TRANSIENT CURRENTS AND VOLTAGES IN A POWER DISTRIBUTION SYSTEM DUE TO NATURAL LIGHTNING

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Abstract: Natural lightning occurred six times on or very near the test site at the International Center for Lightning Research and Testing at Camp Blanding, Florida, during the 1995 and 1996 experiments. Transient currents and voltages in an unenergized test power distribution system, composed of an overhead line, underground cable, padmount transformers, and secondary service entrance, will be presented here for two lightning flashes. One flash struck earth tens of meters away from the test system's conductors, and the other flash struck the overhead line directly.

Keywords: Lightning, Power Distribution System

1. INTRODUCTION

The International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida, is a unique facility for studying various aspects of lightning and lightning protection. The facility is equipped with an unenergized, test power distribution system which is composed of an overhead power line and an underground distribution system, including an underground power cable which may be connected to the overhead line, padmount transformers, and a secondary service entrance located in a simulated house.

Natural lightning occurred six times on or very near the test site during the 1995 and 1996 experiments, and its effects on the test system were recorded. On 10 July 1995, a lightning flash struck earth tens of meters away from the test system's conductors. On 11 August 1996, a flash directly struck the overhead line near one end. The resulting transient currents and voltages in the test distribution system were recorded with considerable detail for both of these flashes [1], and those results are described here.

2. EXPERIMENTAL SET-UP

2.1 Overview of ICLRT

Electrical diagrams of the test distribution system at ICLRT for the lightning flashes analyzed are given in Figs. 1 and 2, respectively. Details of the 1995 and 1996 system configurations are outlined in Table 1.

Labels A1 through A30 in Figs. 1 and 2 indicate measurement locations for current, and the corresponding arrows indicate the direction for current that will produce positive-polarity outputs from the current sensors. Labels V1 through V9 indicate voltage measurement locations. The corresponding plus/minus signs indicate positive-polarity outputs from the voltage sensors when the phase conductors are at a higher, positive electrical potential than the neutral conductors.

The overhead line is approximately 730 meters long and supported by fifteen poles. The line consists of two vertically stacked conductors separated by 1.8 meters and mounted on insulators having a critical flashover voltage (CFO) of about 500 kV [2]. The top and bottom conductors simulate the phase and the neutral, respectively, and the line is terminated in its characteristic impedance of 500 Ω. In Fig. 1, MOV arresters are connected between the phase and neutral conductors at Poles 8, 9, and 10, and the neutral is grounded at Poles 1, 8, 9, 10, and 15. In Fig. 2, MOV arresters are installed at Poles 1, 9, 10, and 15, and the neutral is grounded at each arrester location.

The underground cable is a 15-kV XLPE coaxial cable, approximately 735 meters long, covered with an insulating jacket. The cable was contained in PVC conduit and buried at a depth of 0.9 meters. One end of the cable can be attached to the overhead line at Pole 9, as illustrated in Figs. 1 and 2. Padmount transformers (25-kVA) are located in Instrument Stations (IS) 1 and 4 and can be connected to the cable. The transformers in IS1 (Figs. 1 and 2) and IS4 (Fig. 1 only) have MOV elbow arresters installed at the primaries and are located about 85 meters and 735 meters, respectively, along the length of the cable from Pole 9. The cable neutral is grounded at both IS1 and IS4.

In IS1, the transformer secondary can be loaded with a service entrance of a simulated house (Figs. 1 and 2) via 600-V triplexed service cables buried at a depth of about 0.9 meters. The X1 and X3 secondary phase conductors are

