

Direct Lightning Strikes to Test Power Distribution Lines—Part II: Measured and Modeled Current Division Among Multiple Arresters and Grounds

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Abstract—The division of return stroke current among the arresters and groundings of two unenergized test distribution lines, one horizontally configured and the other vertically configured, was studied at the International Center for Lightning Research and Testing in Florida. The division of return stroke currents for the vertically configured line was initially similar to the division on the horizontally configured line: at the time the return stroke current reached peak value (after one microsecond, or so) the two closest arresters/grounds on both lines passed about 90% of the total current. However, the time during which the return stroke current flowed primarily through the closest arresters to the neutral conductor was significantly shorter on the vertically configured line. On that line, the arrester current was about equally divided among all four arresters after several tens of microseconds. The arrester current division as a function of time measured on the vertical line was successfully modeled using the published VI-characteristic, while the division on the horizontal line after some tens of microseconds was only successfully modeled if the residual voltage of the two arresters closest to the current injection point was reduced by 20%. Based on the triggered lightning current division observed on our line, the minimum energy absorbed in each of the two arresters closest to the strike point during a typical natural first stroke is estimated to be 40 kJ.

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

I. INTRODUCTION

THIS paper discusses the measured and modeled lightning current divisions on two unenergized test distribution lines that were directly struck by rocket-triggered lightning for the case that there was neither arrester disconnect operation nor line flashover. The preceding companion paper contains a detailed description of the experiments, a presentation and verification of the validity of the experimental data, and a performance assessment regarding disconnect operation and flashover.

The division of the lightning current's low-frequency components among the arresters installed on "real world" distribution lines remains unclear [1], [2]. The division needs to be understood to specify the proper testing and design of distribu-

tion arresters and in order to determine their optimal placement on distribution lines. It is not clear whether the low-frequency components of the lightning current divide more or less equally among all arresters on the line, making lightning damage to a given arrester less likely or if these currents preferentially flow through the arresters closest to the lightning strike point potentially causing damage to these arresters. McDermott [3] has modeled the arrester current division on distribution lines using the Electromagnetic Transient Program (EMTP). Nakada *et al.* [4] inferred a 50% reduction of the residual voltage measured across an arrester installed on a test distribution line struck by natural lightning and attributed this observation to a change of the arrester's VI-characteristic due to the arrester's energy absorption. This effect influences significantly the division of the low-frequency lightning current components. Experimental and modeling results are presented here to contribute toward understanding this and other effects influencing the current division.

The experiments were conducted at the International Center for Lightning Research and Testing (ICLRT) in North-Central Florida, where lightning is triggered (artificially initiated) from natural overhead thunderclouds for a variety of purposes using the rocket-and-wire technique [5]–[7]. Two different 3-phase test distribution lines of about 800 m length were subjected to triggered lightning current: 1) a cross-arm horizontal line configuration during Summer 2000, previously described in [8], and 2) a vertical line configuration during Summers 2001, 2002, and 2003 (the 2001 and 2002 experiments were previously reviewed in [9]). This paper discusses and compares the measured division of the lightning current, in the absence of arrester damage and line flashovers, on the horizontally configured distribution line (the "horizontal line experiment") with that on the vertically configured distribution line (the "vertical line experiment"). Additionally, the measured current division on each line is compared to the model-predicted results obtained using the EMTP 1996 (EMTP96).

II. EXPERIMENT

The configuration of the horizontal line experiment has been described in [8] and [10], and the configurations of the horizontal line and vertical line experiments have been described in the preceding companion paper (see also [9] and [11]). What follows is a brief overview of the two experimental configurations.

The horizontal line had 18 poles and three horizontally arranged phase conductors with one neutral conductor below the

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phase conductors. It had arresters installed on all three phases at poles 2, 5, 8, 11, 14, and 16. The vertical line had 15 poles and four vertically arranged conductors, three phase conductors and one neutral conductor, and arresters installed on all three phases at poles 2, 6, 10 and 14. Arresters manufactured by manufacturer “A” or manufacturer “B” were installed at each arrester station of the horizontal and vertical lines. Both lines were unenergized and had $500\ \Omega$ terminators installed between each phase and neutral conductor at both ends to match the characteristic impedances of the lines and hence make the line appear infinitely long to microsecond-scale transients. In 2003, a 50 kVA transformer was installed at pole 2 and connected to the top phase conductor (phase A). The center-tapped secondary of the transformer was terminated in resistive loads of $4\ \Omega$ and $6\ \Omega$. Currents from 34 and 97 triggered-lightning return strokes were injected into phase C of the horizontal line at midspan between poles 9 and 10 and into phase A of the vertical line at midspan between poles 7 and 8, respectively. The lines were also subjected to initial continuous current in some experiments and continuing current in all experiments, as discussed in part I of this two-part paper. In 2000 both currents and voltages on the horizontal line were measured. Only currents were measured on the vertical line during the 2001-2003 experiments.

III. EXPERIMENTAL RESULTS

The measured division of the lightning current and charge among the phase-to-neutral connections and among the neutral-to-ground connections is now analyzed. The analysis applies only to data from strokes that did not cause flashovers or disconnecter operation on the line. A comparison of the measured division with the model-predicted division can be found in Section V. A usable set of arrester currents during the 2001 experiment was not obtained due to instrumentation problems. Two observed modes of operation for the arrester and ground current divisions during the horizontal and vertical line experiments are defined.

