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ROCKET-TRIGGERED LIGHTNING EXPERIMENTS AT CAMP BLANDING, FLORIDA

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1. Introduction

Many aspects of the interaction of lightning with power systems are not yet well understood and are in need of research that requires the termination of the lightning channel on or in the immediate vicinity of the power system. The probability for a natural lightning to strike a given point of interest on the Earth's surface is very low, even in areas of relatively high lightning activity. The simulation of lightning in a high-voltage laboratory has limited application in that it does not allow the proper testing of large distributed systems such as power lines since the laboratory current path is different from that of lightning and since the laboratory discharge does not produce lightning-like electric and magnetic fields. The most promising tool for studying both the direct and the induced effects of lightning on power systems is artificially initiated (triggered) lightning that is stimulated to occur between an overhead thundercloud and a designated point on the power system or on nearby ground The lightning triggering techniques and various lightning discharge processes involved are outlined in Section 2. A relatively new facility for triggered-lightning experiments is the International Center for Lightning Research and Testing at Camp Blanding, Florida, located about 40 km north-east of Gainesville and described in Section 3. The facility was constructed in 1993 by Power Technologies, Inc. (PTI) under the funding and direction of the Electric Power Research Institute (EPRI), and has been operated by the University of Florida (UF) since Fall 1994. In Section 4 we give some examples of the results of the studies conducted there. Additional information on the triggered-lightning studies at Camp Blanding can be found in Uman et al. (1994a,b, 1996a,b, 1997), Rakov et al. (1995a,b, 1996a,b, 1998), Ben Rhouma et al. (1995), Barker et al. (1996), Fernandez (1997), Fernandez et al. (1998a,b,c,d), Wang et al. (1999a,b,c,d), Crawford (1998), and Crawford et al. (1999).

2. Lightning triggering techniques

The most effective technique for triggering lightning involves launching a small rocket trailing a thin grounded wire toward a charged cloud overhead. This triggering method is sometimes called "classical" triggering and is illustrated in Fig. 1. The cloud charge is indirectly sensed by measuring the electric field at ground, with values of 4 to 10 kV/m generally being good indicators of favorable conditions for lightning initiation. When the rocket, ascending at about 200 m/s, is about 200 to 300 m high, the field enhancement near the rocket tip launches a positively charged (for the common summer thunderstorm having predominantly negative charge at 5 to 7 km altitude) leader that propagates upward toward the cloud. This leader vaporizes the trailing wire and initiates a so-called "initial continuous current" of the order of several hundred amperes that effectively transports negative charge from the cloud charge source via the wire trace to the instrumented triggering facility. There often follows, after the cessation of the initial continuous current, several downward dart leader/upward return stroke sequences traversing the same path to the triggering facility. The dart leaders and following return strokes in triggered lightning are similar if not identical to dart leader/return stroke sequences in natural lightning, although the initial processes in natural and classical triggered lightning are distinctly different. The reproduction of the initial processes in natural lightning can be accomplished using a triggering wire not attached to the ground. This ungrounded-wire technique is called "altitude" triggering and is illustrated in Fig. 2 which shows that a bi-directional (positive charge up and negative charge down) leader process is involved in the initiation of the first return stroke. Properties of altitude triggered lightning are discussed by Laroche et al. (1991), Lalande et al. (1996, 1998), Uman et al. (1996a), and Rakov et al. (1996b, 1998).

