Measurement of the Division of Lightning Return Stroke Current Among the Multiple Arresters and Grounds of a Power Distribution Line

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Abstract—A triggered-lightning experiment was conducted during Summer 2000 at the International Center for Lightning Research and Testing (ICLRT) in north-central Florida for the purpose of studying the lightning current division in an 829-m-long, 18-pole, three-phase plus neutral, unenergized, overhead distribution line equipped with six arrester stations. Eight lightning flashes containing a total of 34 recorded return strokes, as well as low amplitude, long duration steady currents, were artificially initiated (triggered) from natural thunderclouds using the rocket-and-wire technique, and the flash currents were directed to phase C (one of the two outer conductors of the three-phase cross-arm-configured line). Six of the eight triggered lightning flashes caused damage to one of the two closest phase C arresters. In the case when no arrester was damaged or was not yet damaged by current in the flash, it is inferred that about 40% of the return stroke peak current and about 25% or more of the return stroke charge transferred in the first millisecond passed to the neutral conductor through each of the two closest arresters located about 70 m away on either side of the strike point. The bulk of the peak current then flowed from the neutral conductor to ground through the groundings of the two closest arresters. The charge transferred in the first millisecond from the neutral to the eight system groundings, six at arrester stations, and one at each of the two line-end poles, appears to be distributed inversely to the low-frequency, low-current grounding resistances. From our measurements of return stroke current division and in view of the available data on the currents of first strokes in natural lightning, we estimate that over half of natural first strokes would result in an arrester failure in our test distribution line, which is representative of some distribution lines in service, within about 450 μs of the initiation of the first return stroke current flow, in the absence of flashovers and other alternative current paths that might be provided by transformers or underground cable connections to allow the stroke current to bypass the arrester. Additional first stroke current flow beyond about 450 μs and currents associated with subsequent strokes and potentially other processes should further increase the likelihood of arrester damage.

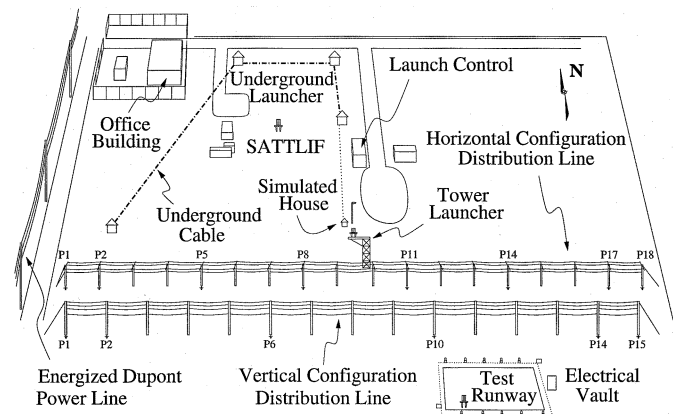*Index Terms*—Grounding electrodes, lightning, MOV arresters, power distribution lines.

Fig. 1. Overview of the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, FL, Summer 2000.

I. INTRODUCTION

THE International Center for Lightning Research and Testing (ICLRT) is located at Camp Blanding, FL, approximately midway between Gainesville and Jacksonville. The ICLRT is an outdoor facility that occupies about 1 km^2 and is used for triggering lightning from natural overhead thunderclouds using the rocket-and-wire technique [1], [2]. An overview of the ICLRT facility during Summer 2000 is shown in Fig. 1 (see [3] for a detailed description of the ICLRT). The facility included an unenergized, four-conductor (three horizontally configured phase conductors plus a neutral conductor underneath), 829-m distribution line (Fig. 1). This distribution line is one of several standard distribution line configurations used by Florida Power and Light. The division of lightning current on the test line is the primary subject of this paper.

II. EXPERIMENT

The line was struck near the center of phase C with triggered flashes containing return strokes a total of eight times between July 11 and August 6, 2000. Six of these flashes produced damage to the phase C arrester at pole 8 at different times in the flashes. Of the two that did not, one had a rocket-trailing wire over the line and the other produced a phase-to-phase 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 56 kA. Each triggered

Fig. 2. Placement of conductors and arresters on the test distribution line.

