Studies of the interaction of rocket-and-wire triggered lightning with various objects and systems (Part 1)

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Abstract. A review of experiments based on using rocket-and-wire triggered lightning and aimed at studying lightning interaction with various objects and systems is given. The test systems included overhead power distribution lines, underground cables, power transmission lines, residential buildings, and an airport runway lighting system. Additionally, briefly reviewed is the use of triggered lightning for testing components of power systems, different types of lightning rods, and other objects, as well as for measuring step voltages and for making fulgurites.

1. Introduction

An understanding of the physical properties and deleterious effects of lightning is critical to the adequate protection of power and communication lines, aircraft, spacecraft, and other objects and systems. Many aspects of lightning are not yet well understood and are in need of research that often requires the termination of lightning channel on an instrumented object or in the immediate vicinity of various sensors. The probability for a natural lightning to strike a given point on the earth's surface or an object of interest is very low, even in areas of relatively high lightning activity. Simulation of the lightning channel in a high-voltage laboratory has limited application, since it does not allow the reproduction of many lightning features important for lightning protection and it does not allow the testing of large distributed systems such as overhead power lines. One promising tool for studying both the direct and the induced effects of lightning is an artificially initiated (or triggered) lightning discharge from a thunderstorm cloud to a designated point on ground. In most respects the triggered lightning is a controllable analog of natural lightning. The most effective technique for artificial lightning initiation is the so-called rocket-and-wire technique. This technique involves the launching of a small rocket extending a thin wire (either grounded or ungrounded) into the gap between the ground and a charged cloud overhead.

In Sections 2, 3, and 4, we consider the triggered-lightning testing of overhead power distribution lines, underground cables, and power transmission lines, respectively. Lightning interaction with lightning protective systems of residential buildings and an airport runway lighting system is discussed in Sections 5 and 6, respectively. In Section 7, we briefly review the use of triggered lightning for testing components of power systems, different types of lightning rods, and other objects, and also for measuring step voltages and for making fulgurites.

2. Overhead power distribution lines

Most of the published studies concerned with the responses of power distribution lines to direct and nearby triggered-lightning strikes have been conducted in Japan and in Florida.

2.1. Nearby strikes

From 1977 to 1985, a test power distribution line at the Kahokugata site in Japan was used for studying the induced effects of close triggered-lightning strikes to ground (Horii 1982). Both negative and positive polarity flashes were triggered. The wire simulating the phase conductor was 9 m above ground, and the minimum distance between the test line and the rocket launcher was 77 m. The peak value of induced voltage was found to be linearly related to the peak value of lightning current, with 25–30 kV corresponding to a 10-kA stroke. Installation of a grounded wire 1 m above the phase conductor resulted in a reduction of the induced voltage peak by about 40%. Horii and Nakano (1995) show a photograph (their Fig. 6.4.2) of the test distribution line being struck directly during the induced-effect experiments. All triggered-lightning experiments in Japan were performed in winter.

In 1986, the University of Florida lightning research group studied the interaction of triggered lightning with an unenergized, three-phase 448-m overhead test line at the NASA Kennedy Space Center. Lightning was triggered 20 m from one end of the line, and acquired data included induced voltages on the top phase (10 m above ground) and fields at a distance of 500 m from the lightning channel (Rubinstein et al. 1994). Two types of induced-voltage waveforms were recorded: oscillatory and impulsive. The former exhibit peak values that range from tens of kilovolts to about 100 kV, while the latter show peak voltages nearly an order of magnitude larger. The oscillatory nature of the waveforms is due to multiple reflections at the ends of the line. Both types of voltage waveforms were observed to occur for different strokes within a single flash. The time domain technique of Agrawal et al.

(1980) as adopted by Master and Uman (1984), Rubinstein et al. (1989), and Georgiadis et al. (1992) was used to model the observed voltages. Some success was achieved in the modeling of the oscillatory voltage waveforms, whereas all attempts to model the impulsive waveforms failed, probably because these measurements had been affected by a flashover in the measuring system. Rubinstein et al. (1994) used only the return-stroke electric field as the source in their modeling, assuming that the contribution from the leader was negligible. In a later analysis of the same data, Rachidi et al. (1997b) found that the overall agreement between calculated and measured voltages of the oscillatory type was appreciably improved by taking into account the electric field of the dart leader.

