Lightning Surges in Low-voltage AC Power Systems

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ABSTRACT

Many research studies show that the waveforms of lightning surges on power systems are closer to 8 x 80 μs than the commonly used 8 x 20 μs standard test wave. In this article, computer modeling is used to calculate the currents and wave shapes of surges that propagate onto low-voltage ac power systems when lightning strikes a nearby overhead distribution line. Surge currents are shown to be generally quite modest, but the long wave shapes are shown to result in considerable duty on service-entrance surge protectors. Surge suppressors on wiring inside a building are shown to offer good protection against lightning surges, but the predicted long-duration surges can cause failure of the commonly-used hybrid suppressors designed according to ANSI C62.41 and UL 1449 standards.

INTRODUCTION

Field studies have shown that lightning current waveforms are very much longer in duration than the standard 8 x 20 μs wave shape, with an 8 x 80 μs wave being most representative.[1,2] The 8 x 20 μs wave was chosen as a test wave for early lightning arresters nearly 70 years ago. The shortcomings of this wave were well-known at the time, but seem to have been forgotten. With the recent increase in demand for surge protection on low-voltage ac power systems, shortcomings of present standards based on the old 8 x 20 μs wave are surfacing. Such problems include a high failure rate of low-voltage suppressors designed to meet modern standards, particularly in lightning prone regions.

Surge suppressors on wiring inside a building offer good protection against lightning surges, but the predicted long-duration surges can cause failure of the commonly-used hybrid suppressors designed according to ANSI C62.41 and UL 1449 Standards.

COMPUTER SIMULATION

In order to assess the surge duty on low-voltage suppressors, a computer model was set up to enable the calculation of lightning current and voltage wave shapes on overhead distribution lines and the 120/240-V service conductors typically used in the U.S. The overhead line conductors were represented by a single phase conductor with an underrunning neutral. A metal-oxide surge arrester rated at 12 kV was connected between phase and neutral. The neutral was grounded at each pole. Pole ground resistance was assumed to be uniform at 30 ohms. The pole ground conductor was modeled by a 10 μH inductor. The conductors were modeled by distributed inductance and capacitance (Figure 1).

Six 100-meter spans of over-

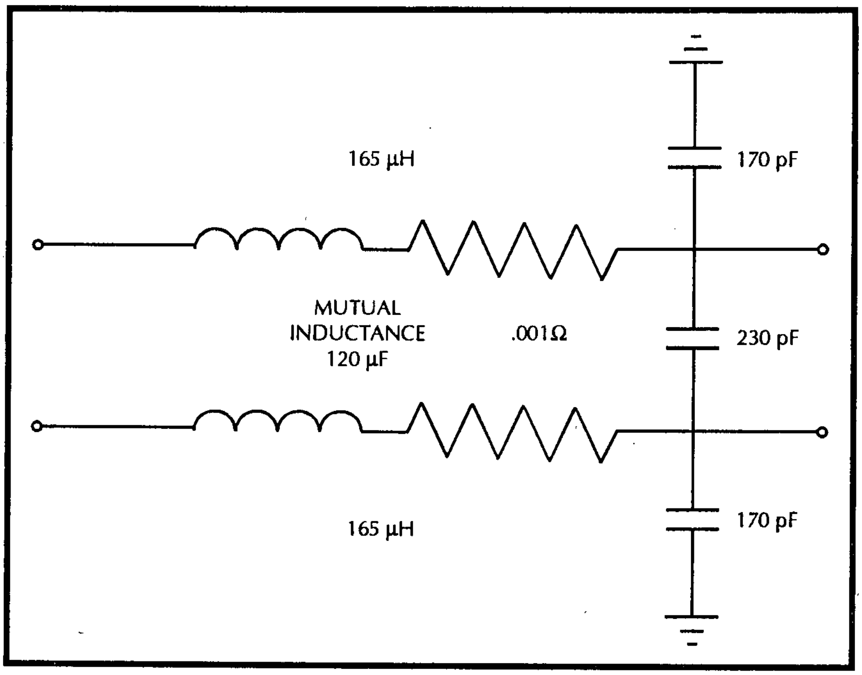

FIGURE 1. *Model of 50 m of Overhead Distribution Line.*

head line were simulated (twelve sections 50 m long), with the outer spans terminated in their characteristic impedance. Transient simulation was accomplished using a SPICE-based software program on a personal computer.