TABLE I
V-I CHARACTERISTICS OF THE 18-kV MOV ARRESTERS OF
TWO MANUFACTURERS

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

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. The placement of conductors and arresters on the test distribution line is illustrated in Fig. 2. A total of six three-phase arrester stations 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 829-m three-phase line was terminated at each end in an impedance of about 500 Ω via two 1000-Ω, 1.75-MJ resistors connected in parallel between the struck phase (phase C) and neutral, and a single 500-Ω, 1.5-MJ resistor connected between each of the other two phases and neutral. The distance between poles on the line varied from 47 to 73 m. The grounding of the neutral at each arrester station pole and at the two terminating poles was accomplished by means of 24-m vertically driven ground rods. The low-frequency, low-current grounding resistance of each pole ground was measured on several occasions using the fall-of-potential method. The measured grounding resistances on September 2000 were 41, 47, 28, 52, 55, 46, 37, and 22 Ω for the ground rods at poles 1, 2, 5, 8, 11, 14, 17, and 18, respectively. Although the long-term variation of grounding resistance should be small, short-term variation can be significant due to sporadic rainfall in Florida, particularly during the summer months [4]. Two different brands of 18-kV MOV arresters were used in the experiment: arresters installed at poles 2, 5, 14, and 17 were from manufacturer "A" and those installed at poles 8 and 11 were from manufacturer "B." Polymer insulators were used at the terminating poles and ceramic insulators on all other poles, all 35 kV rated. The V-I characteristics of the 18-kV arresters are shown in Table I. Arrester currents, line currents, neutral currents, and currents through the terminating resistor at pole 1 were measured with current transformers (CTs), and at each pole ground location with 1-mΩ current viewing resistors (shunts). Arrester voltages were measured with specially designed voltage dividers that were compensated for the additional voltages due to the time-varying magnetic flux produced by the arrester current and coupled to the voltage divider loop.

The voltage and current signals were recorded on LeCroy digitizing oscilloscopes at a sampling rate of 20 MHz. The total triggered-lightning current was measured at the rocket launching unit with a 1-mΩ shunt and recorded with a LeCroy digitizing oscilloscope having a sampling rate of 25 MHz. The oscilloscopes were housed in the launch control trailer (Fig. 1), and the sensor output signals were transmitted via Nicolet Isobe 3000 fiber optic links having a 15-MHz upper frequency response, each system being composed of an Isobe transmitter, a fiber optic cable, and an Isobe receiver. The upper frequency limits of the various current and voltage measurements were between 5 and 10 MHz, determined by the individual CTs, shunts, or voltage dividers. We estimate the potential error in making any given current or voltage measurement as 15%.

