INTERACTION NOTES

Note 256

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HEMP on Commercial AC Power Entries

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Introduction

In this note an estimate of the voltage induced at the main circuit breaker panel by a high-altitude EMP is made. A worst case condition is assumed in that the soil conductivity is poor (10^{-3} mho/m). Also, the power distribution system is assumed to be three-phase, 15 kV. The HEMP is assumed to be a 50 kV/m plane wave with a 250 ns exponential decay time constant. The wave is polarized in such a manner that the peak vertically polarized field strength is 7.5 kV/m and the peak horizontally polarized field strength is 49.5 kV/m.

The induced voltages are estimated for three configurations of the distrubution system: 1) above-ground distribution line with pole-mounted transformers, 2) above-ground distribution line with ground-based transformers, and 3) buried distribution line with ground-based transformers. The above-ground transmission lines are assumed to be about 10 meters high and to have a common mode characteristic impedance of about 300 ohms. The buried transmission line is assumed to be near the surface (i.e., about 1 m deep), to have a characteristic impedance of about 30 ohms, and to be without a shield or sheath.

The velocity of propagation on the above-ground lines is about 97 percent of the speed of light and the attenuation constant is about 3 percent of the propagation factor ($\alpha/k \approx 0.03$).

In the analysis of coupling through the transformers, three single-phase, delta-delta connected (maximum coupling configuration) transformers are assumed. The transformers are assumed to have bushing inductances of about 300 nH, bushing capacitances of about 100 pF, winding-to-case capacitances of about 1000 pF, and a winding-to-winding capacitance of 1000 pF. The common-mode characteristic impedance of low-voltage service entrance conductors in steel conduit is estimated to be 40 ohms, and the conduits are assumed to be 30 m long. The common-mode characteristic impedance of high-voltage cables between the potheads and the ground-based transformers is assumed to be 20 ohms, and these cables are assumed to be 30 m long.

Open-Circuit Voltage of Aerial Lines

The peak open-circuit source voltage induced at the end of a semi-infinite transmission line by the vertically polarized component of the HEMP is approximately 3.0 MV for end-on, grazing incidence of the HEMP wave (wave propagation toward the open-circuited terminals). This peak open circuit voltage occurs approximately 220 ns after the beginning of the HEMP. A line of finite length must be at least 2200 m long for the peak open-circuit voltage to reach this value, but only about 250 m of line is required for the peak open-circuit voltage to reach one half this value (i.e., 1.5 MV).

Even though the horizontally polarized component of the incident HEMP is much larger than the vertically polarized component, the worst-case, open-circuit voltage induced by the horizontally polarized component is considerably smaller than that induced by the vertically polarized component at the end-on, grazing angle of incidence. For elevation and azimuth angles of incidence of 20 degrees, for example, the horizontally polarized component of the EMP will induce a peak open circuit voltage of about 0.67 MV. The waveform of the voltage induced by the horizontally polarized wave is similar to that induced by the vertically polarized component (for the same angles of incidence). Inasmuch as the voltage for the vertically polarized component was obtained by neglecting the bucking voltage induced in the vertical downlead, this voltage is a slight overestimate. For the following estimates of the voltage delivered to the main circuit breaker panel, therefore, the horizontally polarized component will be neglected and the overestimate of the vertically polarized component will be used. This waveform is shown in Figure 1 for a semiinfinite line and for a line 250 m long.

Above-Ground Line with Pole-mounted Transformers

If no lightning arresters are installed on the transformer primary, the bushing capacitance and the winding capacitances will, with the 300 ohm source impedance of the distribution line, integrate the open-circuit voltage of Figure 1. The voltage at the ends of the primary windings will thus rise more slowly than the voltage in Figure 1. With lightning arresters installed, this slower rise time will permit the lightning arresters to ionize and limit the primary voltage to a peak value of the order of 300 kV or less as illustrated in Figure 2(a). Transformer bushing inductance and lead inductance at both ends of the service entrance conduit will suppress the high-frequency response at the main circuit breaker panel. The voltage at the main circuit breaker panel will have a fairly slow rise time (tens of ns), and if the circuit breaker supplies several load circuits, there will be a significant mismatch between the service entrance conduit and these load circuits. The approximate early-time waveform which includes the peak value, for an assumed 10-ohm load on the circuit-breaker panel is shown in Figure 2(b).