- 1) The transient mode is indicated by the dark-shaded area in Fig. 1. This mode occurs during the first tens of microseconds and is characterized by a fast, large magnitude impulsive current through each of the two closest struck-phase arresters/grounds and much slower, smaller magnitude currents through the other struck-phase arresters/grounds. The transient mode ends when the rate of change of all arrester/ground currents becomes similar. The duration of the transient mode (the width of the dark shaded area in Fig. 1) is defined as the equilibration time. Its determination will be discussed.
- 2) The steady-state mode is identified by the more lightly-shaded area to the right of the dark-shaded area in Fig. 1. The steady state is characterized by a similar, approximately linear rate of change of all arrester/ground currents. Typically, all arrester/ground currents decay slowly (within hundreds of microseconds) to zero during the steady-state mode.

Fig. 1 shows representative examples of arrester current divisions on the struck phase for the horizontal line experiment and the vertical line experiment. Fig. 1(a) shows all phase C (the struck phase) arrester currents for stroke FPL0032-4 from the

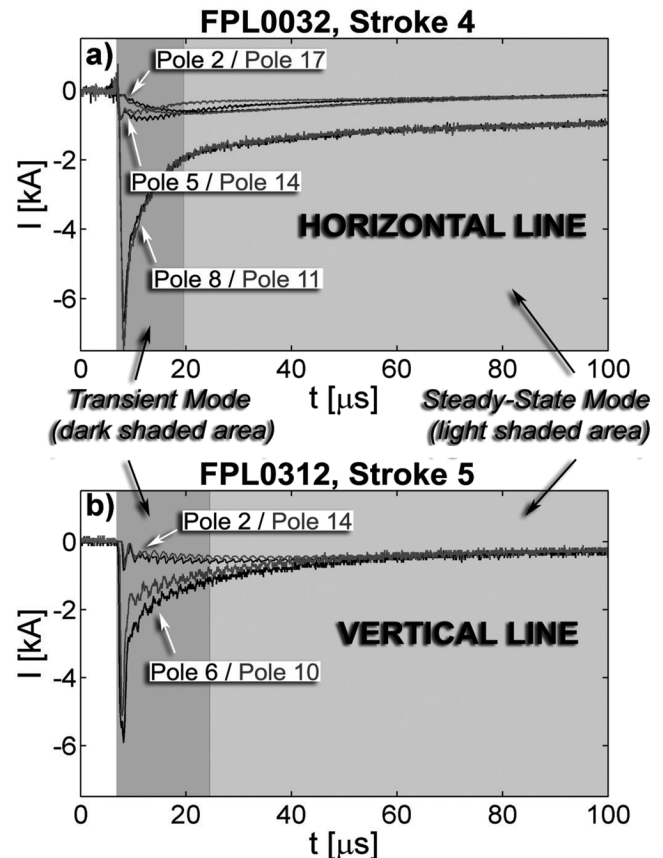


Fig. 1. Struck phase arrester currents during (a) the 2000 experiment (phase C arrester currents during return stroke FPL0032-4) and (b) the 2003 experiment (phase A arrester currents during return stroke FPL0312-5). The transient mode (dark-shaded area) and steady-state mode (light-shaded area) are indicated.

2000 horizontal line experiment¹ and Fig. 1(b) shows all phase A (the struck phase) arrester currents for stroke FPL0312-5 from the 2003 vertical line experiment. Fig. 1 illustrates that current variations during the transient mode in both the horizontal and vertical line experiments are similar, that is, the two arresters closest to the lightning current injection point (pole 8 and pole 11 arresters for the horizontal line experiment and pole 6 and pole 10 arresters for the vertical line experiment) initially pass the bulk of the return stroke current. However, the steady-state modes are quite different in the two experiments—for the horizontal line experiment [Fig. 1(a)] the arrester currents through the two closest arresters (pole 8 and 11) after the equilibration time are much larger than the arrester currents through the other arresters (poles 2, 5, 14, and 17), while for the vertical line experiment [Fig. 1(b)] all four arrester currents have converged to the same value after the equilibration time.

Fig. 2 shows the individual currents flowing between phase A and neutral of the vertical line divided by the total phase A to neutral current for FPL0312, stroke 5 (the currents during this stroke are shown in Fig. 1(b) and in Fig. 4 through 6 of part 1) for a period of $100\ \mu$ s. At the time of the peak value of the return

¹Stroke FPL0032-4 was not discussed in [8]. This event was selected since both closest struck-phase arrester currents were recorded for this stroke, as opposed to the strokes in flash FPL0036 considered in [8], for which only one of the two closest struck-phase arrester currents was recorded. However, all conclusions in [8] also apply to stroke FPL0032-4.