III. RESULTS

Although there is a great deal of information that can be gleaned from the Summer 2000 experiments on the test distribution line, we focus here primarily on one aspect of those experiments: the paths of return stroke current from the strike point on one phase, C, in the middle of the line, between poles 9 and 10, to the eight grounds. We study this division in detail for the five strokes of one flash, flash 0036. During those five strokes, arrester failure did not occur. We examine the return stroke peak currents and the charge transferred from the start of each of the return strokes to a time of 1 ms. Additionally, we summarize in Fig. 6, the peak current distribution among the line grounds for all measured return strokes in all recorded flashes. In flash 0036, an initial continuous current and the currents of the first five recorded return strokes were injected into phase C between poles 9 and 10 prior to arrester failure at pole 8. The arrester on pole 8 failed following the fifth stroke, perhaps from the accumulation of energy from the initial continuous current and the five strokes, or from those currents, any unrecorded continuing current between strokes, any unrecorded continuing current following the fifth stroke, and the currents of any additional unrecorded strokes. As an example, Fig. 3 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, no current was measured through the terminating resistor at pole 18 but that current was
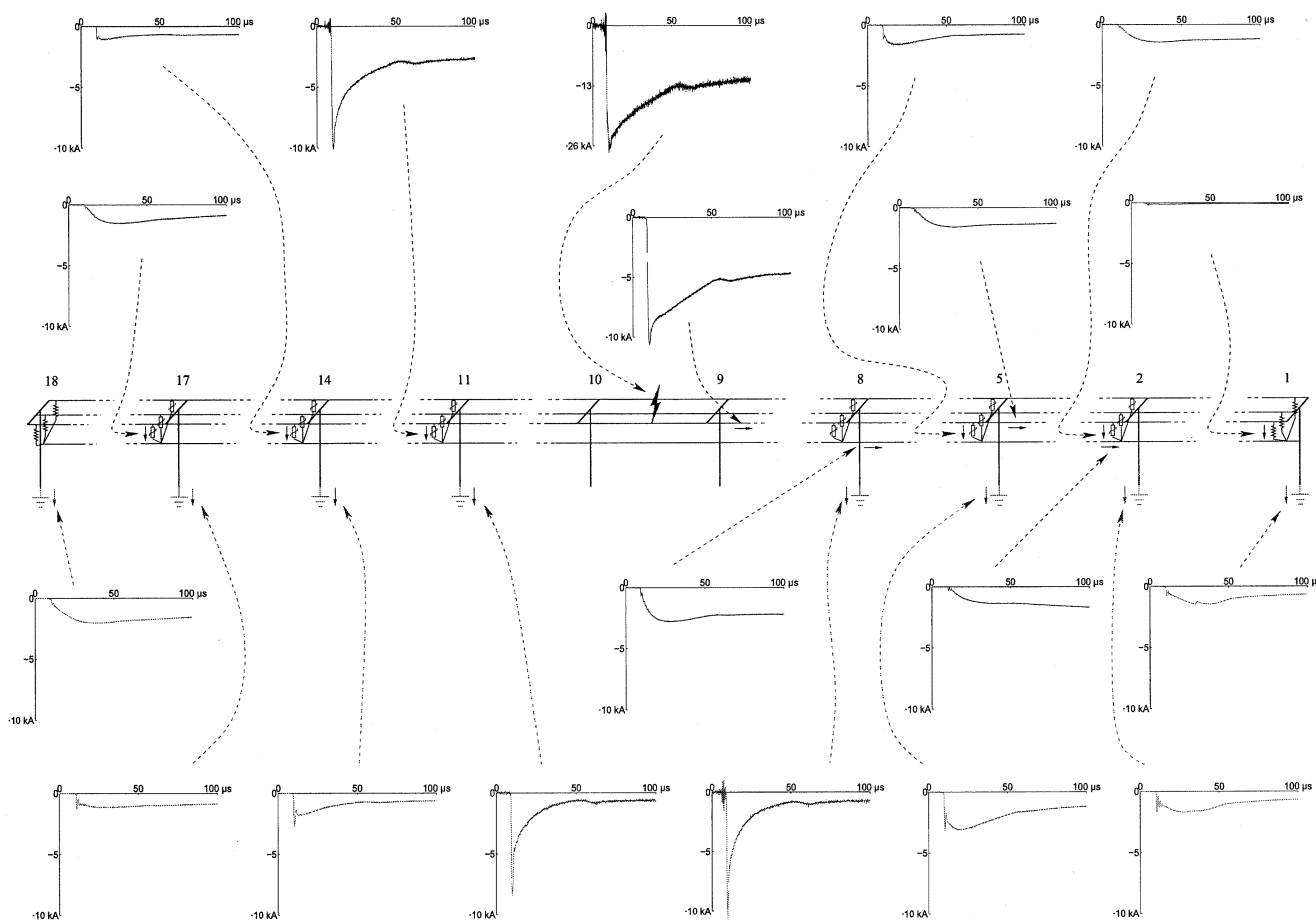
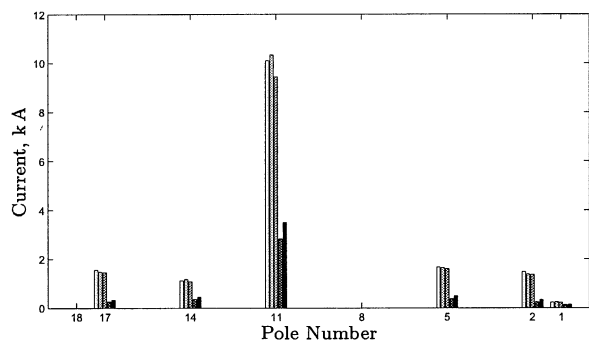Fig. 3. Current distribution for flash 0036, stroke 1.

Fig. 4. 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.
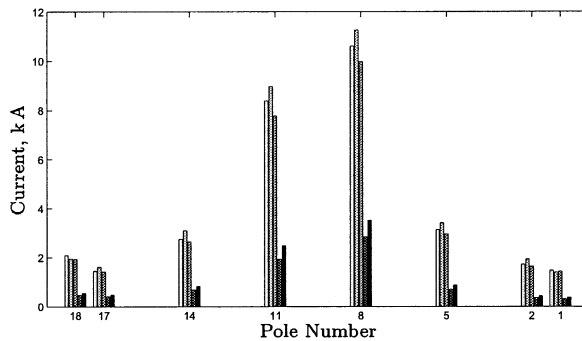
Fig. 5. Measured peak currents to ground for strokes 1 through 5 (in ascending order from left to right) of flash 0036.