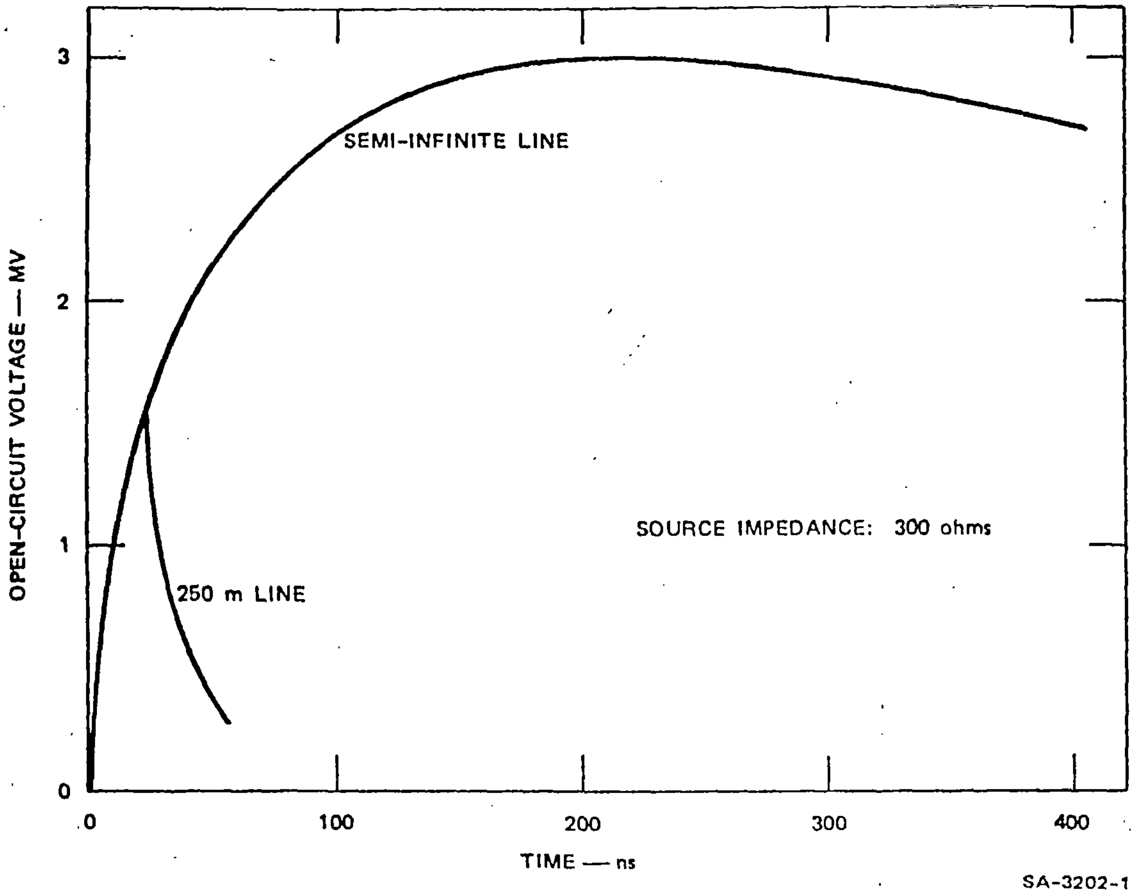
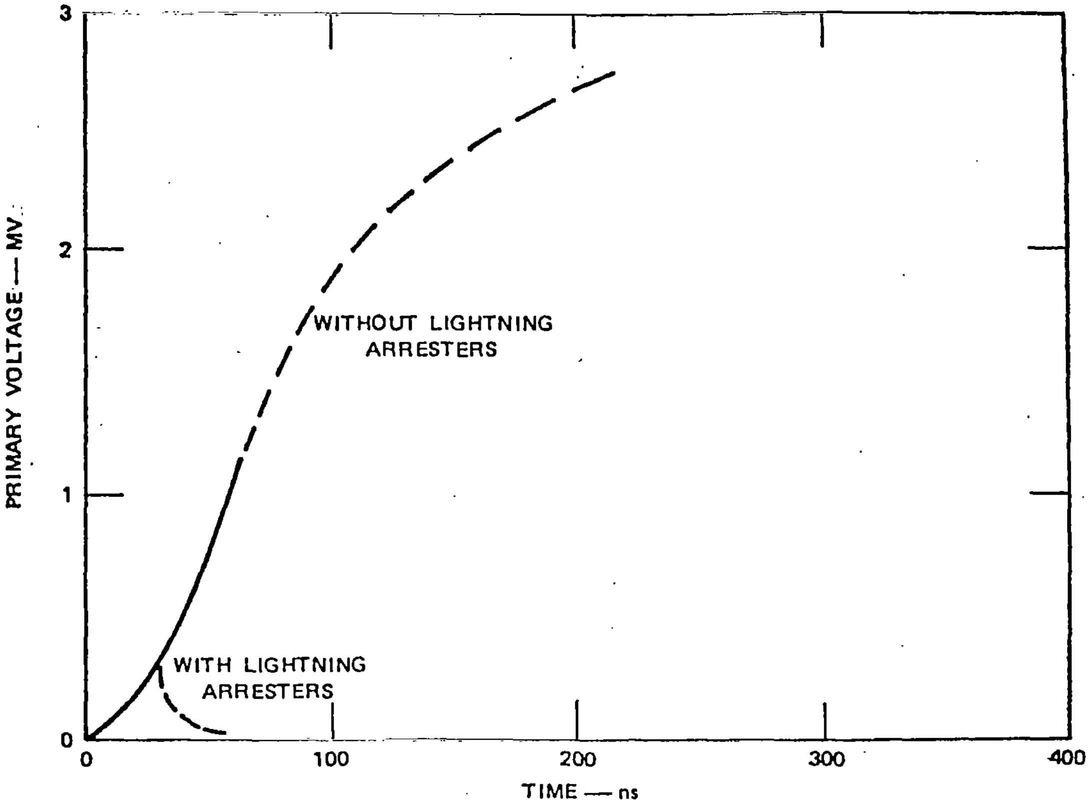
