted on an 11 m high wooden tower that was located about 20 m north of and near the midpoint of the test line (Fig. 1).

The 2002/2003 experiment differed from the 2001 vertical line experiment in that a separate path to ground, other than via the test distribution line, was provided for the initial continuous current (ICC) preceding the return strokes in a triggered flash. The ICC was diverted from the line so that the line arresters would not be subjected to the current and charge transfer of the ICC, only to the return stroke currents and any continuing current that might follow the return strokes. The diverted

[1]The arresters connected in parallel were of the same type from the same manufacturer. However, small differences of the arresters' VI-characteristics due to the manufacturing process of the MOV disks may have existed.

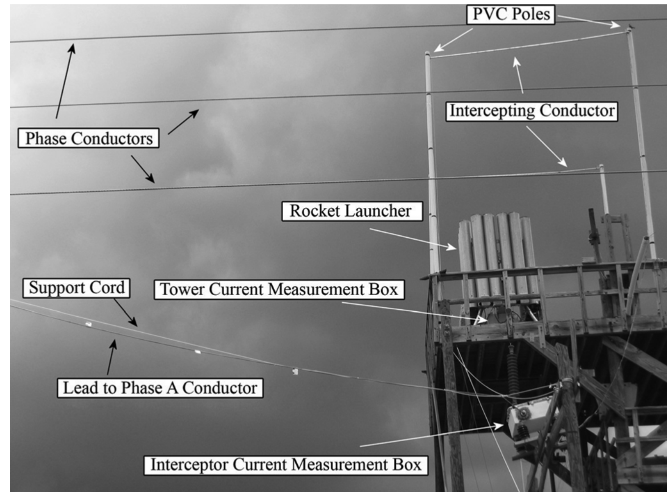

Fig. 3. Tower launcher with interceptor structure used during the 2002/2003 experiment.

ICC flowed through the rocket launcher to ground, while currents of return strokes following the ICC and any continuing current after those strokes were generally injected into a horizontal "U" shaped intercepting conductor mounted above the launcher (Fig. 3) and from there were directed to the line via a wire connection. The triggered-lightning current through the launcher and through the intercepting structure was measured with two 1.25 mΩ current viewing resistors (CVRs) (frequency response: 0 to 12 MHz). CVRs of the same type as well as 1 mΩ CVRs (frequency response: 0 to 9 MHz) were used to measure the currents flowing to ground from the test line. Currents on the line, other than the ground currents, were measured using current transformers (CTs) with frequency responses ranging from 1 Hz to 20 MHz, 7 Hz to 5 MHz, or 5 Hz to 15 MHz. During the 2001 vertical line experiment, one Yokogawa DL716 (with sixteen, 12-bit channels) and seven LeCroy Waverunner LT344L (each with four, 8-bit channels) digitizing oscilloscopes were used to record the sensor outputs, providing 44 digital channels for the experiment. During the 2002/2003 vertical line experiment, two Yokogawa DL716, six LeCroy Waverunner LT344L, and one LeCroy 9354 (with four, 8-bit channels) digitizing oscilloscopes were used to provide 60 channels of digital data recording. The Yokogawa oscilloscopes sampled continuously for 4 s at 1 MHz in 2001 and 2002 and for 2 s at 2 MHz in 2003. The LeCroy oscilloscopes sampled at 20 MHz and recorded in ten 5-ms or five 10-ms segments. The Yokogawa and LeCroy data were lowpass filtered at 500 kHz and 5 MHz, respectively. Each of the current measurements (25, 26, and 27 current measurement points for the 2001, 2002, and 2003 experiments, respectively) were transmitted to the Launch Control trailer (Fig. 1) via a Nicolet Isobe 3000 link (upper frequency response: 15 MHz) composed of a receiver–transmitter pair and a connecting fiber optic cable.