3. The Camp Blanding lightning triggering facility

The Camp Blanding lightning triggering site (see Fig. 3), called the International Center for Lightning Research and Testing (ICLRT), occupies a flat, open field with dimension of approximately 1 km by 1 km and since Fall 1994 has been operated under an agreement between the University of Florida and the Camp Blanding Florida Army National Guard Base. The site includes a 0.8 km test underground power cable, a 0.7 km test overhead power line, four instrumentation stations, IS1, IS2, IS3, and IS4, located along the underground cable and containing padmount transformers, a simulated house fed by one of the transformers, a test runway with operational lighting system, a number of other test structures, including a lightning protected shelter, two launch control complexes, a number of rocket launchers, an office building, and storage facilities. The existing elements of the power system (overhead line and underground cable), presently unenergized, can be connected in a variety of configurations. The facility allows the measurement of the total lightning current injected into the power system's conductors or to nearby ground and the monitoring of voltages and currents at various points of the system. Electric and magnetic field measurements, video recording, and still and high-speed photography are also performed, making the Center a unique facility for studying simultaneously and synergistically various aspects of atmospheric electricity, lightning, and lightning protection. Examples of still photographs of lightning flashes triggered at Camp Blanding, Florida, are shown in Fig. 4. During summers 1995 through 1998 over 30 scientists and engineers (excluding UF faculty, students, and staff) from 13 countries representing 4 continents performed experiments at the Center.

4. Results

The results of triggered-lightning studies provide new insights into the physics of the lightning discharge and the mechanisms of lightning interaction with various objects and systems. Some examples are presented in Sections 4.1 through 4.3.

4.1. Close lightning electric fields

Characterization of the close lightning electromagnetic environment is needed for the evaluation of lightning induced effects and for the validation of various models of the lightning discharges.

4.1.1. Electric field waveshapes. Leader/return stroke vertical electric field waveforms appear as asymmetrical V-shaped pulses, the bottom of the V being associated with the transition from the leader (the leading edge of the pulse) to the return stroke (the trailing edge of the pulse), as described, from earlier Kennedy Space Center (KSC) measurements, by Rubinstein et al. (1995). Examples of leader/return stroke electric fields simultaneously measured at 30, 50, and 110 m from the 1993 Camp Blanding experiment are shown in Figs. 5 and 6. From the 1993 experiment the geometric mean width of the V at half of peak value is 3.2 ?s at 30 m, 7.3 ?s at 50 m, and 13 ?s at 110 m, a distance dependence close to linear. This waveshape characteristic can be viewed as a measure of the closeness of the leader electric field rate of change to that of the following return stroke. As seen in Fig. 5, at 30 m the rate of change of leader electric field near the bottom of the V can be comparable to that of the return stroke field, while at 110 m the two rates differ considerably, with the leader rate of change being appreciably less. This observation, in conjunction with the fact that within some hundreds of meters the leader and return stroke electric field changes are about the same in magnitude (Uman et al. 1994a, Rakov et al. 1998) (see also Figs. 5 and 6), suggests that induced voltages and currents on power and other systems from very close (a few tens of meters or less) lightning subsequent strokes can contain an appreciable component due to the leader.