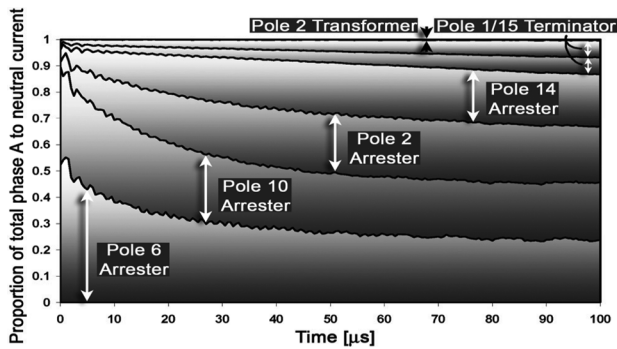


Fig. 2. Vertical line, FPL0312, stroke 5—the individual currents flowing from phase A to neutral divided by the sum of all phase A to neutral currents. The pole 15 terminator current was not measured and was assumed to be equal to the pole 1 terminator current.

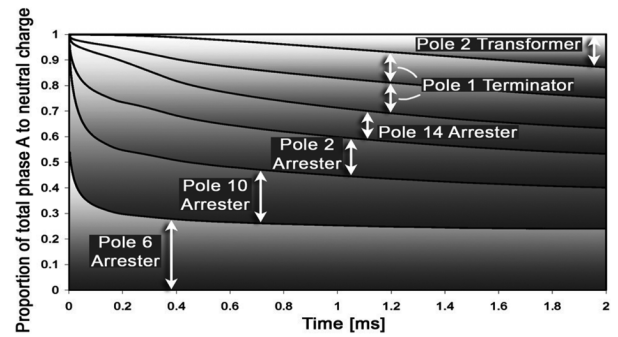


Fig. 4. Vertical line, FPL0312, stroke 5—the individual charges flowing from phase A to neutral divided by the sum of all phase A to neutral charges. The pole 15 terminator charge was not measured and was assumed to be equal to the pole 1 terminator charge.

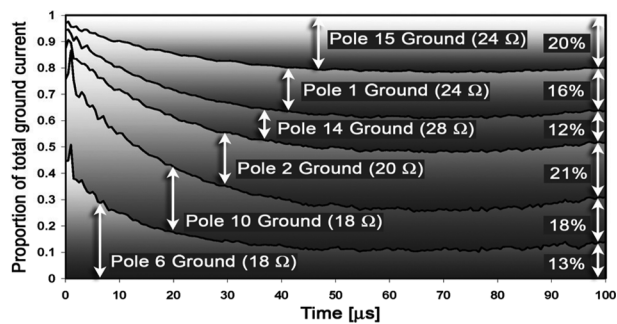


Fig. 3. Vertical line, FPL0312, stroke 5—the individual currents flowing to ground divided by the sum of all ground currents. The dc ground resistance of each pole ground is given in the parentheses. The percentages of the individual currents at 100 μs are displayed on the right side.

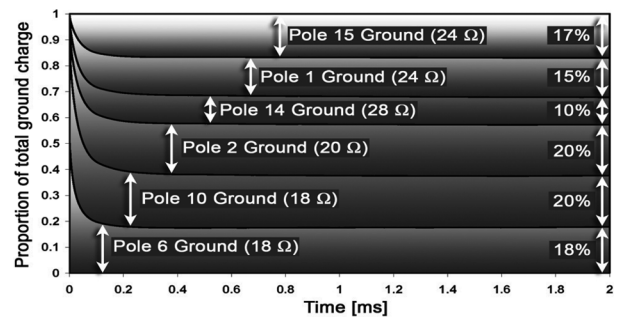


Fig. 5. Vertical line, FPL0312, stroke 5—the individual charges flowing to ground divided by the sum of all ground charges. The dc ground resistance of each of the pole grounds is given in parentheses. The percentages of the individual charges at 2 ms are displayed on the right side.

stroke current (about 2 μs after the return stroke initiation) the two closest arresters pass about 90% of the total phase to neutral current. By about 50 μs, or so, the total arrester current is evenly divided among all arresters. For the first 100 μs, the transformer at pole 2 carries essentially no current and the terminator at pole 1 carries very little current. The arrester current equilibration time determined for this stroke is 20 μs at which time the two closest arresters pass 60% of the total lightning current.

Fig. 3 shows the individual currents to ground divided by the total ground current for the event of Fig. 2. The ground currents initially behave similar to the arrester currents, that is, at the time of peak value the two closest grounds pass about 90% of the total ground current. The percentages of the individual currents at 100 μs displayed in Fig. 3 show that the total ground current at that time is more or less evenly divided among all grounds. The ground current equilibration time determined for this stroke is 20 μs at which time the two closest grounds pass 40% of the total lightning current.

Fig. 4 shows the individual charges transferred from phase A to neutral divided by the total phase A to neutral charge for the initial 2 ms of the lightning current of FPL0312, stroke 5. At 2 ms, the phase A arrester at pole 6 (the arrester closest to the lightning current injection point) had carried the most charge (approximately 30% of the total charge transferred from phase A to neutral). The transformer and terminator, which transfer very little charge during the first 100 μs, passed appreciable charge

by 2 ms (the transformer and the terminator each transferred 7% of the total charge).