III. RESULTS

Table III summarizes information on the number of flashes with return strokes, the number of flashes without return strokes (composed of the initial stage only), the number of return strokes, and statistical information on the lightning return

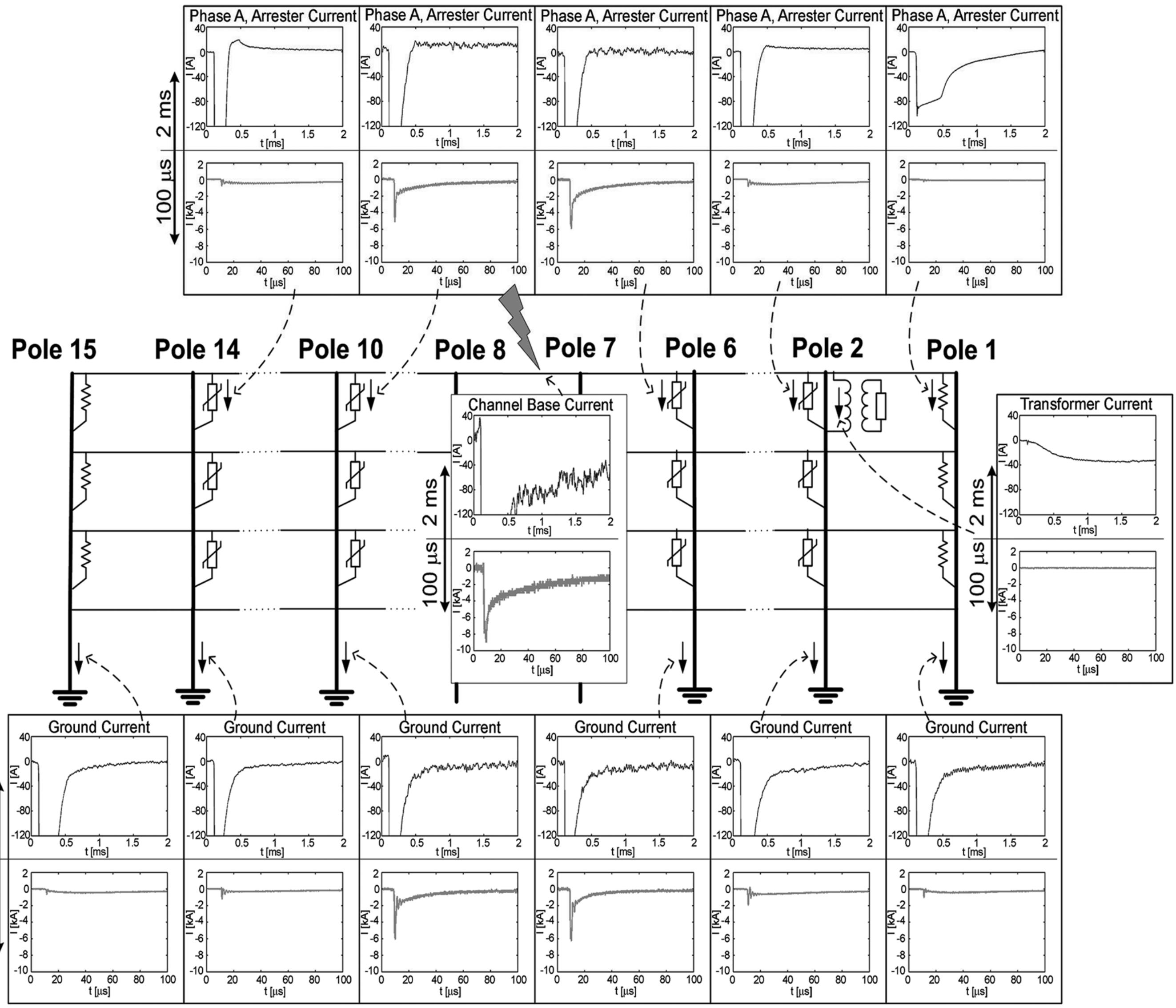

Fig. 4. Measured currents for flash FPL0312, stroke 5.

stroke peak currents, 10–90% risetimes, and charge[2] injected into the line.[3] Note that the 10–90% risetimes for all lightning currents during the 2000 experiment and for most currents during the 2003 experiment could not be determined due to the presence of ringing during the rising edge of the current waveform. Data from the 2003 experiment, flash FPL0312, stroke 5, are presented in Fig. 4. These data are typical for the case where no current bypassed the sensors due to line flashovers (Section III-C). Fig. 4 shows a typical example of 1) the lightning incident current injected into the line (center of figure), 2) all measured phase A arrester and termination-resistor currents (top), 3) all ground currents (bottom), and 4) the transformer current (right). Each measurement is shown on two time scales, 100 μs and 2 ms.