4.1.2. Leader electric field versus distance. From measurements at 30, 50, and 110 m at Camp Blanding in 1993 (Uman et al. 1994a, Rakov et al. 1998) the variation of the leader electric field change with distance was observed to be somewhat slower than the inverse proportionality theoretically predicted by using a uniformly-charged leader model by Rubinstein et al. (1995). The uniformly charged leader model, although clearly a crude approximation, is supported by experimental data, as explained next. Thottappillil et al. (1997) showed that the modified transmission line return stroke model with linear current decay with height (MTLL), developed using the assumption that there exists a uniform distribution of leader charge along the channel, predicts a ratio (R) of leader to return stroke electric field between +0.81 and +0.97 at distances between 20 and 50 km, assuming a total channel length of 7.5 km (see their Table 2). These values of R are consistent with the mean value of R = +0.8 determined experimentally (97 measurements) for this distance range by Beasley et al. (1982, Fig. 23d). On the other hand, the return stroke model that is derived assuming that there exists a distribution of leader charge exponentially decreasing with height (MTLE) predicts values of R between +2.6 and +3.0 (see Thottappillil et al. 1997, Table 2), while the lightning model that is derived assuming that there exists a vertically symmetrical bidirectional leader process (positively charged part propagating upward and negatively charged downward) predicts values of R approximately between +0.2 and +0.3 (see Mazur and Ruhnke 1993, Fig. 25), in both cases inconsistent with the experimental data of Beasley et al. (1982). From the 1993 Camp Blanding experiment, individual leader electric field changes for six strokes, simultaneously recorded at the three distances, are given in Table 1. Arithmetic mean values of the leader electric field changes for the six events in Table 1 are 25, 21, and 16 kV/m at 30, 50, and 110 m, respectively. Using the 50-m value, 21 kV/m, as a reference and assuming an inverse distance dependence, we estimate values of 35 (versus 25) and 10 (versus 16) kV/m at 30 and 110 m, respectively. A relative insensitivity of the leader electric field change to distance was also observed from measurements at 10 and 20 m at Fort McClellan, Alabama (Fisher et al. 1994). An electric field versus distance dependence that is slower than an inverse proportionality, observed within 110 m of the channel, is consistent with a decrease of line charge density with decreasing height near the bottom of the channel. Such a leader charge distribution near ground might be due to the incomplete development there of the radially formed corona sheath that surrounds the channel core and presumably contains most of the leader charge. Some support for this speculation comes from the observation that the propagation speeds of radial corona streamers from conductors subjected to negative high voltage in the laboratory are about 105 m/s (0.1 m/?s) (Cooray 1993), so some microseconds are required for the development of a corona sheath with a radius of the order of meters. Since for dart leaders the downward propagation speeds (107 m/s) are about 2 orders of magnitude higher than the radial-streamer speeds, the delay in corona-sheath formation may be appreciable. On the other hand, Depasse (1994) observed, from triggered-lightning experiments in France, that seven simultaneously measured vertical electric fields due to return strokes at 50 and 77 m, expected to be approximately equal in magnitude to the fields due to the corresponding leaders (Uman et al. 1994a, Rakov et al. 1998) (see also Figs. 5 and 6), exhibited an inverse distance dependence, consistent with a uniform distribution of charge density along the channel. Further, electric field measurements at six distances ranging from 10 to 500 m at Camp Blanding in 1997 suggest that leader field change varies approximately inversely proportional to distance (Crawford et al. 1999). Additional multiple-station data and modeling are needed to interpret the observed variations of leader field change with distance. It is worth noting that, as shown by Rubinstein et al. (1995) based on a uniformly charged leader model, the presence of a triggering structure of about 5 m has a very small effect on the leader field at distances of 30 m and greater. They computed an error of about 1% at 30 m, with fields at greater distances being even less sensitive to the presence of the triggering structure.