From 1993 to 2004, studies of the interaction of triggered and natural lightning with unenergized power distribution systems were conducted at Camp Blanding, Florida. An overview of the Camp Blanding facility in 1997 is given in Fig. 1.

During the 1993 experiment at Camp Blanding, the voltages induced on the overhead distribution line shown in Fig. 1 were measured at Poles 1, 9, and 15. The line had a length of about 730 m. The distance between the line and the triggered lightning strikes was 145 m. The line was terminated at both ends with a resistance of 500 Щ, and its neutral (the bottom conductor; see Fig. 1) was grounded at Poles 1, 9, and 15. The results of this experiment have been reported by Barker et al. (1996) and are briefly reviewed next. Waveforms of the induced voltage and of the total lightning current were obtained for 63 return strokes in 30 triggered flashes. Typical induced voltage waveform at Pole 9 and corresponding lightning return stroke current waveform, are shown in Fig. 2. A strong correlation was observed between the peak values of the return-stroke current, ranging from 4 to 44 kA, and the voltage, ranging from 8 to 100 kV, induced at Pole 9, with a correlation coefficient of 0.97 (see Fig. 3). Voltages induced at the terminal poles were typically half the value of the voltage induced at Pole 9. The 1993 experiment of Barker et al. was modeled by a number of researchers, including Ren et al. (2008), Sumitani et al. (2012), and Andreotti et al. (2014).

In 1994-1997, the test distribution system at Camp Blanding shown in Fig. 1 was subjected to both direct (see Section 2.2) and nearby triggered-lightning strikes. A large number of system configurations were tested, and several important results were obtained. It was observed, for example, that when lightning strikes earth at tens of meters from the system's grounds, an appreciable fraction of the total lightning current enters the system from earth (Fernandez 1997; Fernandez et al. 1998a,b). The observed peak values of current entering the system from earth, in percent of the total lightning current peak, were (for three different events) 10% at 60 m (see Fig. 4), 5% at 40 m, and 18% at 19 m from the ground strike point. These observations have important implications for modeling of lightning-induced effects on power lines.

Additional, more detailed data on lightning currents entering the system from earth, obtained at Camp Blanding in 2003, are presented by Schoene et al. (2009). Triggered-lightning current was injected into the earth a distance of 11 m from one of the termination poles of an unenergized three-phase, 15-pole test power distribution line (see Vertical Configuration Distribution Line in Fig. 5). The line