[2]The charge is obtained by integrating the lightning return stroke current over a 1 ms time interval.

[3]The measured peak currents and charge injected into the line in 2000 have been multiplied by 0.75 to account for apparent errors in the lightning current measurements (see Section III-A).

A. Current Balance Check

The consistency of the data from the vertical and horizontal line experiments were tested by comparing the injected lightning current with 1) the current leaving the system (the sum of all ground currents) and 2) the current flowing from the struck phase to the neutral conductor (for the vertical line experiment the sum of all phase A arrester currents plus the termination currents[4]). The currents shown on a 100 μs time scale for FPL0312, stroke 5 in Figs. 5(a) and 6(a) illustrate that initially, during the first 10 μs or so, the injected current is not equal to the total current leaving the system or the total current flowing from phase A to the neutral conductor. This apparent discrepancy at early times is probably due to reflections from impedance discontinuities on the line. From 10 μs to 5 ms, the measured injected

[4]Only the termination resistor current at pole 1 was measured. The termination resistor current at pole 15 was assumed to be equal to the pole 1 termination resistor current due to the symmetry of the test system with respect to the current injection point.

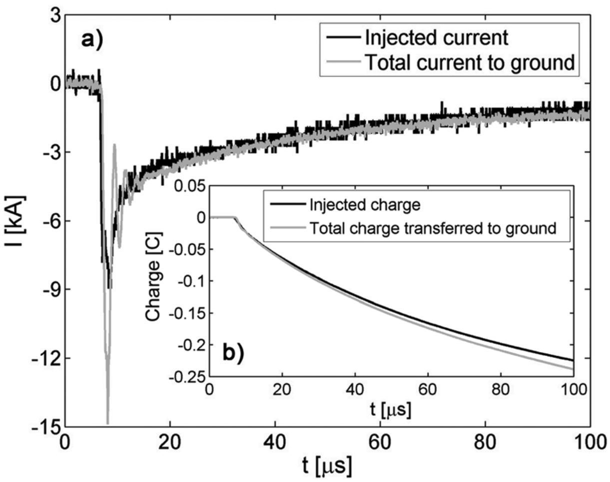

Fig. 5. Flash FPL0312, stroke 5. (a) Lightning current injected into phase A and the sum of ground currents. (b) Charge injected and the sum of charges transferred to ground on a 100-μs time scale. The charge displayed in (b) was obtained by numerically integrating the current waveforms shown in (a).

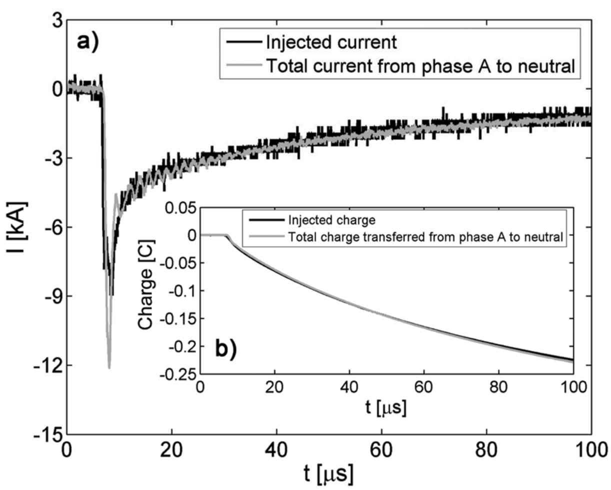

Fig. 6. Flash FPL0312, stroke 5. (a) Lightning current injected into phase A and the sum of currents transferred from phase A to the neutral conductor. (b) Charge injected and the sum of charges transferred from phase A to the neutral conductor on a 100 μs time scale. The charge displayed in (b) was obtained by numerically integrating the current waveforms shown in (a).