4.2. Lightning channel termination on ground

In examining the lightning current flowing from the bottom of the channel into the ground, it is convenient to approximate lightning by a Norton equivalent circuit (Carlson 1996), i.e., by a current source equal to the lightning current that would be injected into the ground if that ground were perfectly conducting (the short-circuit current) in parallel with a lightning-channel equivalent impedance Zch assumed to be constant. The lightning grounding impedance Zgr is a load connected in parallel with the lightning Norton equivalent. Thus the "short-circuit" lightning current Isc effectively splits between Zgr and Zch so the current measured at the lightning-channel base is found as Imeas = IscZch/(Zch + Zgr). Both source characteristics, Isc and Zch, vary from stroke to stroke, and Zch is a function of channel current, the latter nonlinearity being in violation of the linearity requirement necessary for obtaining the Norton equivalent circuit. Nevertheless, if we are concerned only with the peak value of current and assume that for a large number of strokes the average peak value of Isc and the average value of Zch at current peak are more or less constant, the Norton equivalent becomes a useful tool for studying the relation between lightning current peak and the corresponding values of Zch and Zgr. For instance, if the measured channel-base current peak statistics are similar under a variety of grounding conditions, then Zgr must always be much lower than Zch at the time of the current peak.
Camp Blanding measurements of lightning currents that entered sandy soil with a relatively poor conductivity of 2.5 x 10-4 S/m without any grounding electrode resulted in a value of the geometric mean return-stroke peak current, 13 kA, that is similar to the geometric mean value, 14 kA, from measurements at KSC made using a launcher of the same geometry which was much better grounded into salt water with a conductivity of 3-6 S/m via underwater braided metallic cables. Additionally, a fairly similar geometric mean value, about 10 kA, of return stroke current peak was found from KSC measurements using a well-grounded ground-based launcher of significantly greater height, and fairly similar geometric mean values were found from the Fort McClellan measurements using a relatively small-height, poorly grounded launcher (10 kA) and the same launcher well grounded (11 kA). Additionally, Ben Rhouma et al. (1995) give arithmetic mean values of return stroke current peaks in the range from 15 to 16 kA for the triggered-lightning experiments at Camp Blanding in 1993 and at KSC in 1987, 1989, and 1991. The geometric mean values of peak current indicated above along with other pertinent information on the measurements are summarized in Table 2. The values of grounding resistance (probably the dominant component of Zgr) given in Table 2 should be understood as the initial values encountered by lightning before the onset of any breakdown processes in the soil or along the ground surface. Note from Table 2 that the grounding resistance varies from 0.1 ? to 64 k?, while Zch was estimated from the analysis of the current waves traveling along the 540-m high tower to be in the range from hundreds of ohms to several kiloohms (Gorin et al. 1977; Gorin and Shkilev 1984). The observation that the average return stroke current is not much influenced by the level of man-made grounding, ranging from excellent to none, implies that lightning is capable of lowering its grounding impedance to a value that is always much lower than the equivalent impedance of the main channel. On the basis of the evidence of the formation of plasma channels (fulgurites) in the sandy soil at Camp Blanding (Uman et al. 1994b, 1997) and on optical records showing arcing along the ground at Camp Blanding and at Fort McClellan, Alabama (see Fig. 7), we infer that surface and underground plasma channels are the principal means of lowering the lightning grounding impedance, at least for the types of soil at the lightning triggering sites in Florida and Alabama. Injection of laboratory currents up to 20 kA into loamy sand in the presence of water sprays imitating rain resulted in surface arcing that significantly reduced the grounding resistance at the current peak (M. Darveniza, personal communication, 1995). The fulgurites found at Camp Blanding usually show that the in-soil plasma channels develop toward the better conducting layers of soil or toward buried metallic objects that, when contacted, serve to further lower the grounding resistance. The percentages of return strokes producing optically detectable surface arcing versus return stroke peak current, from the 1993 and 1995 experiments at Fort McClellan,

Alabama, are shown in Fig. 8. The surface arcing appears to be random in direction and often leaves little if any evidence on the ground. Even within the same flash, individual strokes can produce arcs developing in different directions. In one case it was possible to estimate the current carried by one arc branch which contacted the instrumentation: approximately 1 kA or 5% of the total current peak in that stroke (Fisher et al. 1994). The observed horizontal extent of surface arcs was up to 20 m, which was the limit of photographic coverage during the 1993 Fort McClellan experiment. No fulgurites were found in the soil (red clay) at Fort McClellan, only concentrated current exit points at several spots along the 0.3- or 1.3-m steel earthing rod (see Table 2). It is likely that uniform ionization of soil, usually postulated in studies of the behavior of grounding electrodes subjected to lightning surges, is not a valid assumption, at least in the southeastern United States, where distinct plasma channels in the soil and on the ground surface appear to be the principal means of lowering the grounding resistance.

4.3. Testing of MOV arresters

One of the projects at Camp Blanding in 1996 was concerned with the performance of 10 kV MOV arresters. Given below are selected results, taken from Fernandez et al. (1998b), for one negative lightning stroke in Flash 9632 whose current was directed to the phase conductor of the overhead line between Poles 9 and 10 (see Fig. 3) which were separated by about 50 m. The test power distribution system was configured so that the underground cable was connected to the overhead line at pole 9, as shown in Fig. 3. The transformer in IS1 was connected to the cable, and the simulated house service entrance was attached to the secondary of the transformer. MOV arresters were installed at the transformer primary (Cooper elbow arrester) and at Poles 9 and 10 (GE Tranquell arresters). Additionally, there were MOV surge protective devices (SPDs) installed at the service entrance of the simulated house. The neutral conductors were grounded at each arrester, at the terminal poles, at the service entrance, and at IS4.