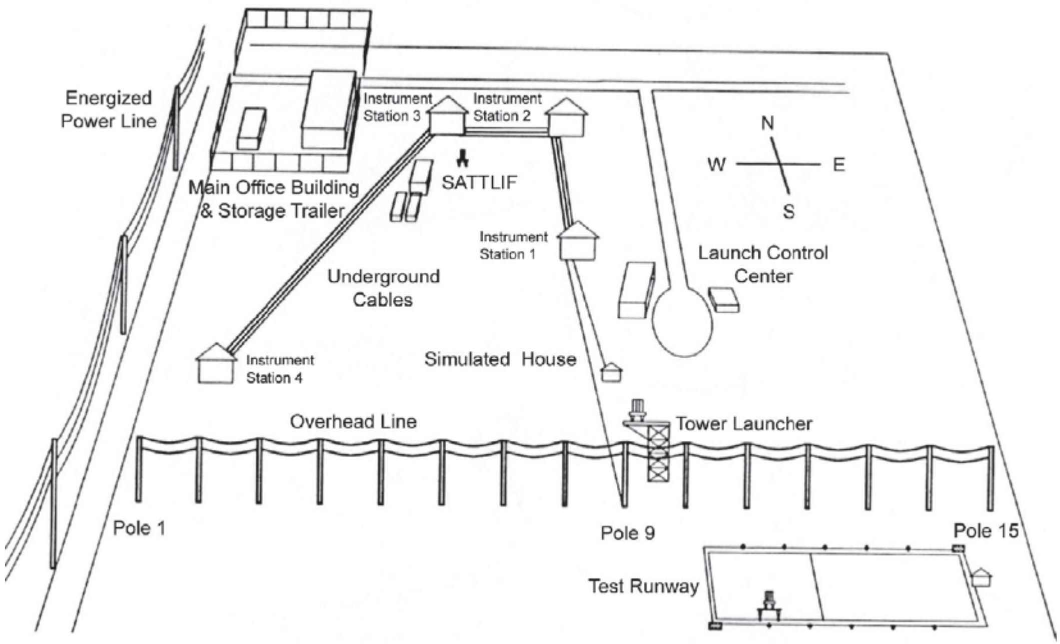

Fig. 1. Overview of the lightning triggering facility at Camp Blanding, Florida, 1997. Artwork by C.T. Mata

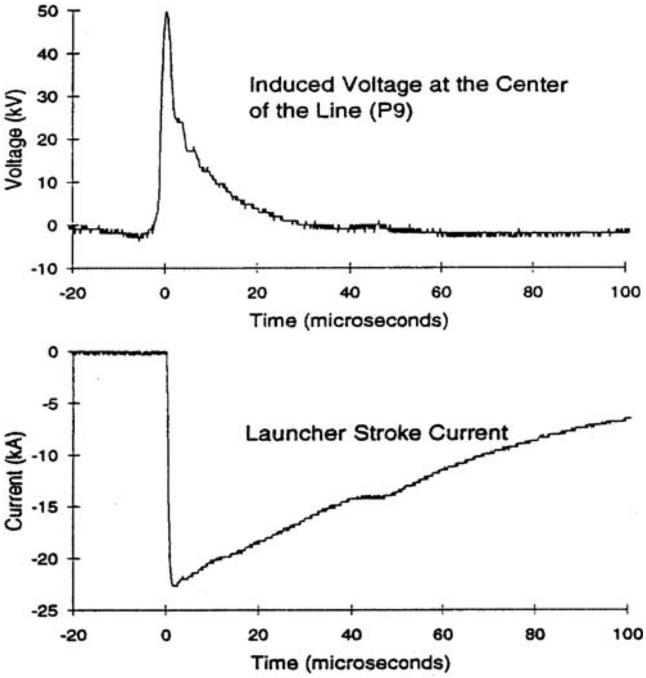

Fig. 2. Typical induced voltage at Pole 9 and corresponding lightning return stroke current (flash 93-05) reported by Barker et al. (1996)

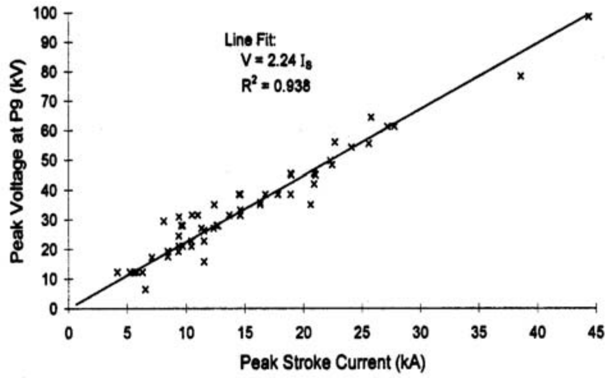

Fig. 3. Peak induced voltage (8 to 100 kV) at Pole 9 vs. return-stroke peak current (4 to 44 kA), *N*=63, reported by Barker et al. (1996)