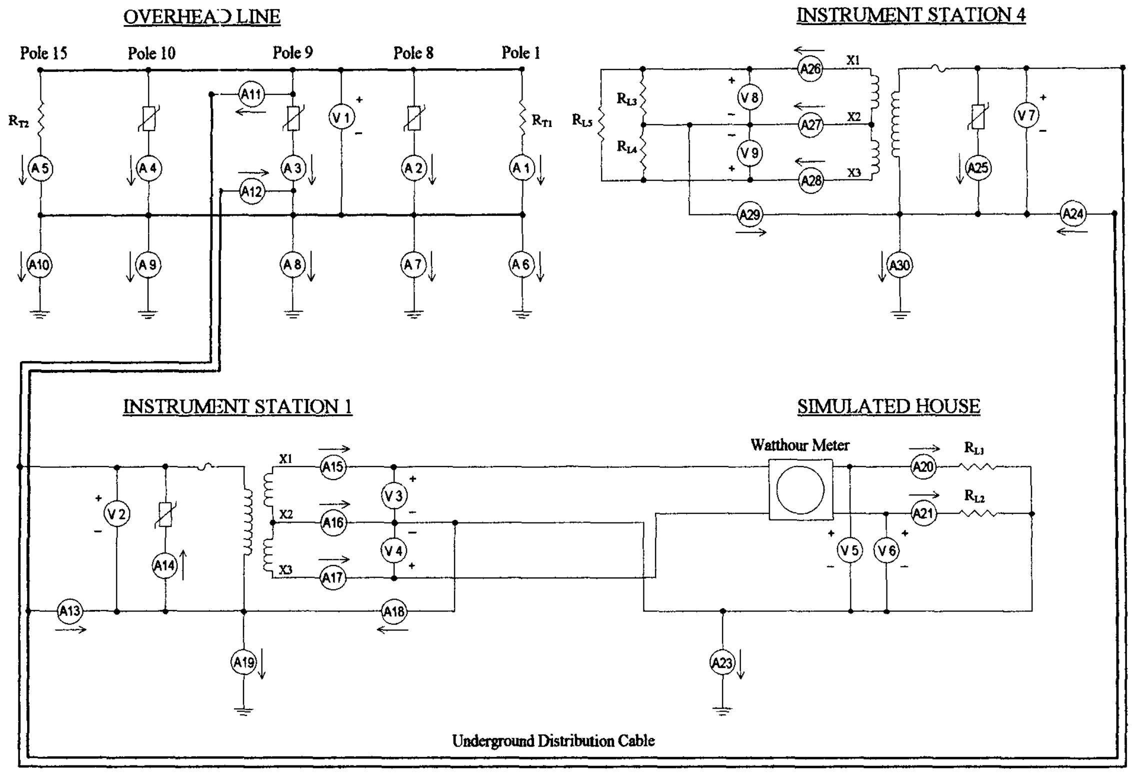

Fig. 1. Electrical diagram of the test distribution system at ICLRT for the lightning of 10 July 1995.

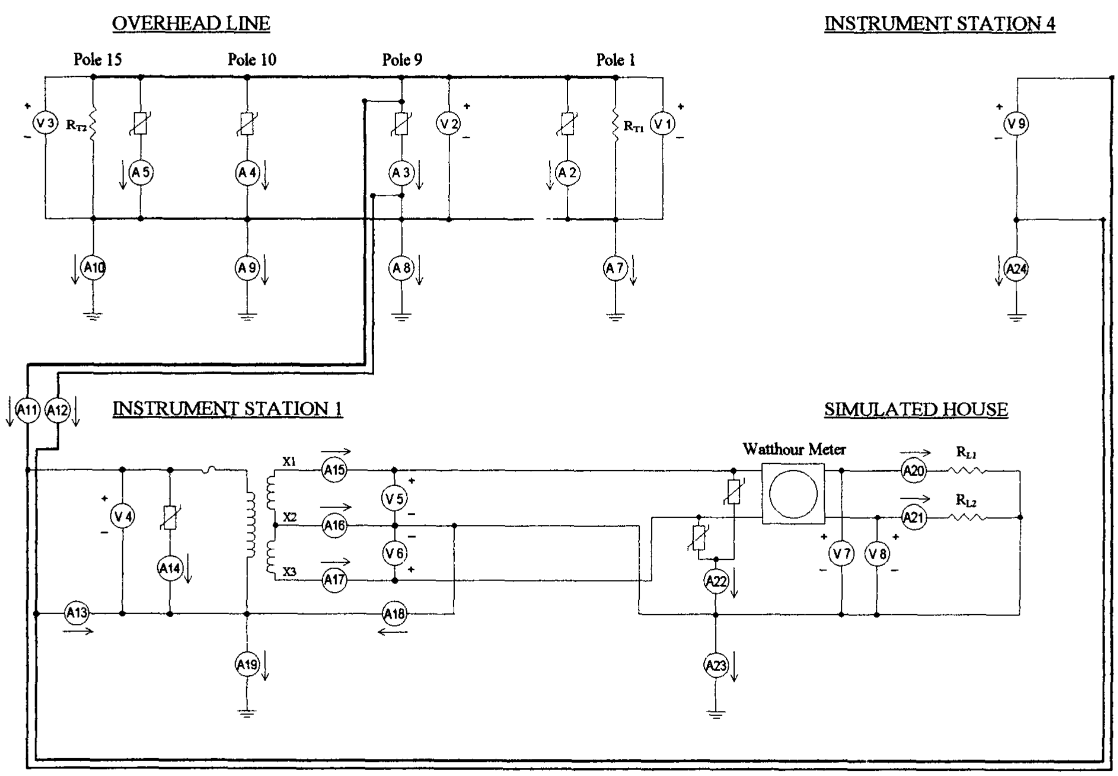

Fig. 2 Electrical diagram of the test distribution system at ICLRT for the lightning of 11 August 1996.

TABLE 1
CONFIGURATIONS OF THE TEST DISTRIBUTION SYSTEM

Date	Description of Overhead Line	Description of Underground System
10 July 95	• Terminated at both ends with 500 Ω • MOV arresters at Poles 8, 9 and 10 • Neutral grounded at Poles 1, 8, 9, 10 and 15	• Cable attached to line at Pole 9 • Transformers at IS1 and IS4 connected to cable • MOV elbow arresters at trans. primaries • Service entrance connected to IS1 trans. secondary • Neutrals grounded at IS1, IS4, and service entrance
11 Aug. 96	• Terminated at both ends with 500 Ω • MOV arresters at Poles 1, 9, 10 and 15 • Neutral grounded at Poles 1, 9, 10 and 15	• Cable attached to line at Pole 9 • Transformer at IS1 connected to cable • MOV elbow arrester at trans. primary • Service entrance connected to IS1 trans. secondary • SPD at serv. entrance • Neutrals grounded at IS1, IS4, and service entrance

connected to the neutral conductor, X2, in the Simulated House via load resistors R_{L1} (4 Ω) and R_{L2} (6 Ω), respectively. The neutral X2 is grounded at both the service entrance and at the transformer. In Fig. 2, surge protective devices (SPDs) are installed at the service entrance.