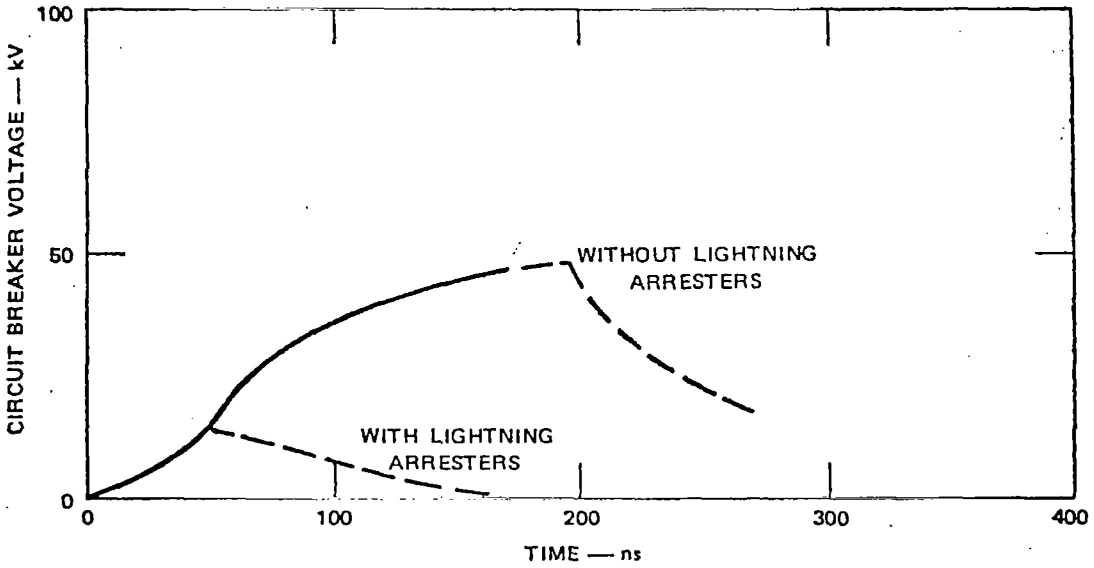