Lightning currents with a peak amplitude of 100 kA and a wave shape of 8 x 80 µs were injected at the central point (center pole) and 50 meters away (mid-span).

The first simulations were performed to establish currents flowing to ground in the various pole conductors, in the absence of any transformers or low-voltage service conductors.

The distribution of current calculated from these runs is shown in Figures 2 and 3.

The predicted distributions in the two cases are in accordance with other theoretical studies and measurements.[3,4] Current is distributed over many kilometers of the distribution line, and significant current flowing over five or six spans on each side of the strike point is common.

Peak currents of from 1/2 to 1/3 of the total flash current are predicted in the poles near the strike, with wave shapes close to that of the original lightning discharge. More distant points see lower currents, but with longer rise times and tail times, due to propagation effects.

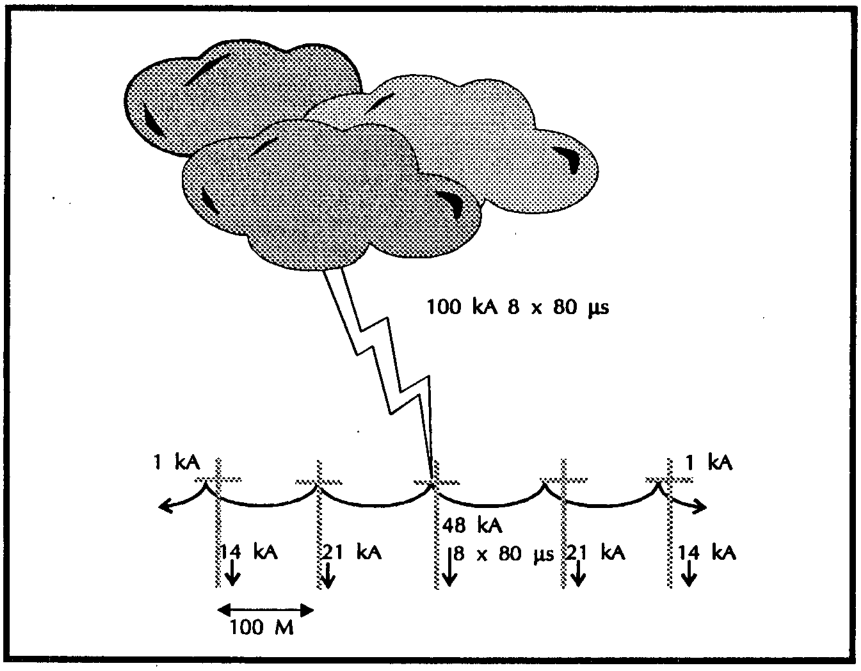

FIGURE 2. *Lightning Currents in Distribution Line, Pole Strike.*

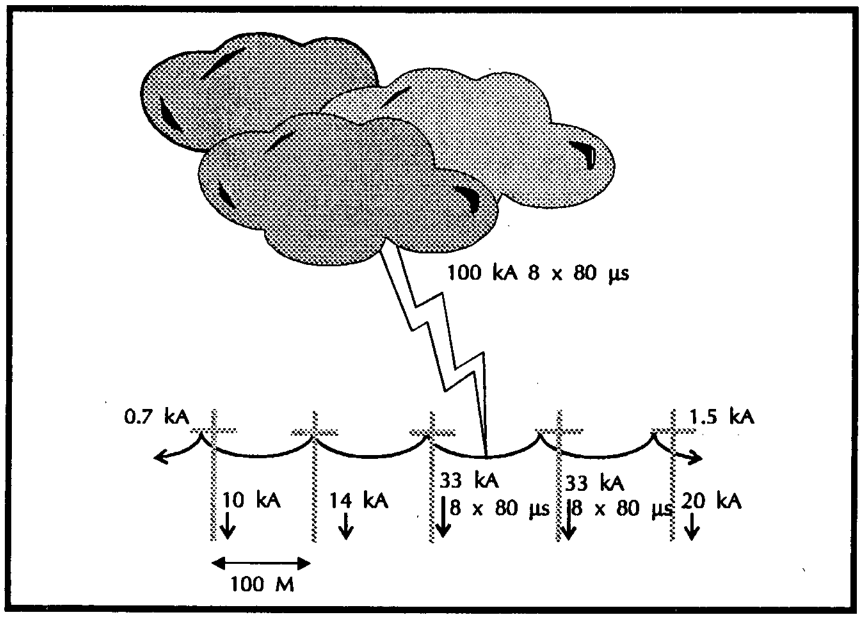

FIGURE 3. *Lightning Currents in Distribution Line, Mid-span Strike.*

To calculate the effects on a low-voltage ac service connected to the overhead distribution line, a single-phase transformer was attached to the central pole between phase and neutral. A neutral and two 120-V phase conductors 15 meters long were attached to this transformer at one end, and to the service entrance on the other. Secondary 250-V rated metal-oxide surge arresters were connected across each end of the 120-V lines for protection. The service entrance ground resistance was assumed to be 5 ohms.

The service conductors were represented by distributed inductance and capacitance, similar to the overhead line. Surge arresters and suppressors were represented by time-independent non-linear resistors, with voltage/current characteristics derived from the publication of a major manufacturer of these devices.

First simulations showed one interesting fact — the transformer made only a minimal contribution to currents flowing in the service conductors, and for most purposes could be ignored. Most current bypassed the transformer through its surge arrester.

A second result was that the low service grounding resistance diverted much of the lightning current to the service entrance away from the distribution line.

Thirdly, currents between neutral and two phase conductors were pretty evenly divided, as might be expected for a closely coupled bundle of wires connected at each end with surge arresters.

A 100 kA strike to the pole resulted in a total of nearly 70 kA flowing in the service conductors; a similar strike to midspan 50 meters away resulted in about 50 kA.

