Interaction Notes

Note 246

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POWER SYSTEM EMP PROTECTION*

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Abstract

Voltage transients induced in electric power lines and control circuits by the electromagnetic pulse (EMP) from high-altitude nuclear detonations may cause widespread power failure and damage in electric power systems. This report contains a parametric study of EMP power line surges and discusses protective measures to minimize their effects. Since EMP surges have considerably greater rates of rise than lightning surges, recommended standards and test procedures are given to assure that surge arresters protect equipment from damage by EMP. Expected disturbances and damage to power systems are reviewed, and actions are presented which distribution companies can take to counter them. These include backup communications methods, stockpiling of vulnerable parts, repair procedures, and dispatcher actions to prevent blackout from EMP-caused instabilities. A long-range program is presented for improving distributors' protection against EMP. This involves employee training, hardware protection for power and control circuits, and improvement of plans for emergency action.

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I. INTRODUCTION

1.1 Background

The gamma radiation from a single high-altitude nuclear explosion can produce an electromagnetic pulse (EMP) which blankets a large fraction of the United States. For example, a height of burst of 100 km will illuminate a circle of 1200 km radius, and if the detonation is of sufficient height (400 km) and suitably placed (over the geographic center) the EMP will blanket the entire continental United States (Fig. 1.1).

This EMP from a high-altitude explosion is very brief in duration, but nevertheless, very intense. The electromagnetic energy from such a pulse will be coupled into all extended conducting structures such as antennas and transmission lines. The surges induced in such structures have been studied and reported.[1,2,3] Voltages induced can exceed one million volts and currents can reach ten thousand amperes. The time of duration of such an EMP-induced surge is typically of the order of a few microseconds or less.

Such surges will be ubiquitous on a power system, figuratively searching out any and all weaknesses in the system. As previous studies have shown, these weaknesses are exploited by EMP to cause arcing and flashover with consequent power follow (the continual flow of ac power across an arc or flashover after its initiation) and circuit breaker and recloser action, puncturing of insulation, and malfunction or damage to unprotected supervisory control as well as to unprotected communications equipment.[2,4] Cumulative effects due to multiple high-altitude nuclear explosions might well cause lockout of reclosing breakers. Collective effects due to the widespread nature of the EMP can affect the stability of the entire power grid.[5]

1.2 Objective and Scope

The objective of the present study is to produce guidance material for use by power companies to upgrade their system with respect to EMP protection.

The scope of the work is as follows:

1. Develop standards and techniques for the use of EMP protection

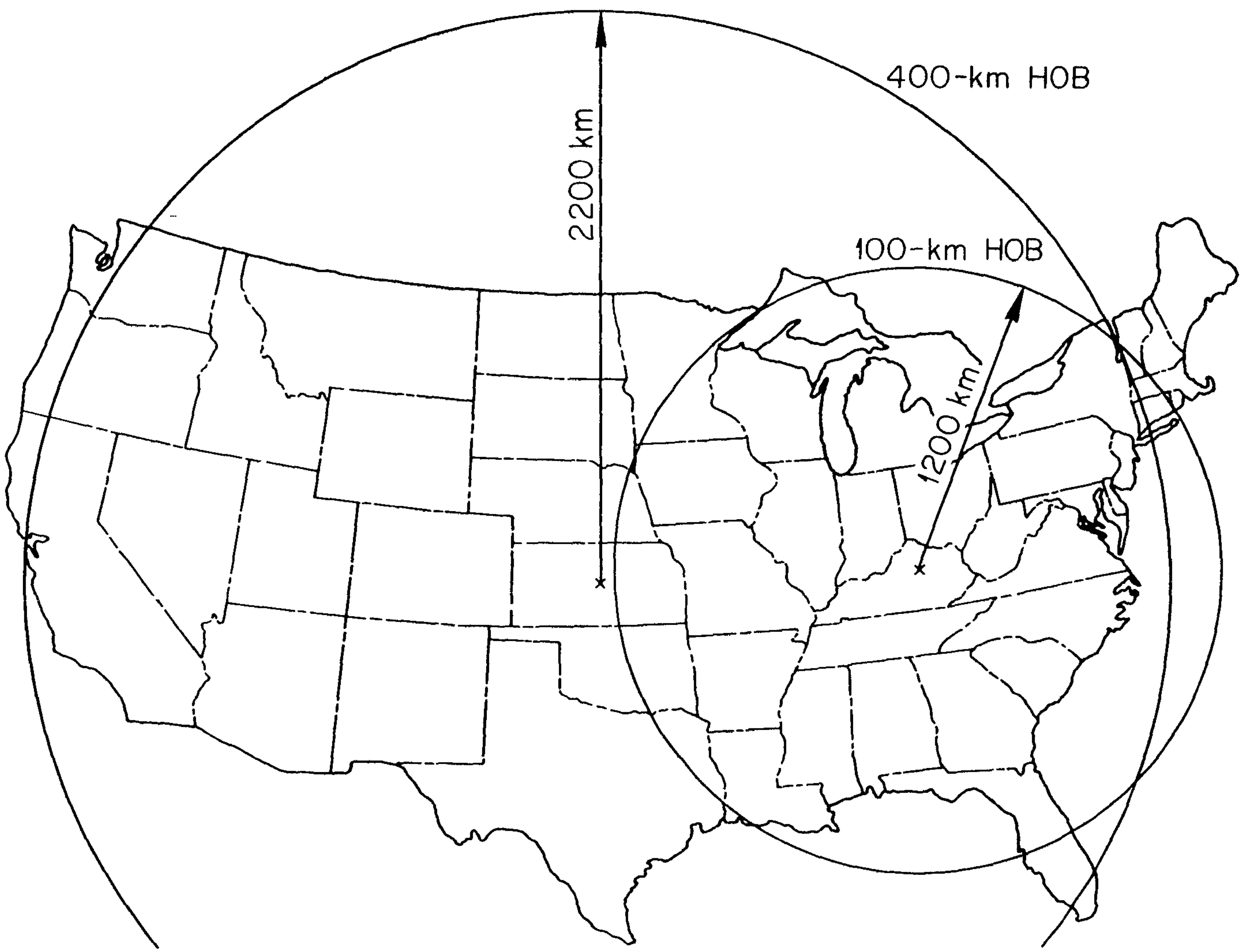

Fig. 1.1. Area of coverage of EMP from High Altitude Detonations.

devices in power transmission and distribution systems. This includes the use of a combined lightning and EMP arrester.

2. Develop measures that could be taken to help protect a local power system, assuming a few minutes warning period.

3. Determine ready recognition means that an EMP event has occurred and what actions can be taken by local power companies. These may include considerations of system instabilities, as well as the recovery of critical civilian systems such as water and sewage.

4. Outline a program by which a power company may upgrade its system with respect to EMP vulnerabilities.

This report serves to outline such a program for protecting power distribution companies against EMP effects.

II. EMP LINE SURGES

2.1 The EMP Environment

The detonation of a nuclear weapon is accompanied by intense transient electric and magnetic fields called the electromagnetic pulse (EMP). The characteristics of EMP have been described in previous reports.[1-3] A brief description is repeated here in order to give the assumptions used in this study.

The electromagnetic fields radiated from nuclear detonations vary greatly with weapon yield and detonation location. An intense EMP is produced by both low- and high-altitude detonations. Compared to high-altitude detonations, the fields produced by low-altitude detonations attenuate quickly with distance from the blast and are normally accompanied by shock waves. Power lines which would be affected by low-altitude EMP would probably be damaged by the shock from the nuclear blast. For this reason, low-altitude EMP is not very significant for commercial power systems.

The fields produced by a detonation at about fifty kilometers or greater is called high-altitude EMP. A single high-altitude EMP can cover hundreds of thousands of square kilometers and will likely encompass an entire commercial power grid. Electrical surges will be induced almost simultaneously in all of the transmission and distribution lines in the system. Most of these lines will be completely free from the shock and other effects of the nuclear blast. In the event of a nuclear attack, commercial power systems in nearly all parts of the nation are expected to be subjected to numerous EMP's produced by the detonation of megaton-range weapons just outside the earth's atmosphere. High-altitude EMP is very significant to commerical power systems, and its effects are considered in this study.