current and the total measured current flowing to ground are in very good agreement (although only the first 100 μs are presented in this paper). The injected current and the total measured current flowing between phase A and neutral are not equal for times after about 2 ms (not shown in this paper), probably due to measurement limitations and errors associated with the core saturation of the current transformers. The currents shown in Figs. 5(a) and 6(a) were numerically integrated to obtain the transferred charge, the results being found in Figs. 5(b) and 6(b), respectively. These figures show that the charge injected into the system is equal to both the charge leaving the system and to the charge transferred from phase A to neutral for the first 100 μs. In fact, the injected charge is equal both to the total measured charge leaving the system and to the total measured charge transferred from phase A to the neutral for at least 2 ms. The above observations are entirely consistent with the data for

TABLE III
DATA FROM THE 2000 THROUGH 2003 EXPERIMENTS

	Horizontal Line	Vertical Line		
	2000	2001	2002	2003
Number of flashes with / without return strokes	8 / 3	4 / 4	9 / 2	5 / 2
Number of return strokes	37	14	59	26
Return stroke peak current, Arithmetic Mean / Standard Dev. (Sample Size)	13.8 kA / 8.4 kA (n = 33)	16.7 kA / 6.2 kA (n = 13)	15.1 kA / 6.7 kA (n = 43)	12.5 kA / 4.3 kA (n = 22)
Return stroke current 10-90% risetime, Arithmetic Mean / Standard Dev. (Sample Size)	-	1.4 μs / 0.3 μs (n = 13)	1.4 μs / 0.9 μs (n = 36)	1.1 μs / 0.6 μs (n = 3)
Return stroke charge transfer within 1 ms, Arithmetic Mean / Standard Dev. (Sample Size)	1.6 C / 1.9 C (n = 32)	2.3 C / 1.8 C (n = 13)	1.2 C / 0.8 C (n = 43)	1.0 C / 1.3 C (n = 17)

other strokes recorded in 2002 and 2003 (the exception being strokes where flashovers cause appreciable charge to bypass the phase A-to-neutral measurement devices). The very good agreement between the input charge, the charge transferred to ground, and the charge transferred from phase A to neutral shows that the charge is conserved and therefore provides confidence in the validity of the data.

For the horizontal line experiment performed in Summer 2000, the input charge (the integrated lightning current) was reported by [16] to be 25% to 30% larger than the sum of the charges transferred to ground for the five strokes discussed. Based on a consistency check of all (published and unpublished) 2000 lightning currents, struck-phase-to-neutral currents, and ground currents, it is now believed that the reason for the discrepancy between the input and ground charges in 2000 is due to a 25% overestimation of the tower lightning current and was not due to a loss of charge due to undetected flashovers, a cause that was not ruled out by [16]. Consequently, a multiplicative factor of 0.75 is here applied to the 2000 measured peak currents and charge transfers, and the corrected data are presented in Table III.

B. Transformer Currents

The peak values of the currents through the primary of the pole-mounted step-down transformer for the 26 strokes whose currents were injected into the vertical line in 2003 ranged from some tens of amperes at a time of a millisecond from the start of the return stroke to 200 A at a time of 4 ms. Currents larger than 200 A could not be measured for more than a few milliseconds due to saturation of the core of the current transformer measuring the step-down transformer current. Fig. 7 shows data for FPL0312, stroke 5 on a 5 ms time-scale. Note that all data in Fig. 7 were low-pass filtered with a 5th order, 25 kHz, Butterworth digital filter. Fig. 7(a) shows the three currents from phase A to neutral at poles 1 and 2, that is, the transformer current, the pole 2 arrester current and the pole 1 terminator current. The