A 50 kA current in the service resulted in almost exactly 16.5 kA in each conductor. The 8 x 80 μs current wave shape deposited 1.5 kJ of energy in each of the four 250-V rated low-voltage arresters, including those at the service entrance. A 10 kA current in the service gave 3.3 kA in each arrester, and deposited only 160 J in each one.

Many lightning flashes comprise multiple strokes. Therefore, the total surge energy deposited in a protection device will be higher than for a single stroke. Fortunately, however, strokes subsequent to the first tend to have lower currents and shorter durations. A typical flash having three strokes would deposit about 30-percent more energy than a single stroke flash in a service entrance arrester.

Taking multiple strokes into account, the simulations suggest that about 6 percent of lightning discharges striking within 1/2 span of the service will result in more than 1 kJ of energy absorption in a typical service entrance arrester.

The most lightning prone region of the country, the Tampa bay area of Florida, experiences about 20 ground lightning flashes per square kilometer annually. These result in an average of one flash per two kilometers of overhead distribution line per year.[4] Thus, the probability of experiencing a flash to the line within 1/2 span is about 5 percent per year. Thus one may conclude that about 0.3 percent of arresters in that area will experience lightning surges depositing 1 kJ of energy or more per year. Since most of the U.S. has lightning rates 1/5 or lower than the Tampa bay area, survivability of service entrance arresters with a 1 kJ one-time energy capability would appear to be very good.

Anecdotal information suggests that experience with metal-oxide suppressors rated at 100 J or less is not good at the service entrance, but that devices rated at 400 to 500 J have good survivability.

Also, if the overhead distribution line is better grounded with respect to the service entrance ground than the 6:1 ratio assumed for this study, duty on the low-voltage arresters will be lower than calculated.

Therefore, the conclusion is that most lightning currents in the service entrance protectors are modest, rarely exceeding 10 kA, and almost never exceeding 25 kA, even for a close severe strike.

Surge suppressors intended for application at the service entrance should be able to withstand currents of this magnitude with an 8 x 80 μs wave shape. Surge arresters rated at 250 V should have a one-time surge energy capability of at least 500 J, and preferably 1 kJ.

LOW-VOLTAGE SERVICE PROTECTION

In the absence of arresters or suppressors at the service entrance, significant surge energy can flow into the building wiring. Such an arrangement could not be recommended anywhere in the U.S. for low-voltage services supplied from an overhead line.

Assuming that service entrance protection was in place, further calculations were carried out to estimate the duty on surge suppressors inside the building.