2.2 Terminology

The lightning flashes on or near the test site in 1995 and 1996 all lowered negative charge to ground. Thus, the lightning return-stroke current was always directed upward from the strike location toward the cloud (electrons being injected into the strike point). In the following sections of this paper, expressions such as "current entering the test system" and "current exiting the test system" are commonly used. In each case, it is in reference to the direction of electron flow. Although this usage contradicts the definition of conventional current, it considerably simplifies the description of the current distribution in the system.

3. FLASH OF 10 JULY 1995

Data for the first stroke of the 10 July 1995 lightning flash (instrumentation did not allow recording of subsequent strokes) will be presented. Lightning struck earth in the vicinity of Pole 1 and IS4 (Fig. 1) which are located 40 meters apart. From the electric field records and the approximate location of the strike point, the return-stroke current is estimated to be about 30 kA, which is typical for the first stroke of natural lightning [3]. Energy from this flash entered the test system in at least two ways: (1) electromagnetic coupling to the overhead line and (2) direct current injection via the system's ground connections near the strike point.

3.1 Overhead Line

The arrester discharge current at Pole 8 along with the currents to ground at Poles 8 and 1 are shown in Fig. 3, displayed on a 50-μs scale. The three waveforms are bipolar, suggesting that these currents were induced on the overhead line due to a strike to earth some tens of meters away from the line [4] (although, it is suspected that the first couple of microseconds in each of the waveforms in Fig. 3 are likely not the measured signal but are probably due to the "turning-on" process of each data recorder [1]).

The arrester discharge current at Pole 8 is shown in Fig. 3a. The waveform reaches a negative crest of 1.6 kA at about 10 μs which is immediately followed by a positive crest of 0.5 kA with a 10-90% transition time (from negative peak to positive peak) of about 0.8 μs. The arrester current changes polarity once more, then gradually returns to zero.

The current to ground at Pole 8 in Fig. 3b has a negative crest of 1.2 kA followed by a positive crest of 0.2 kA with a 10-90% transition time of about 0.8 μs. The waveform changes polarity again and exhibits some oscillations superimposed on a lower-frequency current which slowly increases to a negative peak value of about 1 kA, after which it remains near that value for the remainder of the plot.

The current to ground at Pole 1 is shown in Fig. 3c. The waveform is bipolar, but it is dissimilar to the waveforms in Figs. 3a and 3b in that the positive crest has a larger peak value than the negative crest which precedes it. The negative crest is about 0.62 kA and the subsequent positive crest is shown clipped at 1.2 kA, which is the upper amplitude limit of the data recorder (due to input settings). These crests and subsequent oscillations are superimposed on a lower-frequency current, similar to Fig. 3b, which becomes clipped at 1.2 kA and remains clipped for the remainder of the plot.

Currents to ground from the overhead line (including the two already shown in Fig. 3) and the current in the cable neutral at Pole 9 are shown together in Fig. 4, displayed on a 500-μs scale. The current to ground at Pole 1 in Fig. 4a is the same as that in Fig. 3c but shown on a longer time scale so that the lower-frequency current is seen in its entirety. In Fig. 4a, the waveform is shown clipped (due to the data recorder's upper amplitude limit) at 1.2 kA for nearly 300 μs; thus, it is difficult to estimate the peak value of this current. The current to ground at Pole 8 in Fig. 4b has a negative peak value of 1 kA and a half-peak width (below zero) of about 140 μs. The current to ground at Pole 9 in Fig. 4c has a negative peak value of 0.9 kA with a half-peak width of about 180 μs. The current into the cable neutral at Pole 9 in Fig. 4d has a peak value of 1.1 kA with a half-peak width 220 μs.

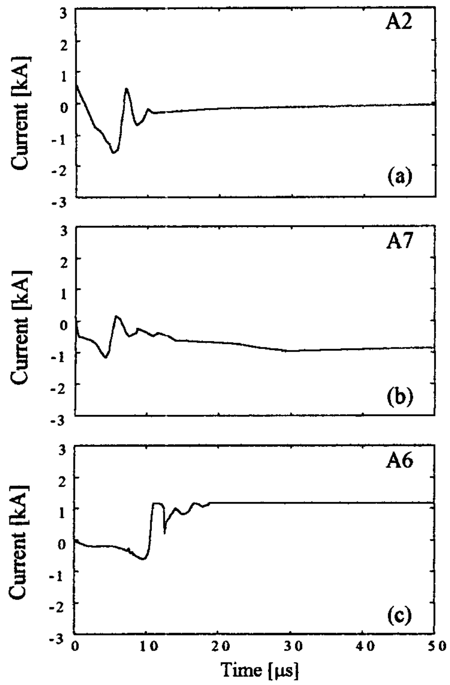

Fig. 3. Current versus time waveforms for the lightning of 10 July 1995, displayed on a 50-μs scale. (a) Arrester discharge current, Pole 8 [A2]; (b) Current to ground, Pole 8 [A7]; (c) Current to ground, Pole 1 [A6].

Since the polarity (positive) of the major portion of the current at Pole 1 is opposite to the polarity of the respective portion of the currents observed at the other locations in Fig. 4, it is clear that some fraction of the total lightning return-stroke current striking ground in the vicinity of Pole 1 entered the test system from earth via the ground connection at Pole 1 and that portions of this current exited the system to ground (or into the cable neutral) at the other locations. Thus, the neutral conductor of the overhead line served to direct the injected lightning current to remote grounds along the line. Although the arrester discharge current at Pole 8 in Fig. 3a is the only available phase-to-neutral current measurement on the overhead line for this flash, it can be inferred that electromagnetic coupling was largely responsible for the current between the phase and neutral. Thus, it appears that very little, if any, of the injected lightning current was shared by the phase conductor of the overhead line.