The high-intensity electromagnetic fields radiated from high-altitude bursts are largely the result of the interaction of the geomagnetic field with the Compton current which is due to the gamma radiation. The direction of the electric field is normally at right angles to the earth's magnetic field. For the continental United States, the geomagnetic dip angle is 60 to 70 degrees. This implies that the incident EMP electric field is likely to lie between zero and 30 degrees off the horizontal, depending on the direction of propagation of the incident wave.

For the purpose of calculating surges induced in power lines by EMP, an analytical representative pulse is used. An EMP line surge is a function of the amplitude and time history of the EMP as well as many other parameters. To reduce the number of parameters in a study of EMP surges and for the purpose of establishing a standard, it is convenient to choose a fictitious plane wave pulse with an amplitude, rate of rise, and a decay time which exceeds those of most EMP's. This fictitious pulse will induce power line surges of magnitudes and durations equal to or larger than those of the possible range of likely EMP line surges. The representative pulse that we have selected is a double exponential with the electric field given by

$$E(t) = E_o(e^{-\alpha t} - e^{-\beta t}) \quad , \qquad (2.1)$$

where

$$E_o = 94.5 \text{ kV/m} \qquad (2.2)$$

$$\alpha = 5 \times 10^8 \text{ sec}^{-1} \qquad (2.3)$$

$$\beta = 5 \times 10^8 \text{ sec}^{-1} \quad . \qquad (2.4)$$

The electric field waveform given by Eq. (2.1) is shown in Fig. 2.1. The peak electric field is 90 kV/m. The time to peak is about 10 ns and the total fall time is near 1 μsec.

2.2 Coupling Analysis

Above-ground power lines are excellent receiving antennas for EMP. They can collect large amounts of energy due to their length; distribution lines have typical lengths of 1-30 miles. The EMP current surges induced in each of the three phases of the line are almost identical. Large voltages are developed between each phase and the earth ground which forms the return conductor for the common mode currents. EMP-induced phase-to-phase voltages are relatively small. Therefore, for the purpose of coupling analysis, it suffices to consider a one-wire model of a power line.

An infinitely long wire of radius a and height h above the earth is shown schematically in Fig. 2.2. The incident representative EMP plane wave and induced current are also shown. The incident direction of the EMP is determined by the angles φ and θ associated with the propagation vector $\vec{k}$ as shown. The direction of the electric field is then specified by the angle ψ between the electric field vector $\vec{E}$ and the vertical plane containing the propagation vector $\vec{k}$. The magnetic field vector $\vec{B}$ is perpendicular to both $\vec{E}$ and $\vec{k}$, such that $(\vec{E}, \vec{B}, \vec{k})$ form a right-handed orthogonal set. The angle between $\vec{E}$ and the horizontal is given by $\sin^{-1}(\sin\theta\cos\psi)$. For example, if $\theta = 0$, the wave propagates vertically downward and both $\vec{E}$ and $\vec{B}$ are horizontal. If $\theta \neq 0$ and $\psi = 90^\circ$, then $\vec{E}$ is horizontal, but $\vec{B}$ has a vertical component. If additionally $\varphi = 90^\circ$, then $\vec{E}$ is parallel to the wire. For detonations over the continental U.S. the angle between $\vec{E}$ and the horizontal is always less than 30°, so θ and ψ are restricted to the range $\sin\theta\cos\psi \leq 1/2$. The values of θ and ψ given in Table 2.1 were chosen to lie in this range.