likely relatively small and similar to the current that was measured through the terminating resistor at pole 1. Fig. 4 shows the arrester and terminator peak currents recorded for all five strokes of flash 0036, while Fig. 5 gives the peak currents entering all eight pole grounds for the five return strokes. It is evident from Figs. 3–5 that the bulk (about 80%) of the peak current injected into phase C passed through the two phase C arresters, at pole 11 and by inference at pole 8, and also went to ground at poles 8 and 11, even though the neutral was available to disperse the peak current to the other six grounds of the system. Fig. 6 shows the measured distribution of peak current

to ground for all strokes triggered. In many of these events, there were flashovers and failed arresters on the line. It is evident that all strokes show a behavior similar to that in the example above from flash 0036, stroke 1. Fig. 3 shows current waveforms only to 100 μs. Nevertheless, incident charge, and hence, incident current, continued to flow in the system at least until 1 ms (see Fig. 7 and 8). Since the recorded currents decayed to the measuring system noise level (roughly ± 200 A) within about 1 ms (the total recording window was 10 ms), the division of current after 1 ms is not known. As follows from Fig. 7, about 25% of the charge flows through each of the two closest arresters on the struck phase, although this percentage may be an underestimate,
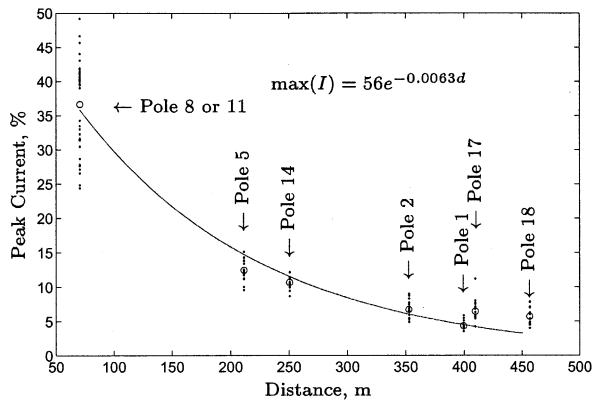
Fig. 6. Measured peak current to ground in percent of the total lightning peak current as a function of distance from the strike point. Dots represent measured peak current to ground for all strokes triggered in 2000 with no severe saturation, circles indicate mean values, and the solid line is the exponential function that fits the mean values.
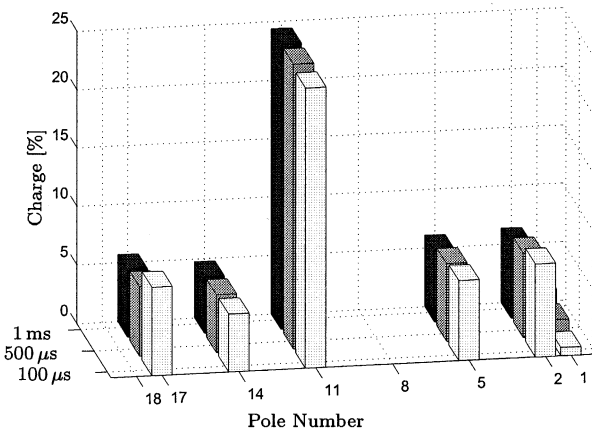

Fig. 7. Percentage of total charge transferred through phase C arresters at different poles and terminating resistor at pole 1, calculated at three different instants of time (100 μs, 500 μs, and 1 ms from the beginning of the return stroke), for stroke 1 of flash 0036. No measurements are available at pole 8 and pole 18.
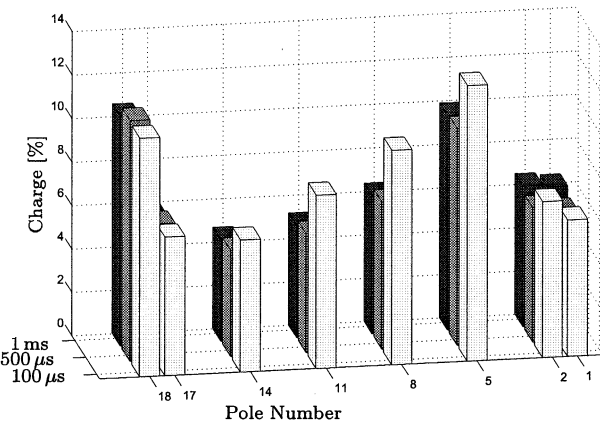

Fig. 8. Percentage of total charge transferred to ground at different poles, calculated at three different instants of time (100 μs, 500 μs, and 1 ms from the beginning of the return stroke), for stroke 1 of flash 0036.