3.2 Underground System

Currents measured at the transformers in IS4 and IS1 are shown in Fig. 5, displayed on a 500-μs scale. The current to ground at the IS4 transformer in Fig. 5a is shown clipped at 1.2 kA for about 200 μs. The current flowing between the transformer LV-side neutral conductor and the HV-side neutral in Fig. 5b has two positive crests separated by about 130 μs with peak values of 620 A and about 60 A, respectively. The first crest has a 10-90% risetime of about 12 μs and half-peak width of 46 μs. The polarities of the waveforms in Figs. 5a and 5b respectively indicate that (1) the lightning current entered the test system from earth and

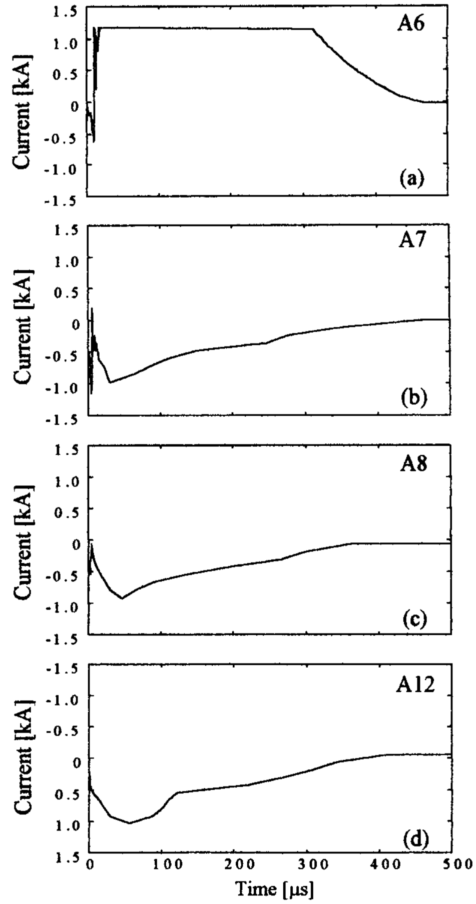

Fig. 4. Current versus time waveforms for the lightning of 10 July 1995, displayed on a 500-μs scale. (a) Current to ground, Pole 1 [A6]; (b) Current to ground, Pole 8 [A7]; (c). Current to ground, Pole 9 [A8]; (d) Current in cable neutral, Pole 9 [A12].

(2) a fraction of this current entered the IS4 transformer secondary from the primary neutral. The bulk of this current probably traveled along the neutral conductor of the underground cable toward the transformer in IS1.

The current to ground at the IS1 transformer in Fig. 5c is shown clipped at 1.2 kA for about 75 μs. The current flowing between the transformer LV-side neutral conductor and the HV-side neutral in Fig. 5d has two positive crests separated by about 130 μs, similar to the corresponding current in IS4 (Fig. 5b), with peak values of 220 A and 40 A, respectively. The polarities of the waveforms in Figs. 5c and 5d respectively indicate that (1) current exited the test system to earth at IS1 and (2) current entered the IS1 transformer secondary from the primary neutral.

Current and voltage from the IS1 transformer secondary are shown in Fig. 6. The current in X1 in Fig. 6a has a peak value of 690 A and a half-peak width of about 120 μs. The polarity of the waveform indicates that current exited the secondary winding at X1. The voltages between X1 and X2 and between X3 and X2 are shown in Figs. 6b and 6c, respectively. The vertical axes for the two waveforms are labeled "uncalibrated" due to uncertainty in the calibration

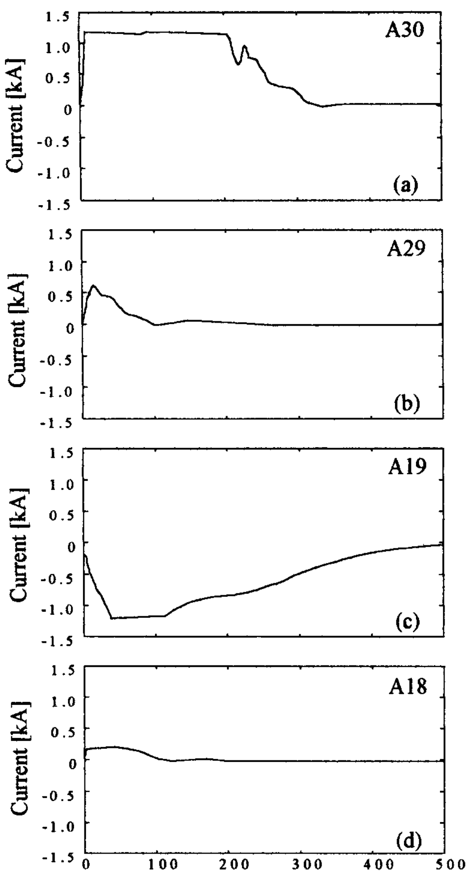

Fig. 5. Current versus time waveforms for the lightning of 10 July 1995, displayed on a 500-μs scale. (a) Current to ground, IS4 [A30]; (b) Current between LV-side neutral and HV-side neutral, IS4 [A29]; (c) Current to ground, IS1 [A19]; (d) Current between LV-side neutral and HV-side neutral, IS1 [A18].

factors for locations V3 and V4. The waveforms have comparable 10-90% risetimes of 120 μs and comparable half-peak widths of also 120 μs.