Fig. 5 shows the individual charges transferred to ground divided by the total ground charge for the initial 2 ms of the lightning current for FPL0312, stroke 5. The individual charges transferred to ground at 2 ms are roughly inversely proportional to the low frequency, low current grounding resistances of the individual grounds (e.g., the least charge, 10% of the total charge, is transferred at pole 14, the pole with the largest ground resistance, 28 Ω). The features of the first 100 μs of ground current and charge divisions for the example from 2003 discussed before are consistent with similar features for other strokes during 2003 and for strokes during 2002 for the vertical line experiment. The ground current division on the vertical line is similar to that on the horizontal line. Although there was no transformer on the vertical line in 2002, the relative division of the lightning currents and charges among the phase-to-neutral paths are similar to the 2003 experiment when there was a transformer on the line, that is, the individual phase-to-neutral paths in 2003 took the same percentages of the injected lightning current and charge as in the 2002 experiment.

IV. MODEL

The division of the lightning current on the horizontally and vertically configured test distribution lines was modeled using the EMTP96, version 3.2d. The model-predicted results are compared to the experimentally determined data to test the

speculation in Section III that the different current divisions on the horizontally and vertically configured lines are due to a change in the VI-characteristics of the two arresters closest to the strike point on the horizontal line. The lightning was represented in the model as an ideal current source, which is equivalent to the lightning channel's characteristic impedance being infinite. The lightning current was either injected into the phase C conductor midway between poles 9 and 10 of the model of the horizontally configured line or into the phase A conductor midway between poles 7 and 8 of the model of the vertically configured line. The modeled distribution line systems consisted of distribution line sections represented by the frequency-dependent transmission line model (the JMARTI model implemented in the EMTP) [12], line groundings modeled using a distributed ground model [13] and [14], the measured low-frequency, low-current grounding resistances given in Section II of the companion paper, and a gapless arrester model (the Type-92, 5555 component in the EMTP) with the manufacturer-provided VI-characteristic (Section II of the companion paper) or with a modified VI-characteristic. In the EMTP the nonlinear arrester resistance is represented by a power function of the form

$$i = p \left(\frac{v}{V_{\text{ref}}} \right)^q \quad (1)$$

where v and i are the arrester voltage and current, respectively, and p , V_{ref} and q are constants. V_{ref} is typically twice the rated voltage of the arrester and is used to normalize the equation and prevent numerical overflow. In the EMTP each segment of the VI-characteristic is defined by a separate power function, except for voltages substantially below V_{ref} for which a linear representation is used to avoid exponential underflow and to speed the solution. Note that this static representation of the VI-characteristic does not take hysteresis or other dynamic effects into account.

Two models are considered for the calculation of the current division on the horizontal line: 1) model 1 uses the published VI-characteristics for all modeled arresters and 2) model 2 uses a modified VI-characteristic for the two arresters closest to the lightning current injection points (poles 8 and 11 arresters installed at phase C) and the published VI-characteristic for all other arresters. The modified VI-characteristic is the manufacturer-provided VI-characteristic (see Table II in part 1 of this two-part paper) with the voltage values reduced by 20%. The 20% voltage reduction was selected by 'trial and error' so that an optimal match between modeled and measured arrester currents at pole 11 of the horizontal line was achieved (the current through the other closest phase C arrester at pole 8 was not successfully measured). For the successful model prediction of the observed current division on the vertical line, the published VI-characteristic was used for all arresters, that is, model 1; whereas for the horizontal line, model 2 provided a good match between experimental and modeled results.

V. MODELING RESULTS

Fig. 6 compares the division of the struck phase (phase C) to neutral currents measured on the horizontal line during stroke

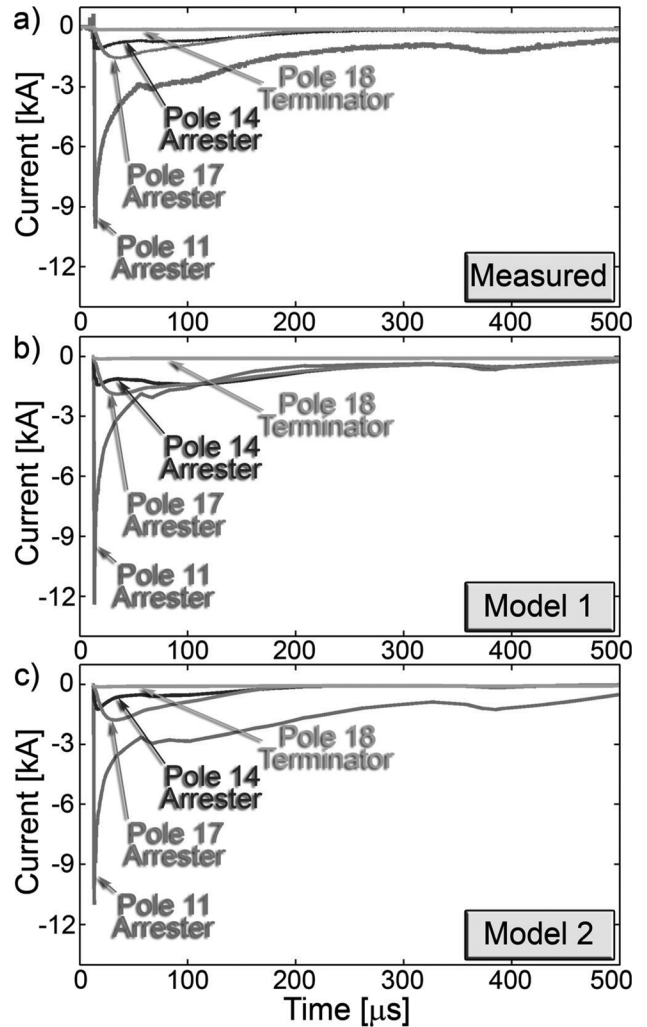


Fig. 6. Horizontal line, FPL0036-1, (a) measured struck-phase (phase C) to neutral currents, (b) model 1 results, and (c) model 2 results displayed on a 500 μs time scale.