FIGURE 1 OPEN-CIRCUIT VOLTAGE INDUCED AT THE END OF AN ABOVE-GROUND DISTRIBUTION LINE BY THE VERTICALLY POLARIZED COMPONENT OF THE HEMP



(a) PRIMARY VOLTAGE



(b) VOLTAGE ACROSS A 10-ohm LOAD AT MAIN CIRCUIT-BREAKER PANEL

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FIGURE 2 APPROXIMATE EARLY-TIME WAVEFORMS FOR ABOVE-GROUND LINE WITH POLE-MOUNTED TRANSFORMERS

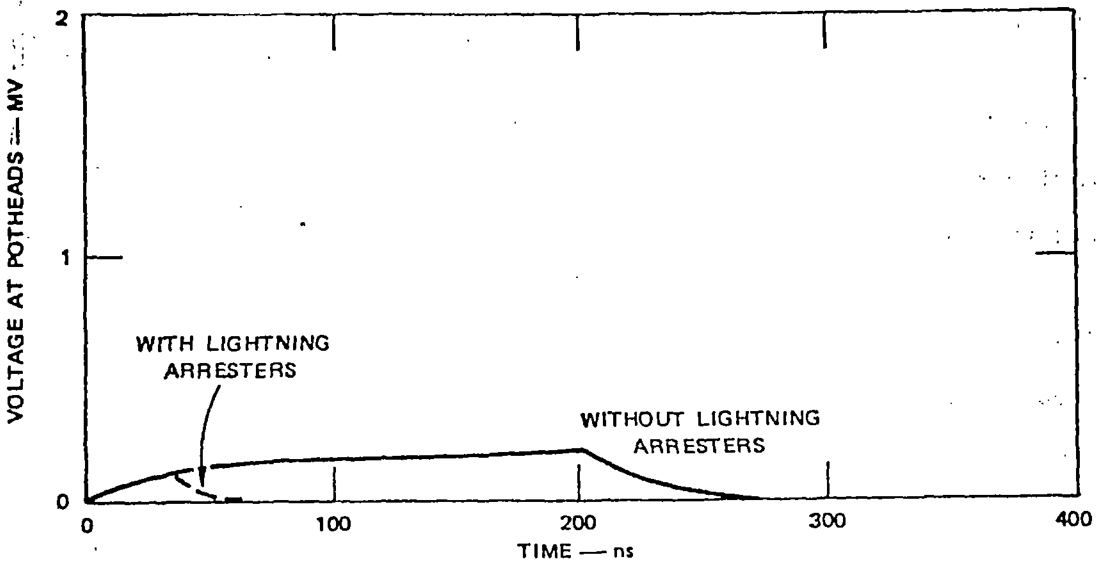
Above-Ground Line with Ground-based Transformers

The problem for the ground based transformers is similar to that for the pole-mounted transformers except that there is an initial mismatch between the aerial line and the cables supplying the transformer primaries, and the early-time source impedance driving the transformer primaries is smaller. Thus the integration time of the bushing capacitance acting with the 20 ohm high voltage cables from the potheads is negligibly short (about 6 ns), but the mismatch between the aerial line and the shielded cables greatly reduces the rate-of-rise of the voltage applied to the primary windings. Figure 3(a) illustrates the early-time voltage waveform at the potheads. A similar waveform is applied to the primary windings (although the charging of the winding capacitances will distort this waveform at later times).