The waveform of the arrester voltage at Pole 9 for Flash 9632 is shown in Fig. 9 along with the total lightning current (recorded in the channel having +/- 7.5 kA measurement range in order to resolve the structure of relatively low level current after the initial peak). The lightning current peak was about 12 kA, typical of subsequent strokes in natural lightning. First strokes in natural lightning have current peaks two to three times larger. The waveforms in Fig. 9 are displayed on a 10-ms time scale. The discharge current of the arrester is not shown because it has insufficient amplitude resolution after some hundreds of microseconds.

After the initial spike (probably associated with both the arrester lead inductance and magnetic coupling to the voltage measuring circuit), the voltage waveform in Fig. 9b is clamped near 20 kV for about 4 ms, then begins to return to zero. The falling trend of the waveform is interrupted, and the voltage exhibits a hump with amplitude of about 3 kV. (A similar feature is also seen in the waveform of the total lightning current in Fig. 9a). After the hump, the voltage further decreases, crosses zero, and produces an opposite polarity overshoot lasting several milliseconds. The overshoot has peak value of about 8 kV.

At 200 ?s, the arrester discharge current is about one-half of the total lightning current. Thus, if we assume that the same fraction (one-half) of the lightning current in Fig. 9a is flowing through the arrester at Pole 9 after 200 ?s and is causing the voltage response in Fig. 9b, we can estimate the energy absorption by the arrester at Pole 9 as a function of time, shown in Fig. 10. As seen in Fig. 10, the energy absorbed during the initial 200 ?s is about 8 kJ or about one-third of the total energy of 25 kJ absorbed during the voltage-clamping stage of the arrester operation lasting 4 ms or so.

For GE Tranquell MOV arresters, the maximum energy capability is 4.0 kJ/kV of rating (Greenwood, 1991) or 40 kJ for this case. Therefore, during the first 4 ms of the event considered here, the arrester was subjected to about 60% of its maximum energy capability. Video and photographic records, along with visual inspection, indicate that physical damage was not sustained to any of the MOV arresters as a result of this test. Barker et al. (1993), who measured voltages across and currents through 10 kV MOV arresters installed in actual four-wire multi-grounded power distribution systems, estimated the dissipated energy for one negative lightning event to be in excess of 80 kJ. Although this energy value exceeded the maximum energy capability of the arrester, the arrester did not fail. The measured lightning current through the arrester exhibited a slow tail lasting for about 2 ms at an average level of about 2 kA, and the bulk of the dissipated energy was associated with this tail.

5. Summary

1. Rocket-triggered lightning appears to be in many respects a controlled analog of natural lightning. The results of triggered-lightning studies provide new insights into both the physics of the lightning discharge and lightning interaction with various objects and systems.

2. At very close ranges (a few tens of meters or less) the time rate of change of the final portion of the dart leader electric field can be comparable to that of the return stroke. This observation, coupled with the fact that within some hundreds of meters the leader and return stroke electric fields are about equal in magnitude, suggests that very close dart leaders can make a significant contribution to induced voltages and currents in power and other systems.

3. The variation of the close dart leader electric field change with distance can be somewhat slower than the inverse proportionality predicted by the uniformly charged leader model, perhaps due to a decrease of leader charge density with decreasing height associated with an incomplete development of the corona sheath at the bottom of the channel. However, the bulk of the presently available data on leader electric field changes within 500 m suggests a more or less uniform distribution of charge along the leader channel. More data and modeling are needed to interpret the observed variations of leader field change with distance.

4. Judging from the similar average current peak values in dissimilar grounding situations, lightning appears to be able to reduce the grounding impedance which it initially encounters at the strike point so that at the time of channel-base current peak the reduced grounding impedance is always (regardless of the initial grounding impedance) much lower than the equivalent impedance of the channel (hundreds of ohms to several kiloohms). Breakdown processes forming distinct plasma channels in the soil and on the ground surface are probably the principal means of lowering the grounding impedance, at least in the case of poorly conducting (of the order of 10-3 - 10-4 S/m) sandy and clay soils.

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