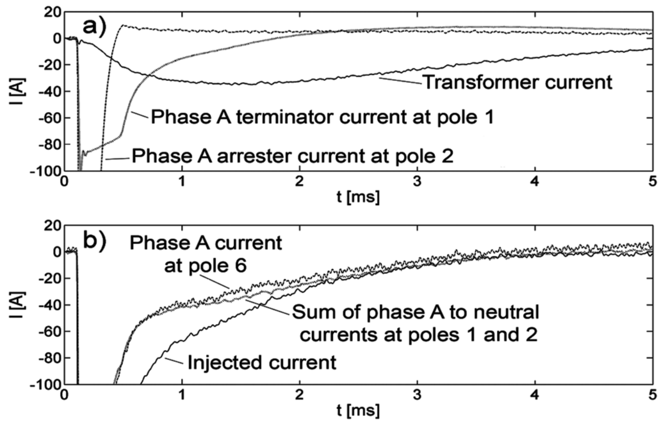

Fig. 7. FPL 0312, stroke 5. (a) Phase A to neutral currents at poles 1 and 2. (b) The injected lightning current, the phase A current measured on the pole-1 side of the pole 6 arrester station (current flowing along the phase A conductor from pole 6 toward pole 1), and the sum of all phase to neutral currents between the pole 6 arrester station and pole 1.

arrester current drops rapidly to a small positive value (it is normally negative) at 0.4 ms, or so (positive polarity means positive current is flowing from the neutral into the phase A), and from there decays slowly to zero, maintaining the positive polarity. The terminator current exhibits a fast dip after 0.5 ms and changes to positive polarity after 2.5 ms. Fig. 7(b) shows the sum of the three currents from phase A to neutral shown in Fig. 7(a) along with the injected current and the phase A current at pole 6 (measured after the injected current passes the phase A arrester at pole 6). The sum of the three phase A currents is equal to the phase A current measured at pole 6 for at least 5 ms (currents larger than 100 A, not displayed in Fig. 7(b), match well, too). This result is expected (since phase A current measured at pole 6 flows to the neutral at the three phase A to neutral connections found at poles 1 and 2) and gives further confidence in the data. After 2 ms, the sum of the three currents from phase A to neutral, with the transformer current being the largest contributor, are equal to the injected lightning current. Note that after 2 ms the transformer current is actually slightly larger than the injected current due to the polarity change of the arrester and terminator currents.

C. Arrester Disconnector Operation and Flashovers

Information is now presented on the performance of the line configurations tested from 2000 through 2003 regarding 1) arresters rendered inoperative due to disconnector operation and 2) line flashovers. The arresters were not examined for internal damage to the MOV blocks although external arrester damage was often observed. Note that disconnectors are designed not to operate on lightning current, whether the arrester functions normally or whether the MOV blocks fail, but rather on the larger rms charge transfer associated with 60 Hz fault current in the event of MOV block failure. Typically there was more than one lightning flash triggered to a line per day, but the line could not be inspected for disconnector operation until the end of the overall triggering session so that there may have been lightning flashes that did not cause disconnector operation followed by flashes on the same day that did cause disconnector

TABLE IV
DISCONNECTOR OPERATION AND FLASHOVERS DURING THE 2000 THROUGH 2003 EXPERIMENTS FOR TRIGGERING DAYS WITH RETURN STROKES

	Horizontal Line	Vertical Line		
	2000	2001	2002	2003
Average number of disconnector operations per triggering day (# of triggering days)	1 (5)	2.5 (2)	2 (4)	0 (4)
Percentage of return strokes causing flashovers (# of return strokes)	24% (34)	92% (13)	91% (43)	85% (26)
Peak currents of return strokes causing flashovers, Arithmetic Mean / Standard Dev. (Sample Size)	18.5 kA / 15.1 kA (7)	17.6 kA / 5.5 kA (12)	15.8 kA / 6.7 kA (39)	13.2 kA / 4.5 kA (18)
Peak currents of return strokes not causing flashovers, Arithmetic Mean / Standard Dev. (Sample Size)	13.1 kA / 5.7 kA (26)	6.0 kA / - (1)	9.0 kA / 3.3 kA (4)	9.6 kA / 1.9 kA (4)

operation. Consequently, it is not possible to determine, in general, the individual flashes which caused disconnector operation. Therefore, the average number of disconnector operation per triggering day is given as the measure of the susceptibility of the line configuration to disconnector operation (Table IV). Note that during the 2000 through 2002 experiments all arresters rendered inoperative were on the struck phase (2000: phase C, 2001–2002: phase A) and no disconnector operated in 2003. For the 2000 horizontal line experiment, the disconnector of one arrester (the arrester at pole 8—one of the two arresters closest to the strike point) operated during each of the 5 triggering days during which ICCs, return stroke currents, and possibly continuing currents were injected into the line. Additionally, one flash without return strokes (ICC only) was positively identified to have operated the disconnector at this location (it was the only flash triggered during that day). For the 2001 vertical line experiment (ICC and return strokes possibly followed by continuing current injected into the line), an average 2.5 disconnectors of the 4 struck-phase arresters operated during each of the 2 triggering days during which ICC, return stroke current, and possibly continuing current were injected into the line. Arresters at poles 2, 6, and 10 had operated disconnectors after the first triggering day and arresters at poles 2, 10, and 14 had operated disconnectors after the second triggering day.