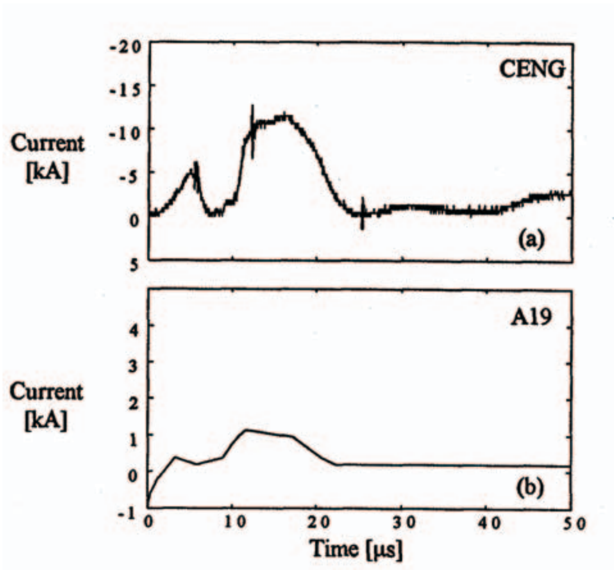

Fig. 4. Current versus time waveforms for Camp Blanding flash 9516, displayed on a 50-мs scale, illustrating injection of lightning current into the system from earth. (a) Total lightning current at the CENG launcher; (b) Ground-rod current, A19, measured 60 m from the lightning strike point. Adapted from Rakov et al. (2003a)

was 812 m long, was equipped with four arrester stations, at poles 2, 6, 10, and 14, and was terminated in its characteristic impedance at poles 1 and 15. The neutral conductor of the line was grounded at each arrester station and at both line terminations. All pole grounds were instrumented. Measurements suggest that a significant fraction of the lightning current injected into the earth a distance of 11 m from pole 15 entered the line through the grounding system of pole 15. The peak value of the microsecond-scale return stroke current entering the line through the pole 15 line ground was 7% of the peak value of the return stroke current injected into the earth. The peak value of the millisecond-scale triggered lightning initial stage current and the millisecond-scale return-stroke and initial-stage charge transfer to the line through the pole 15 line ground was between 12% and 19% of the lightning peak current/charge transfer. This indicates that the percentage values for the injected peak currents are dependent on the current waveshape: for microsecond-scale return stroke currents, possibly due to electromagnetic coupling effects, a smaller fraction of the current peak enters the line via the grounding system compared to millisecond-scale initial stage currents. In the latter case, any influence of electromagnetic coupling to the line on ground currents is expected to be negligible. The effect of lightning current entering the test power line via its grounding system was modeled by Napolitano et al. (2011).

Paolone et al. (2009) modeled responses of the Vertical Configuration Distribution Line (see Fig. 5) to triggered lightning striking ground at a distance of 15 m from pole 4.

2.2. Direct strikes

As noted above, various configurations of unenergized distribution system at Camp Blanding (see Fig. 1) were tested in 1994-1997. In 1996, the responses of MOV arresters in the system, composed of an overhead line, underground cable, and padmount transformer with a resistive load, were measured during direct lightning strikes to the overhead line. Arresters were installed on the overhead line at two locations 50 m apart (on either side of the strike point) and at the primary of the padmount transformer which was connected to the line via the underground cable. Simultaneously-recorded arrester discharge current and voltage waveforms were obtained. Additionally, the energy absorbed by an arrester on the line as a function of time for the first 4 ms for one lightning event was

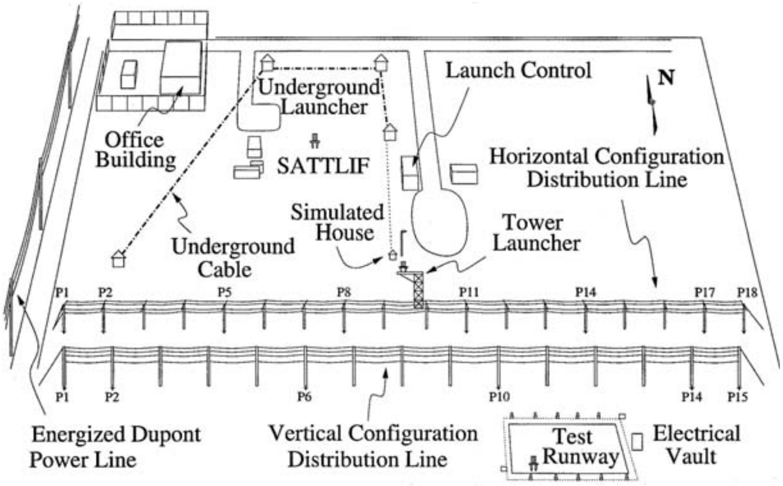

Fig. 5. Overview of the lightning triggering facility at Camp Blanding, Florida, 2000-2003

estimated. The total energy absorbed by the arrester was 25 kJ (about 60% of its maximum energy capability). The energy absorbed during the initial 200 мs was about 8 kJ.