3.3 *MOV Arrester Voltages*

Arrester voltages at Pole 9 and at the IS1 transformer primary are shown in Fig. 7, displayed on a 500-μs scale. Fig. 7a shows the arrester voltage at Pole 9. The vertical axis is labeled "uncalibrated" due to uncertainty in the calibration factors for location V1. The voltage-clamping operation of the arrester is observed after the initial rise to the negative crest. The duration of the voltage-clamping plateau, measured at 50% of the plateau's peak amplitude, is about 110 μs. The waveform then decreases, crosses zero, and exhibits the opposite polarity overshoot with a half-peak width (above zero) of about 32 μs. The waveform in Fig. 7b of the voltage across the elbow arrester at the IS1 transformer primary is similar to the voltage waveform in Fig. 7a. The

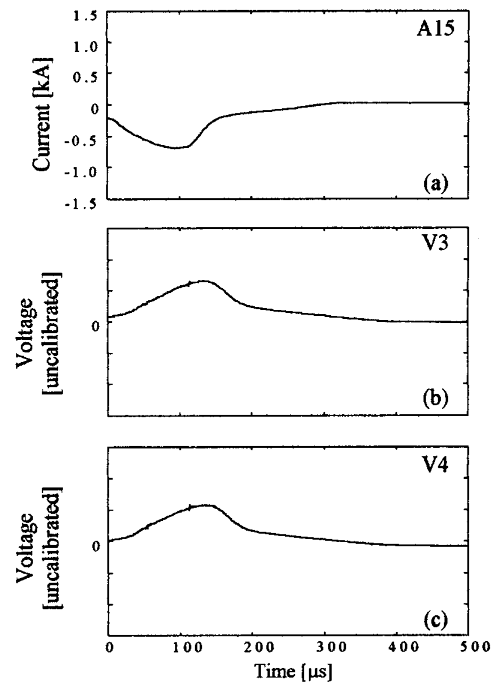

Fig. 6. Current versus time and voltage versus time waveforms for the lightning of 10 July 1995, displayed on a 500-μs scale. (a) Current in X1, IS1 [A15]; (b) Voltage between X1 and X2, IS1 [V3]; (c) Voltage between X3 and X2, IS1 [V4].

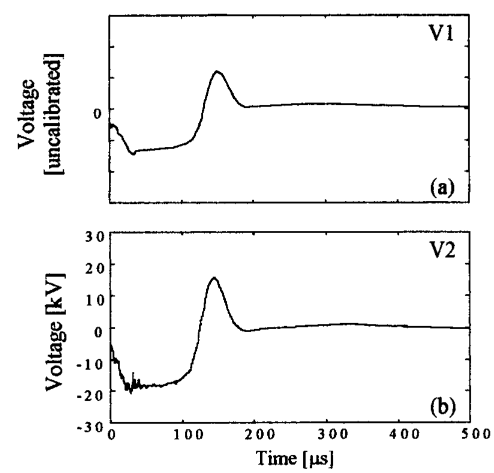

Fig. 7. Voltage versus time waveforms for the lightning of 10 July 1995, displayed on a 500-μs scale. (a) Voltage across arrester, Pole 9 [V1]; (b) Voltage across arrester, IS1 [V2].

waveform rises to a negative crest of about 21 kV with a 10-90% risetime of 75 μs. The clamping level decays from 19 kV to about 13 kV and has a duration of about 110 μs. The overshoot has a positive crest of about 16 kV with a half-peak width (above zero) of about 29 μs.

4. FLASH OF 11 AUGUST 1996

Data for the single stroke of the 11 August 1996 lightning flash will be presented. Lightning struck the phase conductor of the overhead distribution line in the immediate vicinity of Pole 1. Energy from this flash entered the system (1) directly via the lightning current and (2) indirectly via coupling of the electromagnetic fields from the lightning to the line.

4.1 Overhead Line

Arrester discharge currents on the overhead line at Pole 1 along with currents to ground from the overhead line are shown in Fig. 8, displayed on a 200-μs scale. The arrester discharge current at Pole 1 in Fig. 8a is shown clipped at 6.1 kA, which is the upper amplitude limit of the data recorder, for about 50 μs. At 200-μs, over 1.6 kA is still flowing through the arrester. The polarity of the waveform indicates that the lightning current (negative charge) was flowing from the phase to the neutral conductor. The amplitude of the arrester current at Pole 1 (which might easily be two to three times larger than the upper measurement limit of 6.1 kA) is significantly larger than at the other arrester locations (not shown). This strongly suggests that the strike point was on the phase conductor of the line and was very near Pole 1.

The current to ground at Pole 1 in Fig. 8b is almost identical to the corresponding arrester current (Fig. 8a), also shown clipped at 6.1 kA for about 50 μs. The currents to ground at Poles 9 and 10 in Figs. 8c and 8d have negative peak values of 2.8 kA and 1.5 kA, respectively. Both waveforms, more so in Fig. 8c, exhibit higher-frequency oscillations superimposed on a lower-frequency component. Also, the peak value of the current to ground at Pole 9 is similar to that for the arrester current (not shown) at that location. The current to ground at Pole 15 in Fig. 8e is composed of a lower-frequency wave with a negative peak value of 1.1 kA and a duration similar to the lower-frequency components in Figs 8c and 8d. Apparently, the phase-to-neutral path at Pole 1 was preferred by the lightning current. The bulk of this current flowed to ground at Pole 1 while a smaller amount flowed away from Pole 1, toward the other ground locations.