FPL0036-1, the stroke discussed in [8], with the results from model 1 and model 2. Model 1 poorly reproduces the measured arrester and terminator currents while model 2 reproduces the measured arrester currents very well. The most significant difference between the results of model 1 and model 2 is that the current through the pole 11 arrester (one of the two arresters closest to the current injection point) equalizes during the steady-state mode in model 1 (similar to the closest arrester currents during the 2002 and 2003 experiments) while in model 2 the closest arrester current is considerably larger during the steady-state mode (see Section III) than the currents through the other arrester, as was observed for the measured arrester currents. Both, model 1 and model 2, reproduce well the measured ground currents (the modeling results for the ground currents are not presented here). Note that the equilibration time for the arrester currents, defined in Section III, in both models is similar to the equilibration time of the measured currents.

Fig. 7 compares the struck phase (phase C) arrester voltage measured at pole 11 on the horizontal line during stroke FPL0036-1 with the results from model 1 and model 2. Model 1 predicts a voltage that is about 45% larger than the measured

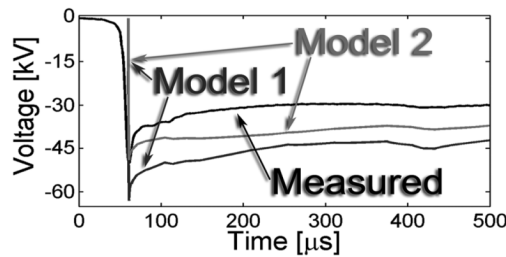


Fig. 7. Horizontal line, FPL0036-1, struck-phase (phase C) arrester voltage measured at pole 11 and filtered with a 4th order, 100 kHz low-pass Butterworth digital filter compared with model 1 and model 2 results. Model 1 and model 2 predicted waveforms exhibit a much faster risetime than the measured ones.

voltage. Model 2, for which the voltage of the two closest arresters' VI-characteristic at pole 8 and pole 11 was reduced by 20%, overestimates the measured voltage by about 25%. Reducing the voltage of the pole 11 arrester's VI-characteristic further improves the match between model-predicted and measured voltages. However, reducing the voltage by more than 20% worsen the match between the model-predicted and measured pole 11 arrester currents. It is important to note that we are not as confident of the accuracy of the measured voltage (there was no way to test the accuracy of the voltages) as we are of the measured currents (the accuracy of the currents was tested via the consistency of multiple simultaneous measurements, see Section III of the companion paper). The arrester voltage measured at pole 8 (not shown here) has a different waveshape during the first 100 μs and is larger by 15 to 20% for times after 100 μs than the voltage measured at pole 11.

Fig. 8 compares the division of the struck phase (phase A) to neutral currents measured on the vertical line during stroke FPL0312-5, the stroke analyzed in Section III, along with the model 1 results. The measured arrester and terminator currents displayed in Fig. 8(a) are in good agreement with the modeled currents in Fig. 8(b). The measured ground currents are also reproduced well in the model (the modeling results for the ground currents are not presented here). Significantly, for the currents measured on the vertical line, no modification of the arrester's VI-characteristic was required to achieve a good match between measured and modeled results. The good agreement is perhaps surprising considering the simplicity of the employed model versus the complexity of the experiment (corona effects and the lightning channel's characteristic impedance are not taken into account in the model) and the limited/inaccurate information about model parameters (for instance, the arrester's VI-characteristic for currents below 1.5 kA), the arresters being represented by their static VI-characteristic (and not by the more realistic dynamic VI-characteristic), the line groundings being represented by a simple model, and the measured low-frequency, low-current grounding resistances being potentially inaccurate and expected to vary with rainfall.

VI. DISCUSSION

During the horizontal line experiment the two closest struck-phase arresters passed the bulk of the lightning current during both the transient mode and the steady-state mode, these modes

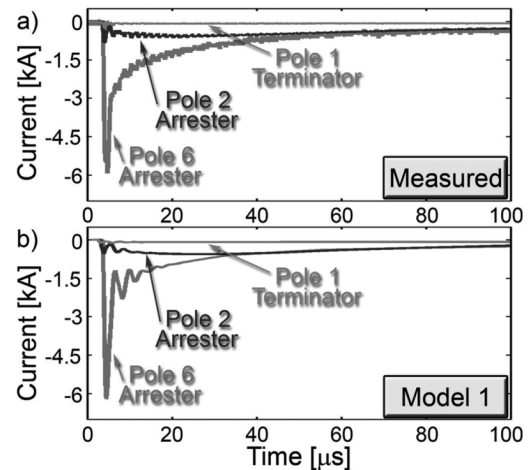


Fig. 8. Vertical line, FPL0312-5, (a) measured struck-phase (phase A) to neutral currents and (b) modeled results displayed on a 100 μs time scale.