Additionally, two flashes without return strokes (ICCs only) were positively identified to not have operated any disconnectors (they were the two only flashes triggered during that day). For the 2002 experiment (ICC diverted), an average 2 disconnectors of the 4 struck-phase arresters operated during each of the 4 triggering days. No disconnector operated during the first triggering day, all 4 disconnectors on the struck-phase operated during the second triggering day, 3 disconnectors operated during the third triggering day, and 1 disconnector operated during the fourth triggering day. For the 2003 experiment (ICC diverted and transformer on the line), no disconnector operated during the 4 triggering days. Table IV also gives information about the percentage of return strokes that caused phase-to-phase flashovers, which were evidenced by appreciable stroke current being measured in a phase not subjected to direct lightning current injection. For the 2000 horizontal line experiment 24% of the 34 strokes caused phase-to-phase flashovers. For the

2001, 2002, and 2003 vertical line experiments flashovers occurred much more frequently—about 90% of the 13, 43, and 26 strokes, respectively, caused flashovers. All 3 flashes that contained strokes which did not cause any flashovers occurred during the 2000 experiment. Statistical information on the peak currents of strokes causing flashovers and of strokes not causing flashovers are also given in Table IV. On average, the peak currents of the former are larger than the peak currents of the latter, as expected. However, for all years strokes with very small peak currents (down to 5.6 kA) caused flashover. Note that the total sample size of the return stroke peak currents is not always equal to the total number of strokes due to failed current measurements.

IV. Discussion

The disconnector operations per lightning triggering day are discussed now. The likely reason for the more frequent disconnector operation during the 2001/2002 experiment than during the 2000 experiment (Table IV) was the different number of arrester stations on the line (2000: 6 arrester stations, 2001/2002: 4 arrester stations); that is, the thermal heating that caused operation of the disconnector was less during the 2000 experiment since the lightning current divided among more arresters. Although the average number of operated disconnectors per triggering day on the vertical line was slightly reduced from 2001 to 2002 (2001: 2.5 disconnector operations, 2002: 2 disconnector operations), the difference is not statistically significant. Therefore, there is no experimental evidence that the two changes made in 2002, that is, employing two arresters in parallel (versus single arresters on phase A in 2001, see Table I) and not injecting the ICC into the line (see Section II) helped reduce the likelihood of disconnector operation. The reason for the insensitivity of the disconnector operation to whether single or two parallel arresters are being used is probably related to the known difficulties of matching two MOVs connected in parallel due to the intrinsic nonuniformity of the MOV disk's microstructure [22]. Ideally, the lightning current through two arresters connected in parallel is equally shared between them, which would double their joint energy handling capability. This was apparently not the case for the arresters connected in parallel during the 2002 experiment. On the other hand, Hitoshi *et al.* [13] investigated the effectiveness of using two arresters in parallel by injecting a current impulse from a surge generator into a 430 m long test distribution line and found that the two arresters equally shared the currents. Note that even though no ICC was injected into the line in 2002, continuing current which has properties similar to the ICC (current of the order of 100 A for some milliseconds to hundreds of milliseconds after return stroke initiation) followed some of the strokes. Note also that the average return stroke charge injected into the line in the initial millisecond was significantly larger in 2001 than in 2002 (2001: 2.3 C, 2002: 1.2 C, see Table III) which also may account for the slightly larger number of disconnector operations per triggering day in 2001. The absence of disconnector operation in 2003 versus 2000, 2001, and 2002, during which there were common disconnector operations, can likely be attributed to the presence of a transformer on the line in 2003 (see Table I), which shunted the low-magnitude, low-frequency lightning current components through the transformer primary to earth as shown in Section III-B. In other words, the transformer may have served to reduce the low-frequency currents through the arresters preventing excessive thermal heating of the disconnectors' cartridges, whereas the arresters initially protected the transformer from damage due to high-voltage transients. Note that even though the average return stroke charge injected into the line in the initial millisecond was slightly larger in 2002 than in 2003 (2002: 1.2 C, 2003: 1.0 C, see Table III) the maximum charge transfer was larger during the 2003 experiment (2002: 4.1 C, 2003: 6.0 C). Also, the 2003 experiment included the flash with the largest number of return strokes of all experiments (a 16-stroke flash).