A parametric study on the EMP line surges has been performed to obtain representative surge waveforms. The results are presented later in this section and in the Appendix. The EMP voltage and current surges depend strongly on the incident EMP parameters and load impedance, and less strongly on the geometric parameters and the line and earth

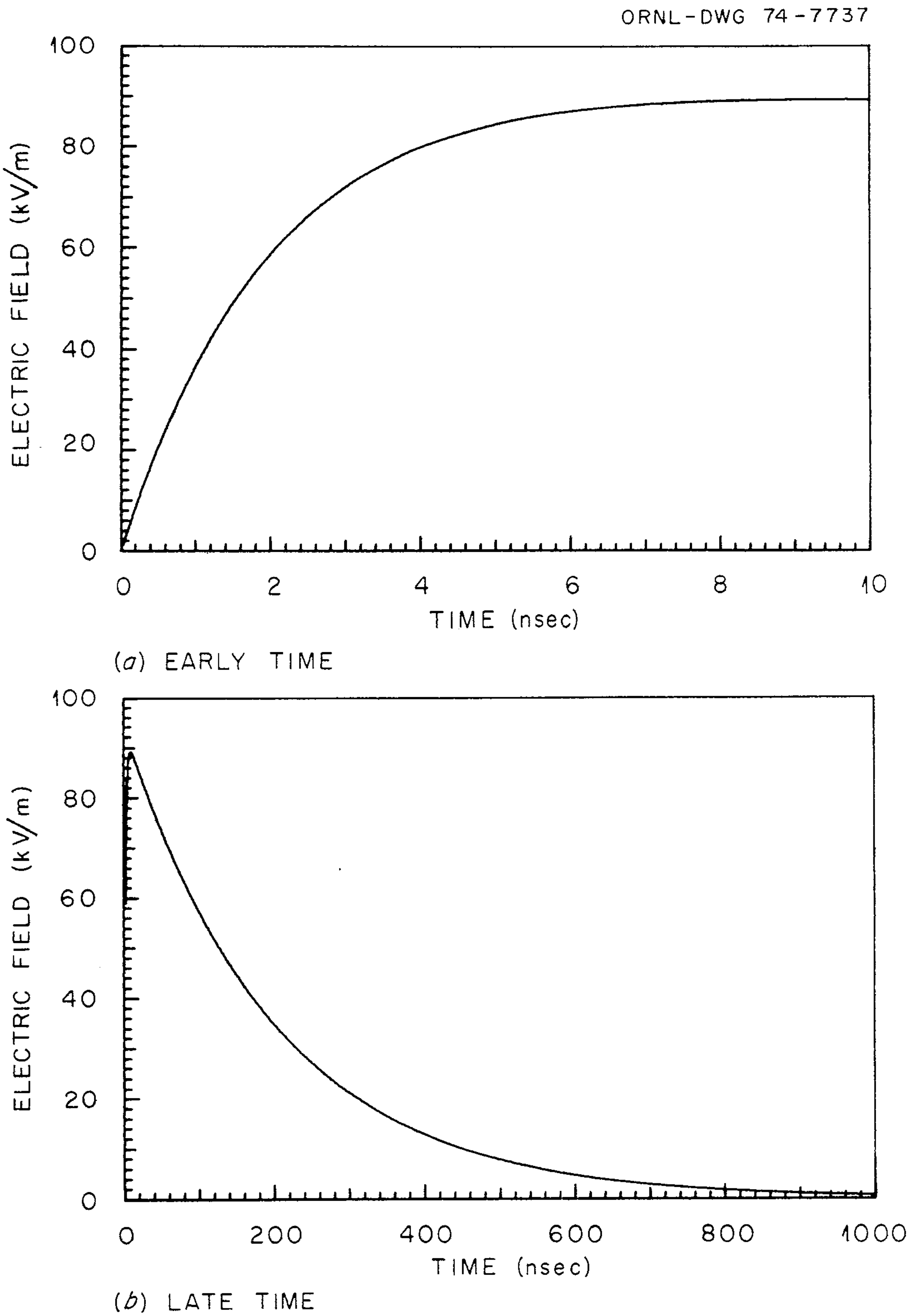

Fig. 2.1. Time history of the representative EMP.