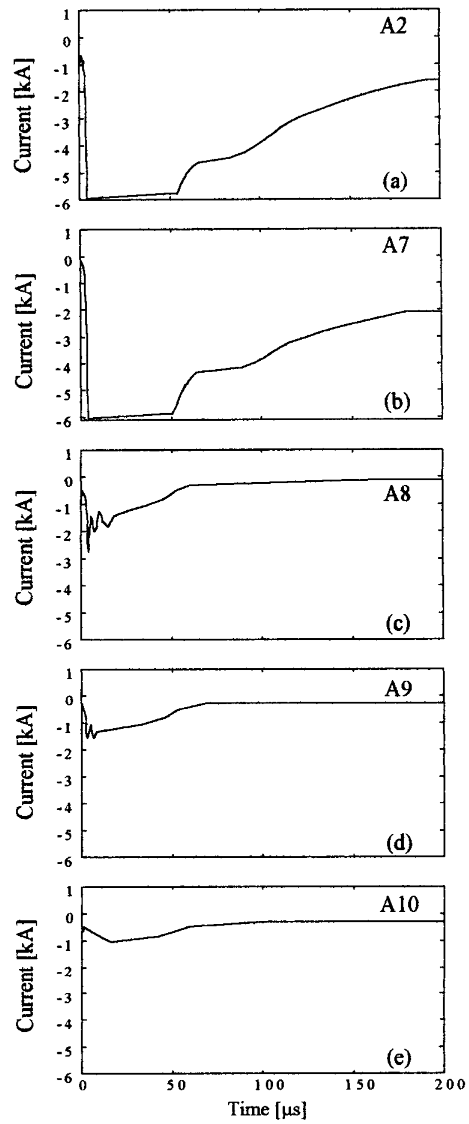

Fig. 8. Current versus time waveforms for the lightning of 11 August 1996, displayed on a 200-μs scale. (a) Arrester discharge current, Pole 1 [A2]; (b) Current to ground, Pole 1 [A7]; (c) Current to ground, Pole 9 [A8]; (d) Current to ground, Pole 10 [A9]; (e) Current to ground, Pole 15 [A10].

4.2 Underground Cable and Transformer Primary

Currents in the distribution cable and the arrester discharge current at the IS1 transformer primary are shown in Fig. 9, displayed on a 200-μs scale. The current in the phase conductor of the cable at IS1 in Fig. 9a has an initial negative peak value of 0.8 kA followed by a smaller crest of 0.4 kA about 18 μs later. The arrester discharge current in Fig. 9b is quite similar to the cable current (Fig. 9a), with an initial negative crest of 0.5 kA and a subsequent crest of 0.3 kA separated by about 19 μs, suggesting that the arrester was the preferred path to ground. The current in the cable neutral in Fig. 9c has a negative peak value of 1.6 kA and a half-peak width of about 50 μs. The current to ground at IS4 in Fig. 9d, on the other hand, has a negative peak value of 5.0 kA, a 10-90% risetime of about 11 μs, and a half-peak width of about 140 μs. Unfortunately, no data are available for currents to ground at IS1 nor at the service entrance; but, from the data that are available, it appears that almost three times more current is flowing to ground at IS4 (Fig. 9d) than is flowing into the cable neutral from Pole 9 (Fig. 9c). It is unclear how such a condition could occur.

Voltage between the phase and neutral conductors of the cable in IS4 is shown in Fig. 10. The waveform has an initial crest of 50 kV, a 10-90% risetime of about 11 μs, and a half-peak width of about 10 μs. Initially, the waveform rises particularly slowly up to about 11 kV, then exhibits a relatively sharp rise to peak followed by damped oscillations superimposed on a relatively constant level, of about 27 kV. The oscillations have a period of about 19 μs which is

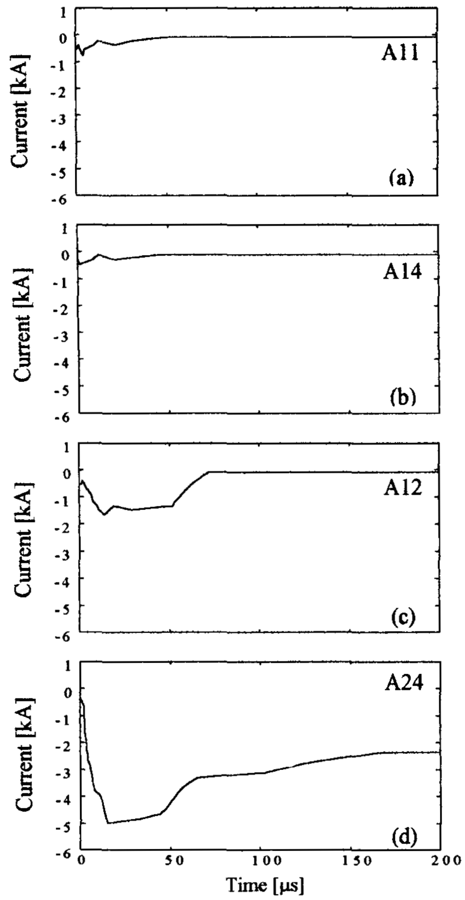

Fig. 9. Current versus time waveforms for the lightning of 11 August 1996, displayed on a 200-μs scale. (a) Current in phase conductor of the cable, IS1 [A11]; (b) Arrester discharge current, IS1 [A14]; (c) Current in neutral conductor of the cable, IS1 [A12]; (d) Current to ground, IS4 [A24].