since the summed charge (transferred through all six arresters, assuming the charge transfer through the pole 8 arrester equals that through the pole 11 arrester, and one termination resistor) only adds up to about 70–75% (for all five strokes) of the inci-

dent charge. The latter was calculated by integrating the current waveform measured at the rocket launcher. We were unable to identify any flashovers in our video records that might have accounted for the remaining 25–30% of the incident charge, but cannot rule out such flashovers. It is not possible to tell if the measured incident stroke current peaks are fully accounted for in the various peak current measurements because the current peaks occur at different times at different locations, and the current waveshapes also change with location on the line.

It is interesting to note from Fig. 3, an observation also illustrated in Fig. 8, that after 25 μs or so, the current to ground no longer flows from the neutral primarily through the grounds closest to the strike point but is more uniformly distributed among the eight grounds. In fact, the currents after 25 μs are distributed roughly inversely to the measured low frequency, low current ground resistance, with the largest current going to the 22-Ω ground at pole 18. Fig. 8 shows that the percentage of charge transferred to a given ground in the first 100 μs is not much different from that transferred in the first millisecond.

IV. DISCUSSION

Based on our observations that about 40% of the return stroke peak current and about 25% of the return stroke charge to 1 ms pass from the struck phase to the neutral through each of the two closest arresters of that phase, we are able to draw some inferences on the energy dissipation and likelihood of failure of those closest arresters for the case of both triggered and, by extrapolation, natural lightning strokes.

A typical maximum dissipation energy for MOV arresters is 4 kJ per kilovolt rated [5]. For our 18 kJ-rated arresters, the typical expected withstand energy is therefore 72 kJ. The exact value depends on the current waveshape and the V-I characteristics of the arrester (the latter being a function of the current waveshape). Typical published V-I characteristics are for 8/20-μs waveforms. For triggered lightning, we have measured the energy (product of the measured current and measured voltage integrated over time) dissipated by an arrester at pole 8 during the initial continuous current of flash 0037 (triggered after flash 0036) that caused arrester failure after 25 ms of current in the tens of ampere to 100-A range [3]. The arrester failed from this relatively low-frequency current at a dissipated energy of 90 kJ. Using the same technique, we found the total energy dissipated by the phase C arrester at pole 11 for the first five strokes of flash 0036, which did not cause arrester failure at either of the two closest arresters, to be approximately 84 kJ. We assume that the energy dissipated by the arrester at pole 8, where the measurement of the current was lost, was about the same as that at pole 11. An illustration of the initial 100 μs of the stroke 1 current waveform of flash 0036 which dissipated 30 kJ at the pole 11 arrester in about 1 ms of current flow is shown in Fig. 3. For each of the five strokes of flash 0036, the current after 1 ms or so, if any, was indistinguishable from the system noise level (roughly ±200 A); and hence, the bulk of the charge passing through the arresters apparently did so in the first 100 μs or so, as is evident from Fig. 7, unless an undetected current below the system noise level persisted for many tens of milliseconds. As noted earlier, the pole 8 arrester failed following the five strokes
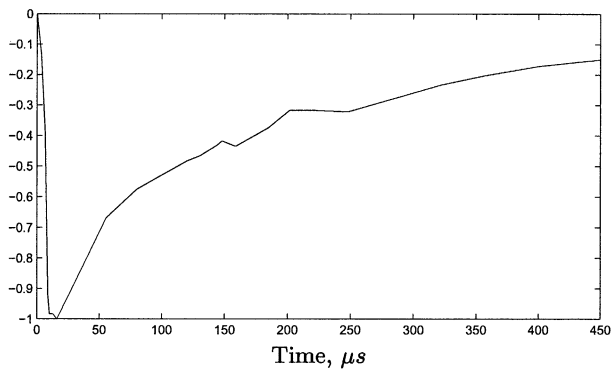
Fig. 9. Averaged first stroke current waveform from natural lightning normalized so that its peak is equal to unity. Adapted from Berger *et al.* (1975).
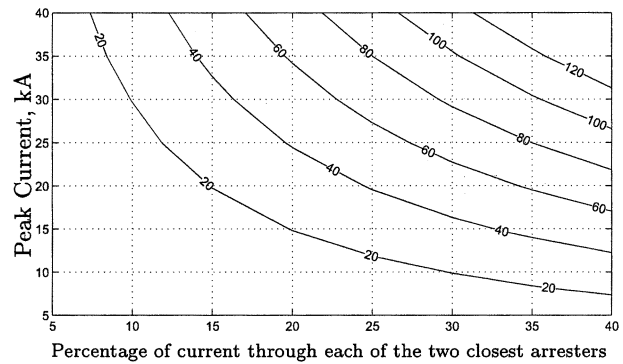