being defined in Section III. During the vertical line experiment the transient mode behavior of the arresters was similar to that during the horizontal line experiment, but the steady-state mode behavior was quite different, that is, during the steady-state mode the lightning current in the vertical line was uniformly divided among all struck-phase arresters while it was not for the horizontal line where the closest arresters carried the most current (see Section III). The reason for the different steady-state mode behavior of the horizontal and vertical lines is not known but is likely related to one of the three following differences between the two experiments.

- 1) A change of the VI-characteristic of the two closest arresters (model 2 in Section V). The VI-characteristics of the two arresters installed on the struck phase of the 2000 horizontal line that were closest to the strike point might have changed due to large energy absorption. The arresters on the 2000 horizontal line experiment were exposed to initial continuous currents (ICCs), to the following fast return stroke currents, and sometimes to continuing currents flowing after the return strokes, while the arresters on the 2002/2003 vertical line were exposed to the latter two types of currents only and not to ICCs. Thus the two closest arresters on the 2000 horizontal line absorbed more energy than the other arresters, the other arresters being the remote arresters on the 2000 horizontal line (these arresters do not pass much current during the transient mode as shown in Section III) and the arresters on the 2002/2003 vertical line (these arresters were not exposed to the ICC). Modeling results presented in Section V show that 1) a good overall match between the modeled and measured arrester currents on the horizontal line can be achieved by reducing the residual voltage of the two closest arresters by 20% (model 2) and 2) the arrester voltage measured at pole 11 and at pole 8 is better reproduced by model 2 than by model 1. Both observations support the view that the two closest arresters changed their VI-characteristic.
- 2) The use of different types of arresters (horizontal line experiment: the arresters at the two closest arrester stations were manufacturer "B" arresters, the arresters at all other

arrester stations were manufacturer “A” arresters; 2002/2003 vertical line experiment: only manufacturer “A” or only manufacturer “B” arresters were used at all stations). Note that the two types of arresters have the same rated voltage and very similar published VI-characteristics for currents above 1.5 kA (based on an $8/20 \mu\text{s}$ waveform, see Table 2 in part 1 of this two-part paper). However, it is known that if two similar arresters that are not carefully matched are connected in parallel can behave such that one arrester passes considerably more current than the other arrester (see Section III-C in Part I of this two-part paper). For the case of the horizontal line during the steady-state mode the impedance of the line conductors separating the 6 struck-phase arresters is very small and the arresters can be viewed as connected in parallel. It is possible that the two closest arresters (manufacturer “B”) on the horizontal line pass more current during the steady-state mode since they are not matched with the other arresters (manufacturer “A”). Note that during the transient mode the impedance of the phase conductors separating the arrester stations is large and consequently the arresters cannot be viewed as connected in parallel (the primary current paths during the transient mode are the two closest arresters, matched or unmatched, due to the large impedance separating them from the other arresters on the line, as will be discussed below).

- 3) The presence of voltage measurement equipment at the two closest arresters on the struck phase (phase C) for the horizontal line experiment that was not present on the vertical line. The voltage dividers possibly have facilitated flashovers resulting in an additional phase-to-neutral current path at the two closest arrester stations. This would have resulted in an overestimation of the arrester current since the arrester current sensor measures the sum of the current through the arrester and the current through the voltage divider. However, flashovers were not evident in the current, voltage, or optical records.

We now discuss the implications of the measured and modeled current divisions for “real world” distribution lines. On both the horizontal and vertical test distribution lines the arresters closest to the strike point pass the bulk of the current during the transient mode (Section III). The reason for this is the inductance of the line segment that separates the closest arrester station from the next station (that is, the impedance of the segment is large during the transient mode, which delays current flow to the next-closest arrester). The current division during the transient mode determined on the test distribution lines can be expected to be similar to that on “real world” distribution lines. Note that the equilibration time depends strongly on the length of the line segments between arrester stations, for instance, the smaller inductance of shorter segments causes the current to equilibrate faster. This has been previously shown by McDermott [3] with EMTP modeling. It is presently unclear if, on a “real world” distribution line, 1) the lower-frequency current components would be evenly divided among all arresters as the experimentally determined current division in the 2002/2003 vertical line experiment that is reproduced by model 1 or 2) the lower-frequency current components would flow primarily through the two closest arresters as the experimentally deter-