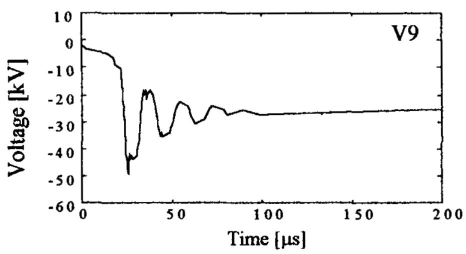

Fig. 10. Voltage versus time between the phase and neutral conductors of the underground cable in IS4 [V9] for the lightning of 11 August 1996, displayed on a 200-μs scale.

indicative of wave reflections between Pole 9 and IS4 (735 meters apart) with a propagation speed in the cable of about one-quarter the speed of light.

4.3 Transformer Secondary and Service Entrance

Voltages at the transformer secondary and at the service entrance are shown in Fig. 11, displayed on a 50-μs scale. The voltage between X1 and X2 at the transformer secondary

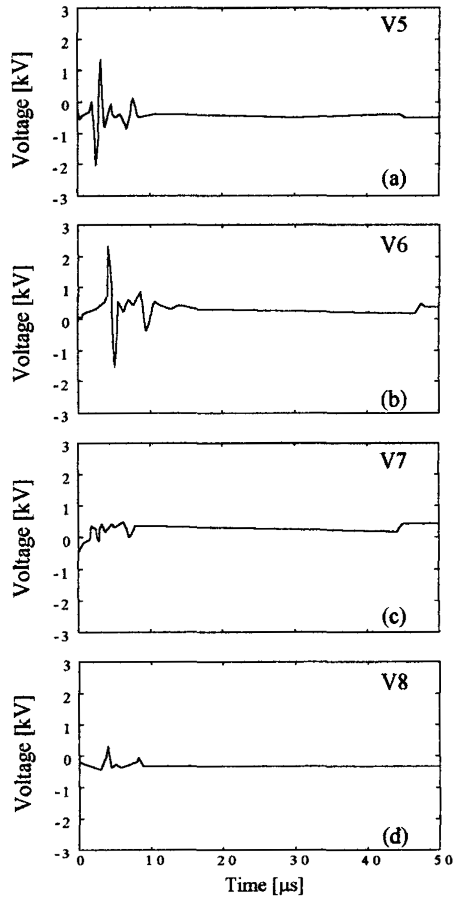

Fig. 11. Voltage versus time waveforms for the lightning of 11 August 1996, displayed on a 50-μs scale. (a) Voltage between X1 and X2, IS1 [V5]; (b) Voltage between X3 and X2, IS1 [V6]; (c) Voltage across R_{L1}, Simulated House [V7]; (d) Voltage across R_{L2}, Simulated House [V8].

in Fig. 11a is initially bipolar, with negative and positive peak values of 2.0 kV and 1.4 kV, respectively, followed by smaller oscillations. The voltage between X3 and X2 in Fig. 11b is also initially bipolar and has positive and negative peak values of 2.3 kV and 1.5 kV, respectively. Following the oscillations, in Figs. 11a and 11b, are lower-frequency voltage components having magnitudes of about 0.5 kV and 0.3 kV (opposite polarities, though, with respect to one another), respectively, for the remainder of each plot. The voltage across R_{L1} in the Simulated House in Fig. 11c has multiple crests separated by about 1.5 μs. The voltage across R_{L2} in Fig. 11d is similar to Fig. 11c, except having an opposite polarity, and its largest crest is 0.4 kV. Both waveforms in Figs. 11c and 11d have lower-frequency components that exhibit magnitudes of about 0.3 kV for the remainder of each plot.

Voltage between the phase and neutral of the underground cable at IS4 and voltages at the transformer secondary in IS1 are shown in Fig. 12, displayed on a 5-ms scale. The cable voltage at IS4 in Fig. 12a is the same as in Fig. 10 but shown on a longer time scale so that the waveform is seen in its entirety. The waveform exhibits a voltage-clamping plateau and an opposite polarity overshoot which are characteristic of

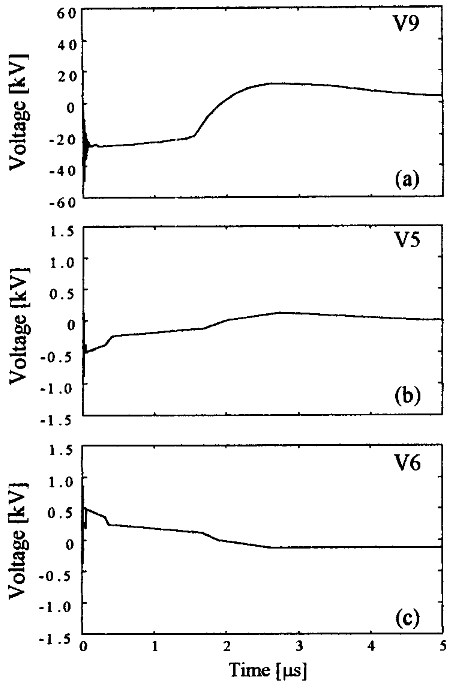

Fig. 12. Voltage versus time waveforms for the lightning of 11 August 1996, displayed on a 5-ms scale. (a) Voltage between the phase and neutral conductors of the underground cable, IS4 [V9]; (b) Voltage between X1 and X2, IS1 [V5]; (c) Voltage between X3 and X2, IS1 [V6].