A single-phase service, 30 meters long, consisting of phase, neutral and ground conductors, was simulated using the transient analysis program.

The line was simulated by six 5-meter sections, using suitable values of distributed inductance, capacitance and resistance, as before.

A 20 kA 8 x 80 μs lightning surge was applied to the service entrance arrester, and the response of the internal wiring was calculated. The first had no surge protection on the internal wiring. The second had three 150-V 20 mm diameter metal oxide varistors (MOVs), one between each pair of conductors at the end of the line.

The first simulation showed that the service entrance arrester clamped the lightning surge to a peak voltage of 1.2 kV, as expected. The impressed surge voltage on the building wiring caused a surge with an oscillation at a frequency of about 1 MHz at the end of the internal wiring.

Peak surge voltage there was predicted to be nearly 1.6 kV for both line-to-neutral and line-to-ground conductors, and 10 V for the neutral-to-ground conductors (Figure 4).

The second simulation showed the value of the three MOVs in limiting the voltages at the line end. Voltages were limited to 420 V line-to-neutral and line-to-ground and less than 1 V neutral-to-ground.

Of greatest interest, though, are the predicted voltage and current wave shapes. The voltage wave shape across the line-to-neutral and line-to-ground MOVs is approximately rectan-

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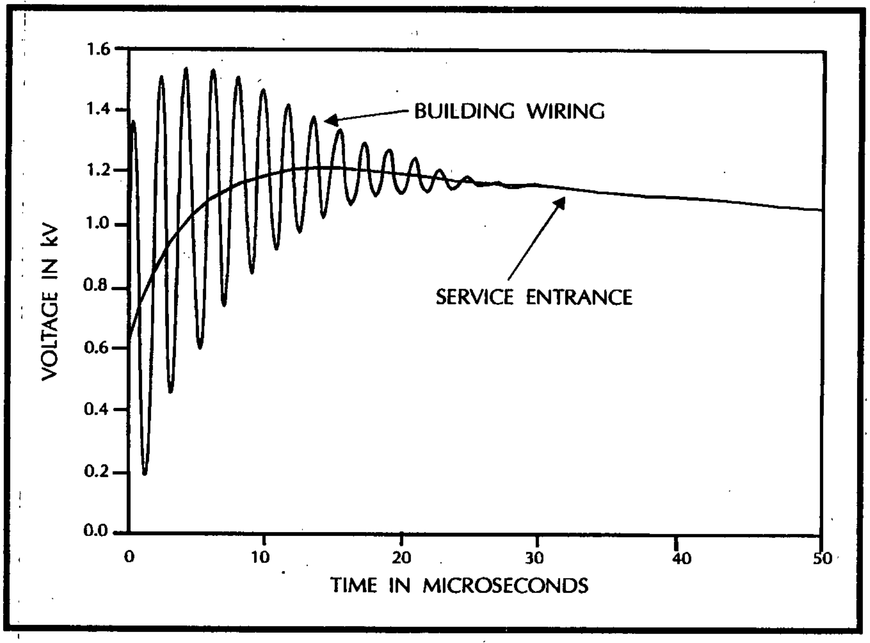

FIGURE 4. *Line-to-Neutral Voltage at Service Entrance and 30 m in Building Wiring.*