More details on findings from the 1994-1997 experiments at Camp Blanding are found in Uman et al. (1997), Fernandez (1997), Fernandez et al. (1998c, 1999), and Mata et al. (2000).

Presented below are results of triggered-lightning experiments conducted in 2000, 2001, and 2002 at Camp Blanding, Florida, to study the responses of four-conductor (three-phase plus neutral) overhead distribution lines (see Fig. 5) to direct lightning strikes. Presented first are direct-strike results for the line with horizontally-configured phase conductors obtained in 2000 and then for the line with vertically-configured phase conductors obtained in 2001 and 2002. The lines were not energized.

Horizontal Configuration Distribution Line

The horizontal configuration, 856-m line was subjected to eight lightning flashes containing return strokes between July 11 and August 6, 2000 (Mata et al., 2003). The line was additionally subjected to two flashes without return strokes that are not considered here. The lightning current was injected into the phase C conductor in the middle of the line. Six of the eight flashes with return strokes produced damage to the phase C arrester at pole 8. Of the two that did not, one had a triggering wire over the line and the other produced a flashover at the current injection point. The eight triggered flashes contained 34 recorded return strokes. These return strokes were characterized by submicrosecond current risetimes and by peak currents having geometric and arithmetic means between 15 and 20 kA with a maximum peak current of 57 kA. Each triggered flash also contained an initial continuous current of the order of hundreds of amperes, which flowed for a time of the order of hundreds of milliseconds, and some flashes contained a similar continuing current after subsequent strokes. A total of six three-phase sets of arresters were installed on the line, at poles 2, 5, 8, 11, 14, and 17, the arresters being connected between the phase conductors and the neutral conductor. The neutral of the line was grounded at these poles and at the two line-terminating poles, 1 and 18. The 856-m three-phase line was terminated at each end in an impedance of about 500 Щ. The distance between poles of the line varied from 47 to 73 m.

The focus of the study was on the paths of return stroke current and charge transfer from the current injection point on one phase, C, between poles 9 and 10, to the eight grounds. This current division was examined in detail only for flash 0036, for which an initial continuous current and currents of 5 return strokes were injected into phase C between poles 9 and 10 prior to the arrester failure at pole 8. As an example, Fig. 6 shows a drawing depicting the division of the incident current for the first stroke of flash 0036. This stroke had a peak current of about 26 kA. Note that the arrester current at pole 8 was lost due to instrumentation (fiber optic link) malfunction, but it likely was similar to the arrester current at pole 11, given the symmetry of the other currents on the line. Also, current through the terminating resistor at pole 18 was not measured.

Fig. 7a shows the arrester and terminating-resistor peak currents recorded for all five strokes of flash 0036, while Fig. 7b gives the peak currents entering all eight pole grounds for the five return strokes. It is evident from Figs. 6 and 7 that the bulk of the peak current injected into phase C passed through the arrester at pole 11, and by inference at pole 8, and also went to ground mostly at poles 8 and 11.