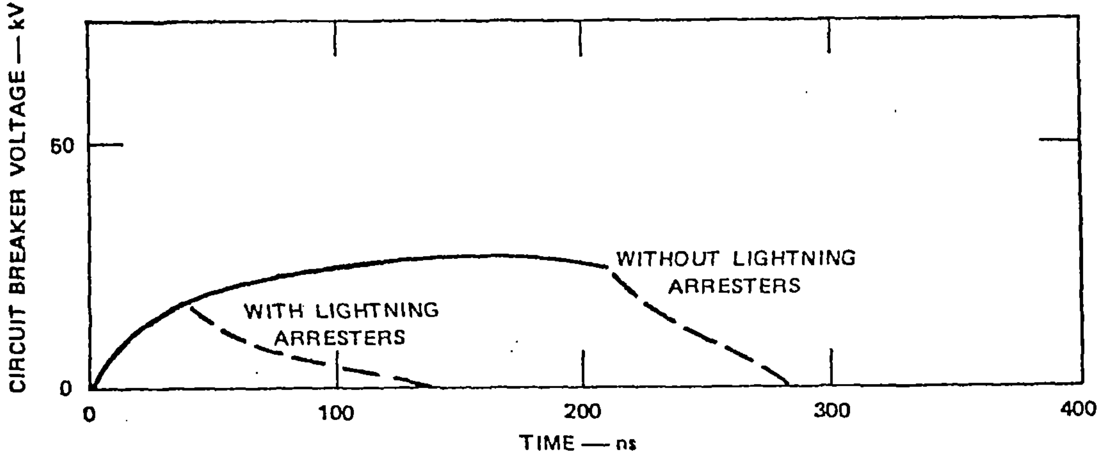
The voltage delivered to the circuit breaker panel (through the service entrance conduit) is about 1/3 the primary voltage at early times, but for a 10 ohm load, the load circuits discharge the transformer secondary windings faster than the source can charge them through the primary windings. Thus at later times ($t \gg 80$ ns) the integration performed by the high voltage cable impedance and lumped primary capacitance is differentiated by the interwinding capacitance and the load impedance. The waveform of the voltage across a 10 ohm load on the main circuit breaker panel is shown in Figure 3(b).

Buried Line with Ground-based Transformers

The buried distribution line can be treated as a current source driving the primaries of the transformers. The short-circuit current induced in the buried distribution line (by a vertically incident wave with the electric vector parallel to the line) has the waveform shown in Figure 1 with a peak current at about 220 ns of 1500 A. The source impedance of the buried line is about 30 ohms. Although the transformer bushing capacitance causes some integration of the leading edge of the