It is an important result of this study that disconnectors frequently operated during the 2000 through 2002 experiments even though 60 Hz fault current was not present (disconnectors are designed to operate only on the 60 Hz power frequency fault current that follows MOV block failure). There is direct evidence that long duration currents caused disconnector operation: some disconnectors operated during events that contained ICC only. There is also evidence that disconnector operation on the test distribution lines was not exclusively caused by long-duration currents: the disconnectors of arresters closest to the strike point, which pass the bulk of the impulsive lightning currents during the initial tens of microsecond after the return stroke initiation (see part 2 and [16]) operated most often. It appears that disconnector operation on the test distribution lines was typically caused by excessive heating due to the combined charge transferred during both the return stroke current transients and the long duration currents. Significantly, disconnector operation on the 2003 line was eliminated, apparently by the absence of the long duration currents through the arresters due to the alternative current path provided by the transformer. This implies that even though the energy absorbed during both long duration currents and return stroke transients contribute significantly to disconnector operation, as noted above, the energy absorbed during the return stroke current transients alone is typically not large enough to cause disconnector operation. It is important to note that this statement applies to disconnector operation from rocket-triggered lightning on the test distribution lines only and not necessarily to 'real world' distribution lines, where natural lightning first return stroke currents have typically a much larger energy content than rocket-triggered return stroke currents, where the long-duration currents divide among many more arresters, and where distribution and zone substations transformers are present.

Phase-to-phase flashovers occurred much less frequently during the horizontal line experiment than during the vertical line experiments (Table IV) even though the distance of the struck phase to the next closest phase was smaller for the horizontal line than it was for the vertical line (horizontal line: 70 cm, vertical line: 80 cm). The reason for the fewer phase-to-phase flashovers on the horizontal line is likely related to one or more of the following differences between the horizontal and vertical line experiments.

1) The differences in arrester spacings (horizontal line: arrester stations every 3 spans, vertical line: arrester stations

every 4 spans). The arresters reduce the voltage on the struck phase thereby preventing flashovers. However, the voltage reduction does not occur instantaneously, but is delayed by the time it takes for the voltage signal to travel from the injection point to the arrester, be reversed in polarity, and from there travel back to any point between the arrester stations. For the horizontal line, the distances from the lightning current injection point to each of the two closest arresters were 1.5 spans (span length: 50 m). Due to symmetry, the weakest point on the horizontal line (that is, the point on the line where the voltage relief wave from the arresters arrives last and therefore is most likely to experience a flashover) is the current injection point. This means that, for the horizontal line, the voltage relief wave has arrived everywhere on the struck phase after 0.5 μs (the roundtrip distance from the weakest point to the strike point, 3 spans or 150 m, divided by the speed of the traveling wave, we assume $c = 3\times10^8\ \mathrm{m/s}$ although the actual speed of the wave is slightly less than c). For the vertical line, the distance from the lightning current injection point to the closest arrester in one direction was 1.5 spans and to the closest arrester in the other direction was 2.5 spans (span length: 58 m). A calculation similar to the one performed for the horizontal line above shows that the voltage relief wave has arrived everywhere on the line after 0.7 μs (that is, 0.2 μs later than for the horizontal line). The larger delay time for the vertical line can have a significant impact on the voltage at the weakest point. At the time the relief wave arrives (horizontal line: 0.5 μs, vertical line: 0.7 μs) the voltage at the weakest point on the vertical line is estimated to be about 40% larger than the voltage at the weakest point on the horizontal line (assuming the voltage builds up linearly during the first 0.7 μs[5]), which increases the probability of flashovers on the vertical line.