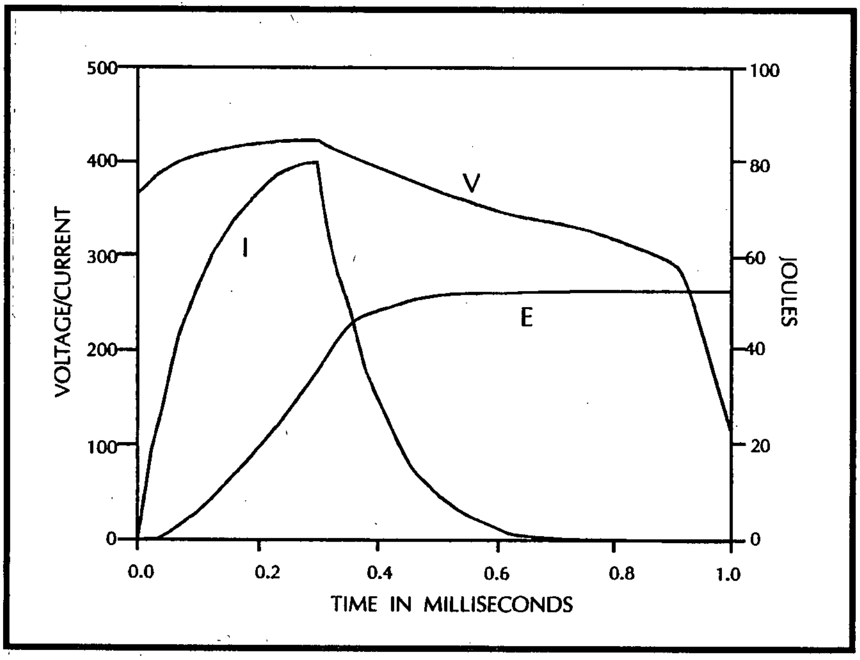

FIGURE 5. *Surge Current, Voltage and Energy in L/N MOV in Building Wiring.*

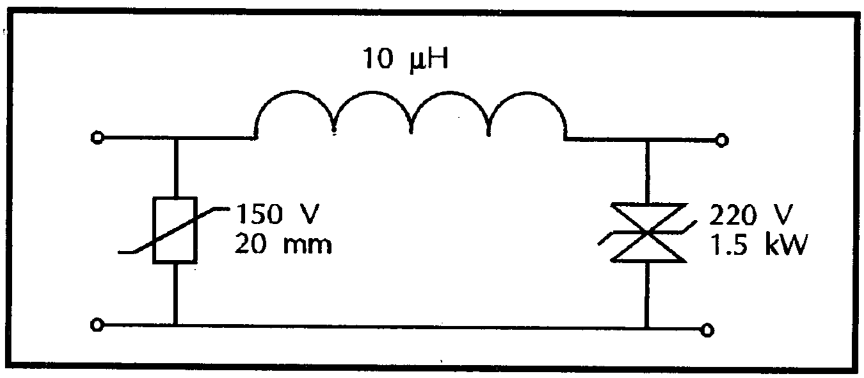

FIGURE 6. *Typical Hybrid Surge Suppressor.*

gular, with a rise time of less than 1 μs and a duration of over 1000 μs.

The surge current flowing through these MOVs reached 400 amps in a time of just over 300 μs, and decayed to zero at just over 1000 μs. Energy deposition in these MOVs exceeded 50 J, a significant fraction of their one-time capability (Figure 5).

The predicted surge currents and voltages in the building have much longer durations than is generally believed, or reflected in standards, and this does have some important consequences for protection.

HYBRID SUPPRESSORS

Hybrid surge suppressors, many of which have circuits based on that shown in Figure 6, are used to protect connected equipment, such as computers.

The purpose of the series inductor is to provide impedance to surge currents in order to drive most current through the MOV. The resulting low currents which flow in the silicon avalanche diode (SAD) result in superior clamping levels.

These hybrid circuits are designed and tested with surge current waves described in national standards, such as ANSI C62.41 and UL 1449. In these standards, 8 x 20 μs current waves are used to simulate the effects of lightning.

Computer-modeled predictions of the distribution of surge current and energy between the MOV and the SAD, when the hybrid is subjected to a UL-1449 standard 500 amp 8 x 20 μs wave, are shown in Figure 7. Clamping is excellent (<300 V peak), and all components operate within their specifications.