(a) VOLTAGE AT POTHEADS



(b) VOLTAGE ACROSS A 10-ohm LOAD AT MAIN CIRCUIT-BREAKER PANEL

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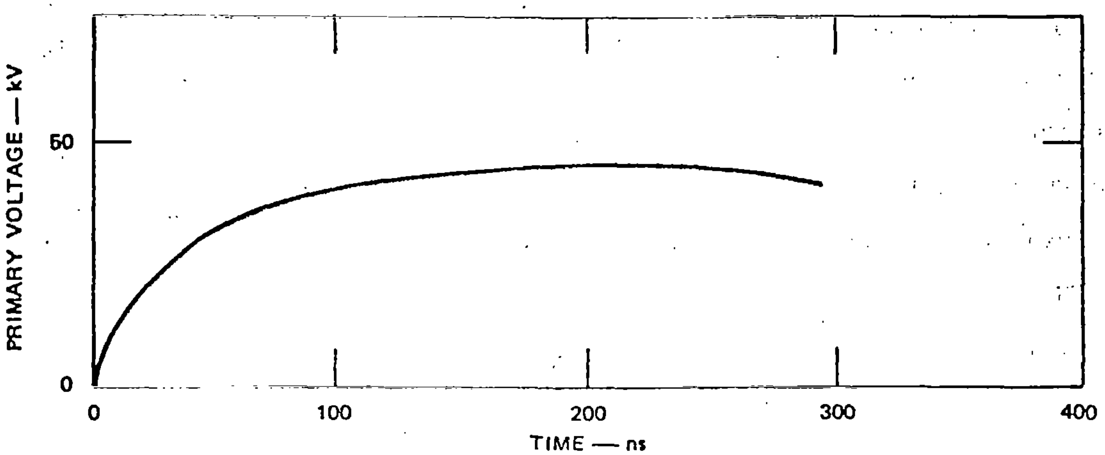
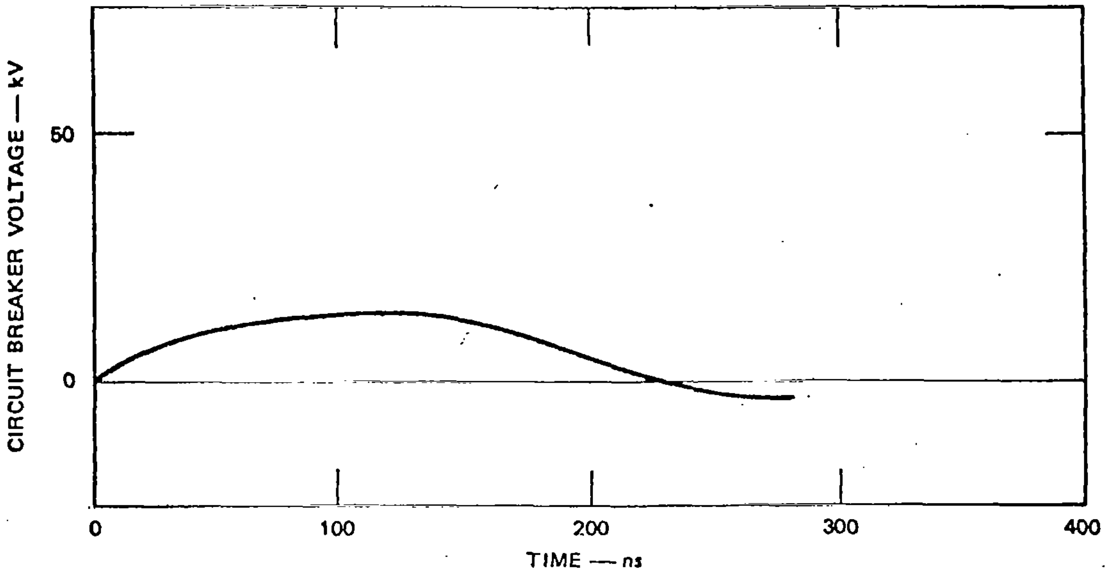
FIGURE 3 APPROXIMATE EARLY-TIME VOLTAGE WAVEFORMS FOR ABOVE-GROUND LINE WITH GROUND-BASED TRANSFORMERS pulse, the integration time constant is quite short (a few ns) so that the voltage applied to the primary terminals is essentially the open-circuit voltage of the buried line. The peak voltage applied to the primary is thus 45 kV and it occurs at 200 ns. The secondary voltage and circuit-breaker load voltage are initially about 1/3 the primary voltage but at later times (t > 160 ns) the interwinding capacitance and load/conduit impedance differentiate the primary voltage. The approximate primary and load voltage waveforms are shown in Figure 4. Because there is some doubt that lightning arresters across the primary windings of the transformer would fire with a 45 kV transient, no estimates have been made for the case when the lightning arresters fire.



(a) VOLTAGE AT TRANSFORMER PRIMARY



(b) VOLTAGE ACROSS 10-ohm LOAD AT MAIN CIRCUIT-BREAKER PANEL

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FIGURE 4 APPROXIMATE EARLY-TIME VOLTAGE WAVEFORMS FOR BURIED DISTRIBUTION LINE