mined arrester current division in the horizontal line experiment that is reproduced by model 2. It is possible that, similar to the effect hypothesized as the reason for the model 2 current division on the horizontal line, the energy absorbed in the arresters closest to the strike point of a natural lightning strike to a “real world” distribution line is large enough to change their VI-characteristic. Support for this view is found in [4] where Nakada *et al.* explained the reduction of the measured arrester voltage by 50% during a natural strike by a change in the arrester’s VI-characteristic due to energy absorption and introduced a simple arrester model in which the manufacturer specified residual voltage is reduced by 50%. Also, an argument for model 2 is made in [1] from the fact that [2] measured a significant low-frequency arrester current (approximately 2 kA after 1 ms) in a 10 kV MOV arrester installed on an actual power distribution line. Note that during a natural lightning strike to a “real world” distribution line the arresters closest to the strike point are expected to absorb the largest amount of energy of all arresters on the line (the closest arresters pass the bulk of the current during the transient mode) and that the energy of a natural lightning first return stroke is typically significantly larger than the energy content of return strokes in rocket-triggered lightning. It was estimated by Mata *et al.* [8], based on the model 2 lightning return stroke current division determined in the horizontal line experiment and the available statistics on the current amplitudes and waveshapes of first strokes in natural lightning, that, within about $450 \mu\text{s}$ of the initiation of the first return stroke current flow, the energy input from about half of all natural lightning first strokes delivered to each of the two closest arresters exceeds 70 kJ and thus would likely damage them (in the absence of flashovers or other alternative paths for the return stroke current to bypass the arresters). If model 1 applies to the current division on “real world” distribution lines, then the arrester damage rate on “real world” lines would be lower than the arrester damage rate on the horizontal test line estimated by Mata *et al.* [8] since the low-frequency current components are divided evenly among multiple arresters on the line (that is, the arresters further away from the lightning strike point absorb a significant portion of the lightning energy and thus help protect the arresters closer to the lightning strike point from damage and degradation). For instance, McDermott [3] using the EMTP found a considerably lower arrester absorbed energy (30 kJ) than Mata *et al.* (70 kJ) for a typical natural lightning first return stroke current injected into the phase conductor of a distribution line, which is mostly attributable to the fact that McDermott adopted the model 1 current division and Mata *et al.* implicitly adopted the model 2 current division. It is important to note that for both model 1 and model 2 the MOV block of arresters on “real world” lines closest to the lightning strike point may be damaged since they pass most of the impulsive lightning current and therefore absorb most of the energy during the transient mode.

We now calculate the energy absorbed in each of the two arresters closest to the strike point during a typical natural lightning first return stroke² using model 1 and lines of different

²The current waveshape found in [15] with a peak value of 30 kA, which is the median value. The same current waveshape was used in [8] to estimate the arrester absorbed energy based on the horizontal line experiment results.

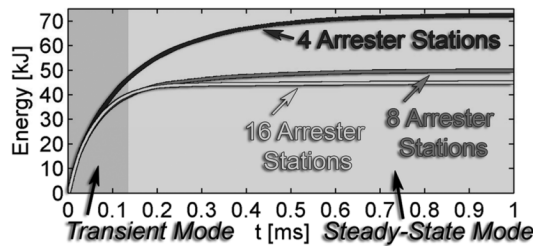


Fig. 9. EMTP-calculated absorbed energy in one of the two closest arresters during a typical natural lightning first return stroke current injected into the phase conductor at midspan. The vertical line contained 1) 4, 2) 8, or 3) 16 arrester stations. The transient mode (dark-shaded area) and steady-state mode (light-shaded area) determined from the arrester currents for case 1) are indicated.

lengths and different numbers of arrester stations. The energy is calculated using the EMTP³ for the following line configurations: 1) the vertical distribution line tested from 2001 through 2003 (4 arrester stations), 2) the vertical line extended to about 1.5 km (8 arrester stations), and 3) the vertical line extended to about 3 km (16 arrester stations). The distance between arrester stations is the same for all line configurations (that is, 4 spans or 200 m). The manufacturer-provided VI-characteristic of the manufacturer “B” arrester was used in the model (Table I). The energy capability of this arrester is rated at 40 kJ. The calculated energies are displayed in Fig. 9 for 1 ms. The equilibration time in the figure (the duration of the transient mode as defined in Section III) was determined for case 1) to be 130 μ s.

The following information can be gleaned from Fig. 9.

- 1) The arrester absorbed energies at 1 ms for cases 2) and case 3) are very similar (50 kJ and 45 kJ, respectively). This demonstrates that the arrester absorbed energy becomes insensitive to the increase of the number of stations and that consequently cases 2) and 3) are good representations of long “real world” distribution lines with a large number of stations. The modeling results of McDermott [3] confirm that the arrester absorbed energy converges with the increasing number of arresters.
- 2) For cases 2) and 3), almost all of the total arrester absorbed energy during a natural lightning first return stroke with the median peak current value found in [15], 30 kA, is absorbed during the transient mode. The absorbed energy during the transient mode, 40 kJ, can be viewed as the minimum arrester absorbed energy, since this energy will not be reduced by adding additional arrester stations to the line (the energy becomes insensitive to the increase of the number of stations, as noted in the previous item) or by the presence of transformers on the line (the transformer current during the transient mode is negligible, as shown in part 1). Therefore, it can be concluded that for a “real world” distribution line of any length with 4 spans between arrester stations about 50% of natural lightning first strokes dissipate at least 40 kJ into the closest arrester, which is a value identical to the energy capability of the manufacturer “B” arrester used in the model. More energy

will be absorbed in the closest arresters due to 1) larger first return stroke currents, 2) presence of subsequent stroke currents, 3) presence of continuing currents if model 2 applies, and 4) strike locations not equidistant between the two arrester stations (for this case, the energy would not divide equally and the closer arrester would absorb more energy). Less energy will be absorbed for lines with shorter equilibration times, which can be achieved by reducing the line length between arrester stations, as noted before and shown in [3].