However, when the current wave

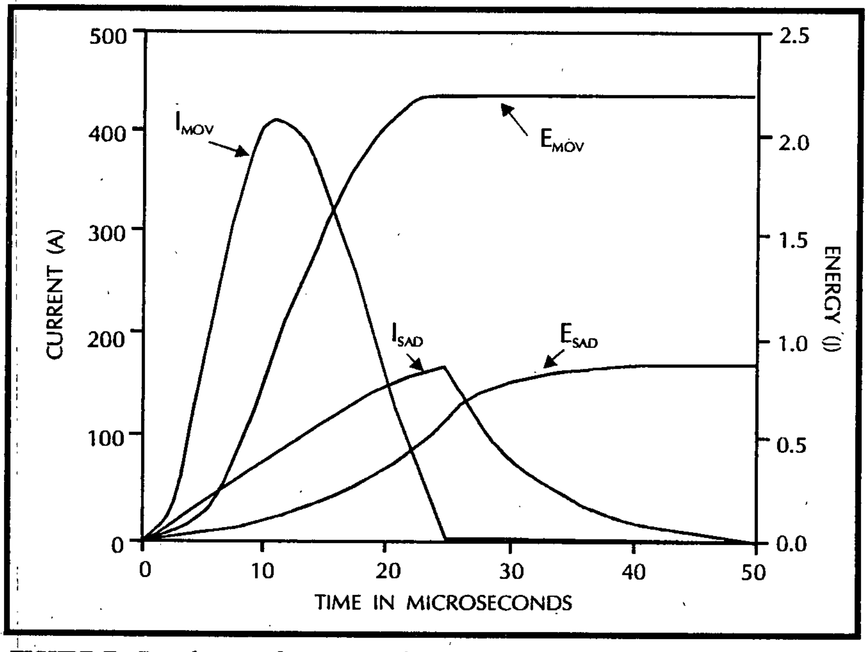

***FIGURE 7.** Distribution of Current and Energy Between the MOV and the SAD in a Hybrid Suppressor for an 8 x 20 µs Wave.*

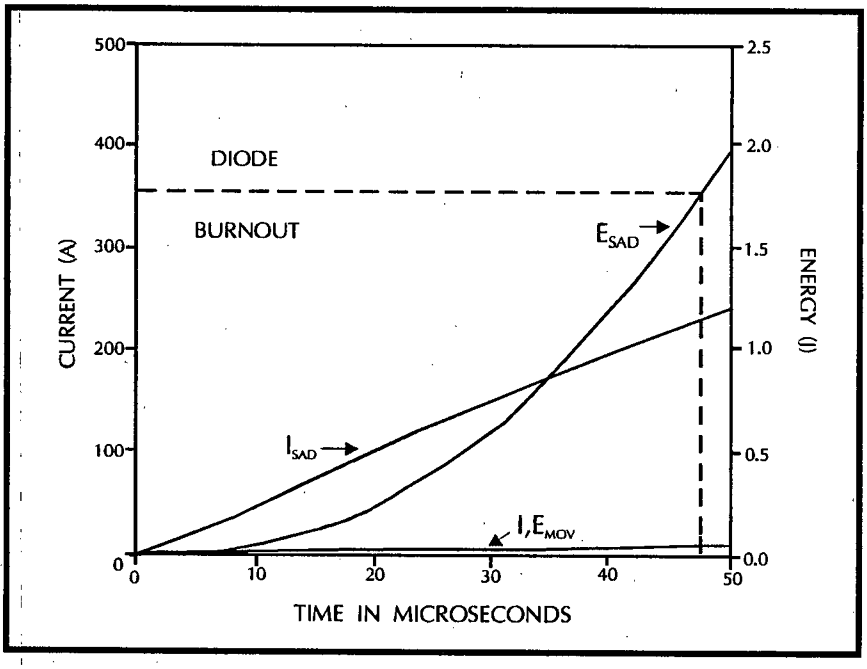

***FIGURE 8.** Distribution of Current and Energy Between the MOV and the SAD in a Hybrid Suppressor for 300 x 600 µs Wave.*

predicted earlier in this study, approximately a 300 x 600 µs wave, was applied to the hybrid, the avalanche diode was quickly overstressed (Figure 8). Little current flows through the MOV, and the SAD energy capabilities are exceeded in under 50 µs.

The relatively low-frequency current wave is not adequately inhibited by the inductor, resulting in high current flow in the fragile diode.

CONCLUSIONS

This study shows that lightning currents in low-voltage ac power circuits rarely exceed 20 kA, much lower than is generally assumed. However, these currents have much longer durations than standard test waves, particularly the commonly used 8 x 20 µs standard.

Energy deposited by lightning surges in typical 250-V service entrance arresters should rarely exceed 1 kJ, even for close lightning strikes.

Lightning surge currents and voltages in low-voltage building wiring have much longer durations than standard waves used to simulate lightning.

Waves with the predicted duration of several hundred microseconds could overstress certain designs of surge suppressors, especially hybrids which utilize series inductance protecting low-energy diodes.

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