2) The presence of voltage measurement equipment on the horizontal line. The voltage dividers might have helped to prevent phase-to-phase flashovers by passing current or by facilitating phase-to-neutral flashovers which could not easily be detected, thereby reducing the potential difference between the struck phase and the next closest phase.
3) The differences in phase arrangements. In the presence of both direct current injection and the electric and magnetic fields of the leader/return stroke sequence, the horizontal arrangement of the phases in the horizontal line might experience a smaller potential difference between the struck phase and the next closest phase than the potential difference of the vertically arranged phases in the vertical line. However, the induced voltages have been calculated using the LIOV-EMTP96 code [23] (the calculation results are not presented here) and were found to be very small compared to the voltages caused by the direct lightning current injection.

Interestingly, the percentages of strokes causing flashovers were essentially the same for all three years during which the vertical line was tested (2001: 92%, 2002: 91%, and 2003: 85%) even though the disconnector operation during the 2001/2002 experiments and the 2003 experiment was quite different (2.5 and 2 disconnector operations per triggering day for the 2001 and 2002 experiments, respectively, versus no disconnector operation for the 2003 experiment). Apparently, the tendency of the vertical line configuration to experience flashovers is neither significantly influenced by the number of disconnected arresters on the line nor by the presence of the transformer on the line (a transformer was only present during the 2003 experiment).

[5]This is a reasonable assumption since the injected current waveforms, which are expected to have the same waveshape as the voltages, have an average 10–90% risetime of well above 1 μs (see Table III in Section III).

V. Summary

What follows is a summary of the results presented in this paper. It is important to remember that the results summarized here were obtained from tests with rocket-triggered lightning currents injected into unenergized, test distribution lines of 800 m length and hence that "real world" distribution lines exposed to natural lightning may not react in exactly the same manner.

1) The disconnector operation common during the 2001/2002 vertical line experiment was absent during the 2003 vertical line experiment, probably due to a transformer on the line which protected the arresters by shunting the long-duration current to ground.
2) Disconnector operation during the 2000 horizontal line experiment was considerably less frequent than during the 2001/2002 vertical line experiment, which was possibly due to the larger number of arrester stations on the 2000 horizontal line reducing the long-duration current through each individual arrester.
3) Typically, the disconnectors of arresters closest to the lightning current injection point, which conduct the bulk of the lightning return stroke transients, were the ones that operated.
4) The results summarized in items 1)–3) and other results given in the paper indicate that the combined energy input of the return stroke transients and long-duration currents in triggered lightning is sufficient to activate disconnectors. However, the absence of disconnector operation in 2003 where the long-duration current was considerably reduced by a transformer implies that the return stroke current transients in rocket-triggered lightning alone do not commonly activate disconnectors.
5) No statistically significant experimental evidence was found that employing two arresters in parallel instead of single arresters reduces the likelihood of disconnector operation.
6) No statistically significant experimental evidence was found that not injecting the initial continuous current of triggered lightning into the distribution line reduces the likelihood of disconnector operation.
7) Theory presented in the previous section shows that the voltage between the struck phase and the next closest phase at the weakest point on the vertical line (arresters every 4 spans) is about 40% smaller than the voltage at the weakest point on the horizontal line (arresters every 3 spans) due to the different arrester spacing. The smaller number of flashovers on the horizontal line compared to the number

of flashovers on the vertical line appears to reflect this difference in voltage, although other explanations for the different flashover behavior of the lines are possible.

8) The tendency of the vertical line configuration to experience frequent flashovers was apparently neither influenced by the number of disconnected arresters nor by the presence of a transformer on the line.

Acknowledgment

The authors would like to thank M. V. Stapleton, R. Sutil, P. Diaz, and R. Rey for participating in the experiments as well as Dr. C. A. Nucci, Dr. F. Rachidi, and Dr. M. Paolone for providing the LIOV-EMTP96 code, and Dr. M. Darveniza and the anonymous reviewers for very helpful discussions, which helped the authors considerably improve this paper.

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For photographs and biographies, see Part II.