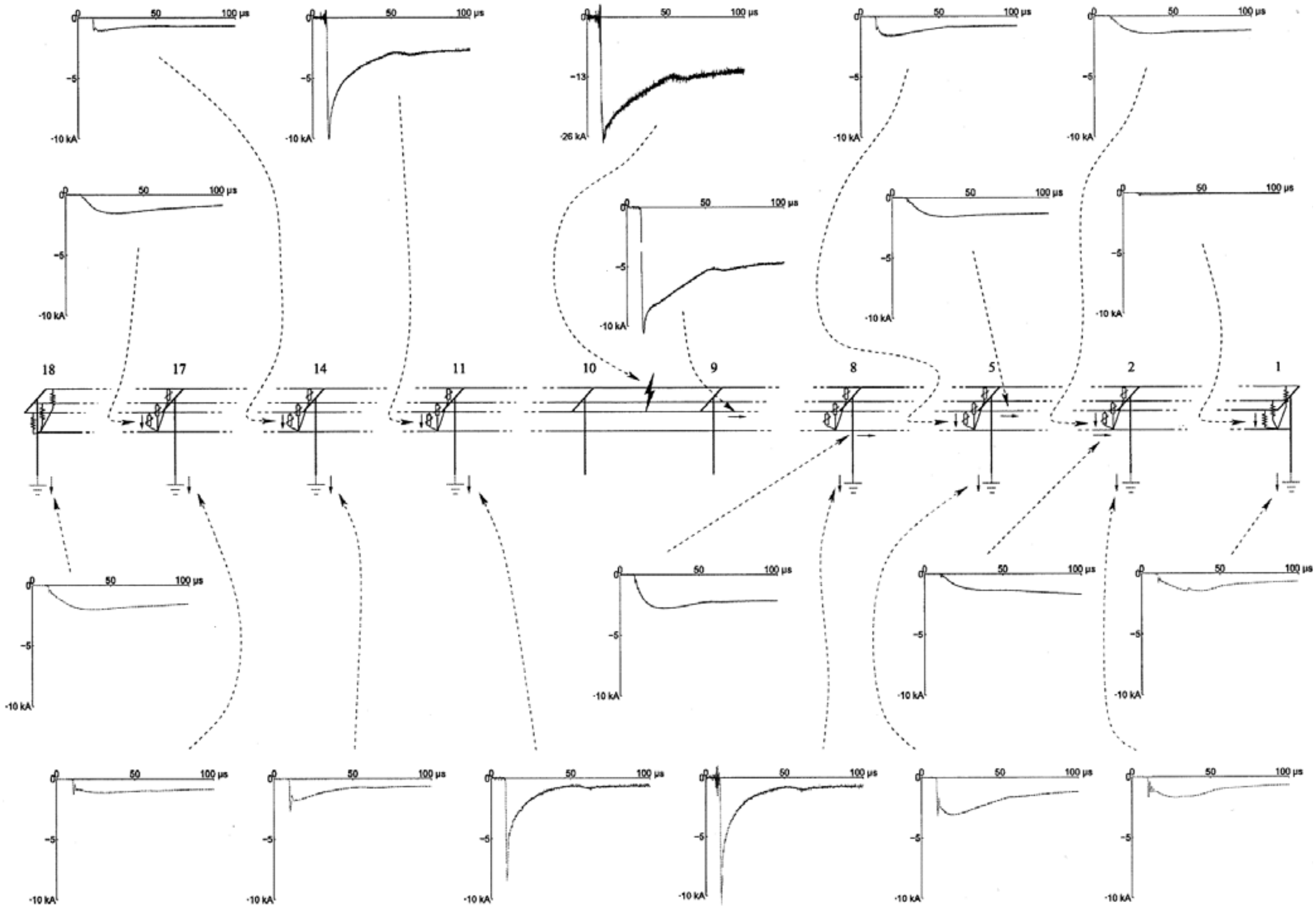

Fig. 6. Horizontal configuration distribution line experiment. Current distribution for flash 0036, stroke 1, reported by Mata et al. (2003)