MOV arrester operation [1], although no arresters are installed at IS4. The cable voltage is likely conforming to voltages imposed by arresters elsewhere in the system. In Fig. 12a, the voltage-clamping plateau is in the range from 27 kV to 21 kV for about 1.5 ms. The opposite polarity overshoot has a peak value of 12 kV and has a total duration (above zero) of over 3 ms. The secondary voltages between X1 and X2 and between X3 and X2 are shown in Figs. 12b and 12c, respectively. Although poorly resolved, the general waveshape seen in Fig. 12a is recognizable in both Figs. 12b and 12c.

5. SUMMARY

Current from the 1995 lightning strike to earth entered the test distribution system at two different connections to ground some tens of meters from the strike point. This current traveled through the overhead and underground systems via the neutral conductors. Electromagnetically induced currents were also evident on the distribution system.

The 1996 lightning struck the phase conductor of the overhead line. The bulk of the lightning current flowed to ground via an MOV arrester on the line located near the strike point. Some current traveled through the overhead system to its other grounds and into the underground system.

In both cases, the neutral conductors of the test distribution system played a significant role in directing the injected lightning current to remote grounds throughout the system. More data are needed to improve our understanding of the interaction of lightning with power distribution systems.

6. ACKNOWLEDGMENTS

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8. BIOGRAPHIES

Mark I. Fernandez received his Bachelor's degree from Florida Institute of Technology (FIT), Melbourne, in 1995, and his Master's degree from the University of Florida (UF), Gainesville, in 1997. Mr. Fernandez was involved in magnetospheric and space plasma research as an undergraduate in the Department of Physics and Space Sciences at FIT. From 1995 to 1997, he held a graduate research assistantship in the UF Lightning Research Laboratory. He is author or co-author of five publications (including two in press) in reviewed journals, eleven published abstracts or conference proceedings, and four technical reports. Mr. Fernandez is a member of the American Geophysical Union and IEEE.

Vladimir A. Rakov is Professor of the University of Florida's (UF) Department of Electrical and Computer Engineering. He is author or co-author of over 30 patents and over 160 papers and technical reports on various aspects of lightning, with over 60 papers being published in reviewed journals.

Dr. Rakov received the Master's and Ph.D. degrees from Tomsk Polytechnical University (Tomsk Polytechnic), Russia in 1977 and 1983, respectively. From 1977 to 1979 he worked as an Assistant Professor of Electrical Engineering at Tomsk Polytechnic. In 1983, he became involved in lightning research at the High Voltage Research Institute, a division of Tomsk Polytechnic, where from 1984 to 1994 he held the position of Director of the Lightning Research Laboratory. In 1985, Dr. Rakov received the rank of Senior Scientist in High Voltage Engineering. He has been named an Inventor of the USSR (1986) and received a Silver Medal from the (USSR) National Exhibition of Technological Achievements (1987). During 1988-89 he spent a 10-month sabbatical at the UF Lightning Research Laboratory. In 1991, he joined the faculty of the Department of Electrical and Computer Engineering at UF.

Dr. Rakov is a member of the American Geophysical Union (AGU), the American Meteorological Society (AMS), the AGU Committee on Atmospheric and Space Electricity (CASE), the CIGRE Working Group 33.01 "Lightning", and a Senior member of IEEE. He is Chairman of the

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Martin A. Uman is Professor and Chair of the University of Florida's Department of Electrical and Computer Engineering. Dr. Uman has written 3 books on the subject of lightning (two now in revised second editions), as well as a book on plasma physics, ten book chapters and encyclopedia articles on lightning, and has published over 130 papers in reviewed journals and over 140 articles and reports in unreviewed publications. He holds 5 patents, 4 in the area of lightning detection.

Dr. Uman received his Bachelor's, Master's and Doctoral degrees from Princeton University, the latter in 1961. He was an associate professor of electrical engineering at the University of Arizona in Tucson from 1961 to 1964. Dr. Uman joined the University of Florida faculty in 1971 after working for seven years as a Fellow Physicist at Westinghouse Research Labs in Pittsburgh. Dr. Uman co-founded and served as president of Lightning Location and Protection, Inc. (LLP) from 1975 to 1985.

Dr. Uman is the recipient of the 1996 IEEE Heinrich Hertz Medal for... "*outstanding contributions to the understanding of lightning electromagnetics and its application to lightning detection and protection.*" Dr. Uman was named the 1990 Florida Scientist of the Year by the Florida Academy of Sciences. Honored as 1988-89 University of Florida Teacher-Scholar of the Year, the highest UF faculty award, he is a Fellow in three professional organizations: the American Geophysical Union (AGU), the American Meteorological Society (AMS), and the Institute of Electrical and Electronics Engineers (IEEE). Other awards include NASA's 1992 and 1996 Group Achievement Award to the Galileo Probe Spacecraft Team.