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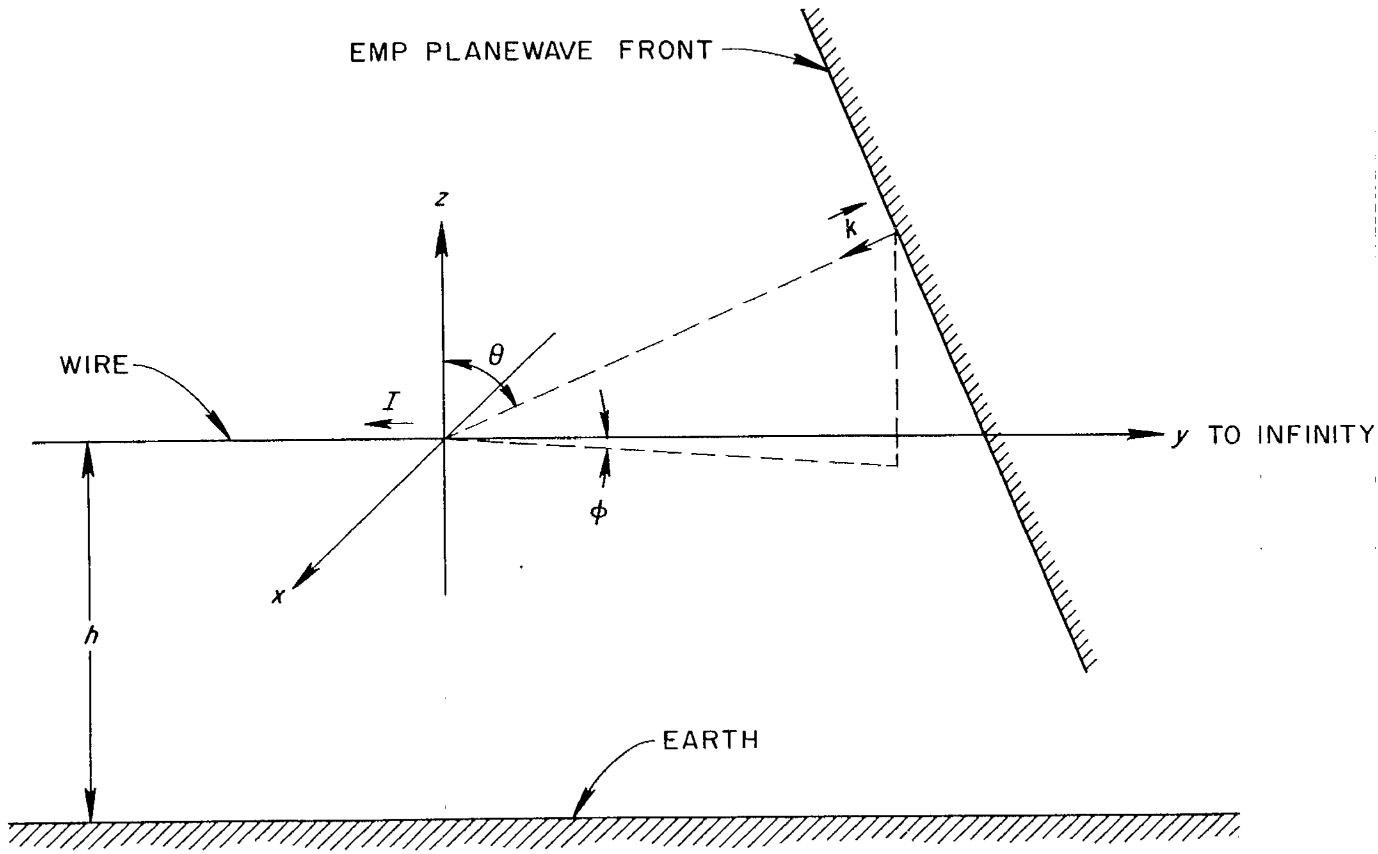


Fig. 2.2. Long wire above the earth and an incident EMP planewave.