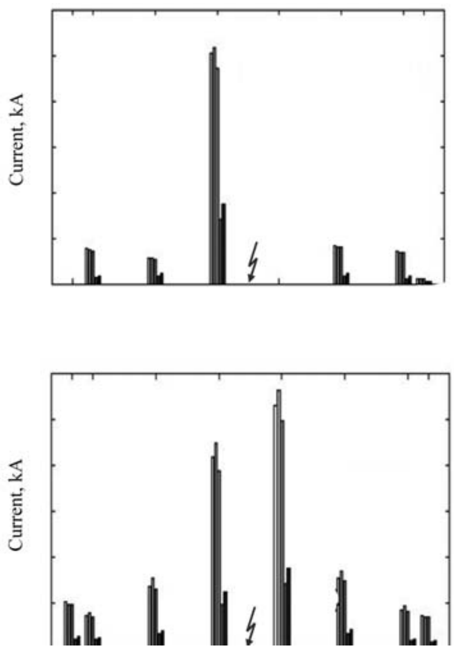

Fig. 7. Horizontal configuration distribution line experiment. (a) Measured peak currents through arresters and terminating resistor at pole 1 for strokes 1 through 5 (in ascending order from left to right) of flash 0036. Arrester currents at pole 8 were lost due to instrumentation malfunction. Currents through the terminating resistor at pole 18 were not measured. (b) Measured peak currents to ground for strokes 1 through 5 (in ascending order from left to right) of flash 0036. Adapted from Mata et al. (2003)

Fig. 6 shows current waveforms only to 100 мs, although the total duration of current records is 10 ms. Fig. 8a shows percentages of charge transfer through arresters and terminating resistor at pole 1, and Fig. 8b percentages of charge transfer through ground rods, at 100 мs, 500 мs, and 1 ms.

It is clear from Fig. 6, an observation also illustrated in Fig. 8b, that after 25 мs or so the current from the neutral to ground no longer flows primarily through the grounds closest to the strike point but is more uniformly distributed among the eight grounds. In fact, the currents after 25 мs are distributed roughly inversely to the measured low frequency, low current grounding resistance. Fig. 8b shows that the percentage of charge transferred to a given ground rod in the first 100 мs is not much different from that transferred in the first millisecond.

As seen in Fig. 6, there are considerable differences among the waveshapes of currents measured in different parts of the test system. As a result, the division of peak current to ground (Fig. 7b) is very different from the division of associated charge transfer (Fig. 8b). It appears that the higher-frequency current components that are associated with the formation of initial current peak tend to flow from the struck phase

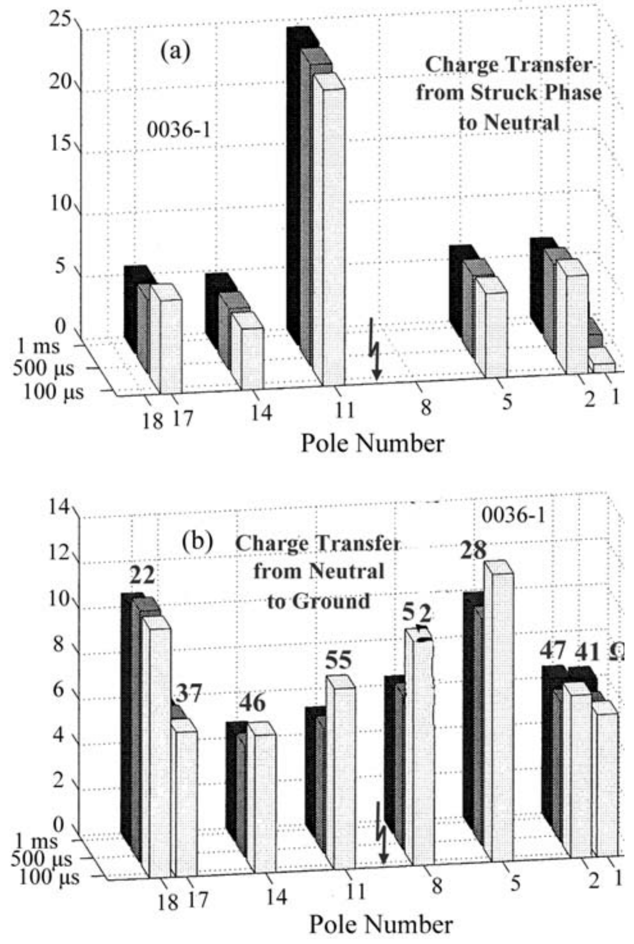

Fig. 8. Horizontal configuration distribution line experiment. (*a*) Percentage of total charge transferred through phase C arresters at different poles and terminating resistor at pole 1, calculated at three different instants of time (100 мs, 500 мs, and 1 ms from the beginning of the return stroke) for stroke 1 of flash 0036. No measurements are available at pole 8 and pole 18. (*b*) Percentage of total charge transferred to ground at different poles, calculated at three different instants of time (100 мs, 500 мs, and 1 ms from the beginning of the return stroke) for stroke 1 of flash 0036. Low frequency, low current grounding resistance values of the poles are indicated in (b). Adapted from Mata et al. (2003)