- 3) The arrester absorbed energy during the transient mode is similar or the same for all three cases (case 1): 45 kJ, case 2) and case 3): 40 kJ). This indicates that the data obtained from our test distribution line are suitable to estimate the minimum arrester absorbed energy for the closest arresters on “real world” lines.

It was found for the vertical line that initially the bulk of the total ground current goes through the two closest grounds and at 100 μ s the total ground current is more or less evenly divided among all grounds (see Section III). Interestingly, [8] found ground currents on the horizontal line after 25 μ s (and the charge transfer within 100 μ s, 500 μ s, and 1 ms) to be roughly inversely proportional to grounding resistance. The reason why the inverse proportionality for ground currents at 100 μ s on the vertical line was not observed is likely because of the relative small variance of the low-frequency grounding resistances for the vertical line (the measured low-frequency, low-current grounding resistances ranged from 22 Ω to 55 Ω for the horizontal line and from 18 Ω to 28 Ω for the vertical line, see Section II in part 1 of this paper). It was found that for the vertical line the individual charges transferred to ground (the integrated ground currents) at 2 ms are roughly inversely proportional to the measured low-frequency, low-current grounding resistance of the individual ground (see Section III). Apparently, the trend of the individual ground currents to be divided inversely to the individual grounding resistances, not observed for the first 100 μ s, is revealed by integrating the ground currents over 2 ms.

VII. SUMMARY

- 1) During the 2002/2003 vertical line experiment, the primary path of the return stroke current for the first tens of microseconds was through the two arresters closest to the lightning current injection point. This finding is consistent with the arrester current division for the first tens of microseconds during the horizontal line experiment discussed in [8] and with the modeled results presented here using model 1.
- 2) During the 2002/2003 vertical line experiment (no initial continuous current), the lightning current was evenly divided among all arresters after an equilibration time of a few tens of microseconds. This finding is in contrast with the arrester current division during the horizontal line experiment (ICC was injected into the line) where after a few hundreds of microseconds the two closest arresters still passed the bulk of the lightning current [8]. The model 1 arrester currents match well the currents measured during the

³The EMTP model has been verified to some extent in Section V by successfully modeling the arrester currents on the vertical line. It is also shown in Section V that the EMTP-predicted voltages are larger than the measured results, which may be due to model inaccuracies or measurement errors.

2002/2003 experiment. The published arrester's VI-characteristic was used for all arresters in model 1.

- 3) The model-predicted arrester currents do not match the arrester currents measured during the 2000 horizontal line experiment if the published VI-characteristic is used for all arresters on the line (model 1). The model-predicted arrester currents match well all arrester currents measured on the horizontal line if a modified VI-characteristic is used for the two arresters closest to the lightning current injection point (model 2). The findings summarized in the first two bullets of this summary suggest that the current division on the horizontal line during the steady-state mode is caused by the large energies absorbed in the two arresters closest to the lightning current injection point that resulted in a reduction of their residual voltages. Other explanations for the current division on the horizontal line are that the division is caused by unmatched arresters installed on the horizontal line or may be essentially an artifact caused by the presence of voltage dividers in the horizontal line experiment.
- 4) The minimum arrester-absorbed energy during the transient mode for natural lightning first strokes to "real world" distribution lines with a large number of arrester stations separated by 4 spans was estimated. Based on the assumptions given in the previous section, at least 40 kJ of energy is absorbed in each of the two arresters closest to the strike point for 50% of all natural lightning first strokes to the line. This estimate does not take energy absorbed in the closest arrester during the steady-state mode and during subsequent stroke currents into account. Also, this energy is larger for a lightning strike point not equidistant to two arrester stations and smaller if the inductance of the line segment separating arrester stations is reduced by, for instance, reducing the number of spans between stations.
- 5) During the 2002/2003 vertical line experiment, the primary path of the return stroke current to ground for the first tens of microseconds was through the two grounds closest to the lightning current injection point. This finding is consistent with the ground current division for the first tens of microseconds during the horizontal line experiment discussed in [8].
- 6) It appears that the charge transfer to ground within 2 ms is inversely proportional to the grounding resistance in the vertical line experiments. This trend was previously found for ground currents after 25 μs , or so, and for the charge transfer within 100 μs , 500 μs , and 1 ms for the horizontal line experiment, as reported in [8].

Note added in proof: The VI-characteristic of the manufacturer-B arrester given in Part I of this two-part paper and used here to model the current divisions on the horizontal and vertical lines is adopted from [8]. We recently found that the voltages in the VI-characteristic in the manufacturer-B arrester specification published in 2004 are about 6% lower than the voltages in the VI-characteristic in [8]. Modeling results with the 2004 VI-characteristic support the hypothesis presented in this paper that the different current divisions on the horizontal and the vertical lines are due to mismatched arresters on the horizontal line (see 2) on page 2249).

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