Fig. 10. Arrester dissipated energy in kilojoules as a function of peak current for the fixed current waveform shown in Fig. 9 and the percent of total lightning current through the arrester about 70 m from the strike point in the absence of flashovers and other alternate paths for current to bypass the arrester.

of flash 0036. We did not record the energy dissipation associated with the initial continuous current of flash 0036, any continuing current near ± 200 A that may have occurred between strokes, or the event or events after stroke 5 that was followed by the failure. Thus, it appears that the arrester energy for this sequence of impulse currents (note that there may have been some arrester cooling between strokes) exceeded 84 kJ.

We have estimated the energy delivered to the pole 11 and by inference pole 8 arresters by the five strokes of flash 0036 using two methods: ① from the measured current and voltage waveforms integrated over time (the technique discussed in the previous paragraph), and ② from the measured current waveform and a voltage waveform determined from the published V-I characteristic of the arrester (Table I, manufacturer "B"), the V-I characteristic being presumably obtained for an 8/20-μs waveform. The values determined the two different ways are in reasonable agreement, at least for the larger energy inputs. For method ①/② and stroke 1, 30 kJ/39 kJ; stroke 2, 30 kJ/35 kJ; stroke 3, 19 kJ/20 kJ; stroke 4, 2.7 kJ/1.5 kJ; and stroke 5, 3.1 KJ/2.1 kJ. Assuming that this reasonable agreement would hold for first strokes in natural lightning and using a knowledge of natural first stroke currents, we can estimate the energy delivered to a close arrester on a line similar to our test line by a natural first stroke. Berger *et al.* (1975) averaged about 100 first stroke current waveforms to arrive at the average current waveform shown in Fig. 9. The peak current in Fig. 9 is normalized to unity and the waveform extends to 450 μs at which point the current has decreased to about 15% of peak value. If we multiply the current waveform of Fig. 9 by the voltage waveform derived from the same V-I characteristic used for calculating the energy dissipated for the strokes in triggered flash 0036 and integrate to 450 μs (method ② above), we find the resultant arrester dissipated energy plotted in Fig. 10 as a function of peak stroke current versus percent of that total current going through each of the two closest arresters. For example, if we assume conservatively (based on our measurements) that 25% of the current goes through one arrester and that the first stroke peak current is the median value found by Berger *et al.* (1975) of about 30 kA, about 70 kJ is dissipated in the arrester, an energy near the nominal failure value. Since the tail (beyond the 450 μs depicted by Berger *et al.* 1975) of the first stroke waveform will further increase the dissipated energy, it follows that over half of first

strokes should cause failure to the closest arrester in the absence of processes such as flashover and alternate paths such as transformers or underground cable connections that can allow current to bypass the arrester. Further, since the energy delivered by natural subsequent strokes (similar to all strokes in triggered lightning) and any continuing current flowing through the arrester must be added to the first stroke energy, although some cooling may occur between strokes, the fraction of close arrester failures should be even larger. The typical number of strokes in natural negative flashes is 3 to 5.

In the triggered lightning experiments discussed in this paper, most of the return stroke charge transfer that was observed above the system noise level of about ± 200 A was via the impulse currents of return strokes. Our future experiments will be aimed at both accumulating more data on the current division of impulsive current components and at determining the current division of the low level (order of 100 A), long duration (tens to hundreds of milliseconds) continuing currents that follow individual strokes in about half of natural flashes [7]. If a significant fraction of the continuing current, associated with a typical charge transfer of 10 C [7], flows through the nearest two arresters, as opposed to being divided among many arresters, then the stress to the nearest arresters will be increased significantly above the estimates given in the previous paragraph. It would then follow that, in the absence of flashover or other alternate paths for current flow to ground such as through transformer windings, one of the two closest arresters will likely fail in the case of natural lightning strikes to the line.

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Dr. Rakov has been named an Inventor of the USSR in 1986, and received a Silver Medal from the (USSR) National Exhibition of Technological Achievements in 1987. Dr. Rakov is Chairman of the Technical Committee on Lightning of the biennial International Zurich Symposium on Electromagnetic Compatibility and of the AGU Committee on Atmospheric and Space Electricity.