to ground through the arresters and ground rods at the two poles closest to the current injection point. The low-frequency, low-current grounding resistances of the ground rods apparently have little or no effect on determining the paths for these current components. The lower-frequency current components that are associated with the tail of current waveforms are distributed more evenly among the multiple ground rods of the test system and appear to be significantly influenced by the low-frequency, low-current grounding resistances of the ground rods. In fact, the distribution of charge transfer in Fig. 8b is very similar to the distribution of the inverse of the low-frequency, low-current grounding resistances of the ground rods, with poles 5 and 18 having the largest charge transfer and the lowest grounding resistances. Since the current waveshapes may differ considerably throughout the system, charge transfer is apparently a better quantity than the peak current for studying the division of lightning current among the various paths in the system.

Vertical Configuration Distribution Line

The vertical configuration, 812-m line was subjected to four lightning flashes containing return strokes (also to four flashes without return strokes) between July 26 and September 5, 2001 and to ten flashes with return strokes between June 27 and September 13, 2002 (Mata et al. 2001, 2002). In 2001, return-stroke peak currents ranged from 6 to 28 kA and in 2002 from 6 to 34 kA. Arresters were installed at poles 2, 6, 10, and 14. Lightning current was injected into the top conductor near the center of the line.

In 2001, for one of the flashes having return strokes, an arrester failed early in the flash, probably during the initial stage. The three other flashes with return strokes were triggered with failed arresters already on the line. Two flashes without return strokes did not damage arresters. One flash with return strokes was triggered when the line contained two damaged arresters, resulting in the failure of a third arrester.

In 2002, in order to reduce arrester damage during the initial stage of rocket-triggered lightning, a different configuration of the tower launching system was used. This new configuration allowed the diversion of most of the initial-stage current to ground at the tower base. Additionally, two arresters were installed in parallel on the struck (top) phase conductor. In 2002, arresters failed on three storm days out of a total of five (60%), compared with two out of three storm days (67%) in 2001. Flashovers on the line were very frequent during the direct strike tests. Significant currents were detected in phase B, which was not directly struck by lightning, with the waveshape of phase B currents being similar to that of the corresponding current in phase A that was directly struck.

Overall, the results presented in this section suggest that many direct lightning strikes to power distribution lines are capable of damaging MOV arresters, unless alternative current paths (flashovers, transformers, underground cable connections, etc.) are available to allow the lightning current to bypass the arrester.

In 2003, the vertical configuration line was equipped with a pole-mounted transformer, With the transformer on the line, the bulk of the return-stroke current injected into the line after about 1 ms flowed from the struck phase to the neutral through the transformer primary protected by an MOV arrester. Very little lightning current was passing through the transformer primary during the first few hundred microseconds.

To be continued in № 6/2014.

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Исследование взаимодействия молнии, инициированной запуском ракет с тросом, с различными объектами и системами (Часть 1)

РАКОВ В.А.

Статья содержит обзор экспериментальных результатов по действию молниевого разряда, инициированного запуском в грозовое облако ракеты с длинным проводящим шлейфом, на различные объекты и системы. В качестве объектов, находящихся под действием молниевого разряда, рассматриваются воздушные распределительные сети, подземные кабели, ЛЭП, жилые здания и светосигнальные системы взлетно-посадочных полос аэропортов. Дополнительно дается краткий обзор использования инициированного молниевого разряда для тестирования компонентов систем питания, различных типов молниеотводов и других объектов, а также для измерений шагового напряжения и исследований фульгуритов.

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