Table 2.1. Summary of EMP line surges

Incident angles (degrees)			Infinite line			Transformer termination			Short circuit
			I_p	V_p	ROR	I_p	V_p	ROR	I_p
θ	φ	ψ	(kA)	(kV)	(kV/ns)	(kA)	(kV)	(kV/ns)	(kA)
60	0	60	2.2	950	13.8	2.75	1700	8.5	4.1
60	30	60	2.53	945	36.4	3.9	1640	12.0	4.6
60	30	90	2.0	760	19.6	3.0	1000	8.0	3.55
60	90	90	1.85	0.0	0.0	1.57	525	4.5	1.87
80	90	90	0.75	0.0	0.0	0.70	190	1.72	0.75
80	30	60	1.65	700	10.0	2.25	1320	5.8	3.0
80	30	90	1.23	540	34.6	2.2	590	6.0	2.35
80	0	60	10.0	4850	28.2	9.7	9000	32.8	19.5

NOTE: I_p = Peak current

V_p = Peak voltage

ROR = Rate of rise from 10 to 90 percent of peak.

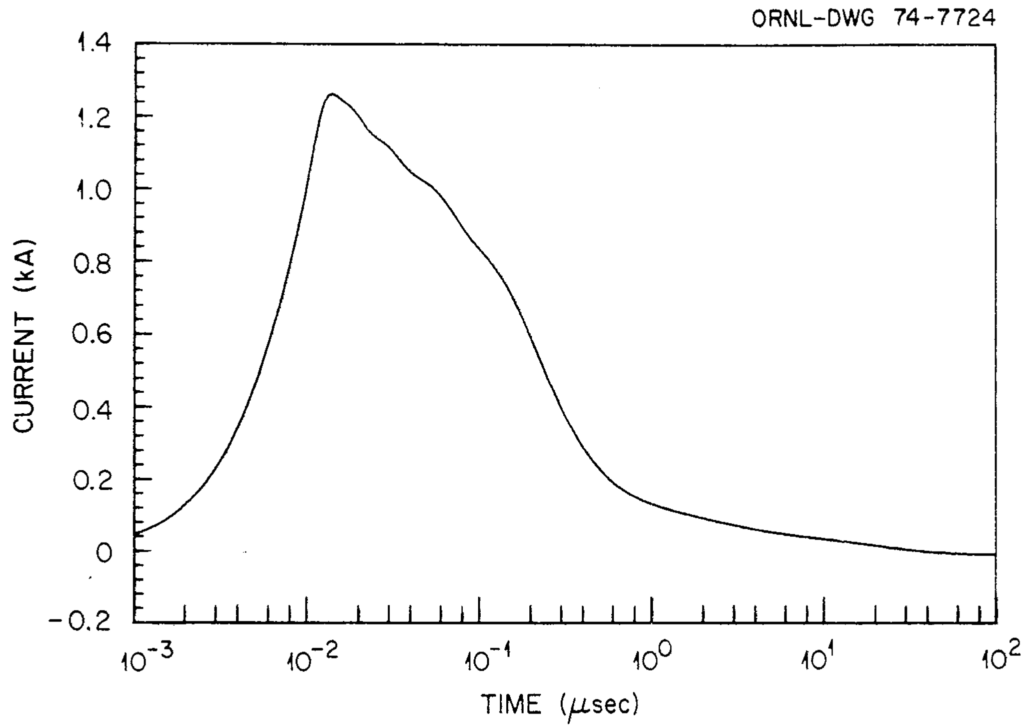
conductivities. To simplify the parametric study, we have chosen typical values for the geometric parameters and conductivities. Typical values for distribution lines are: line height, h, equal to 10 meters; wire radius, a, equal to 5 millimeters for 2/0 wire; the resistivity for commercial annealed copper is 1.724×10^{-6} centimeter-ohms; and a common earth conductivity is 5 millimhos per meter. The angles φ, θ, and ψ are varied over practical ranges, three load impedances are used, the characteristic impedance of the line (the infinite line case), a short circuit, and a mid-frequency model of a transformer.

2.3 Surges on a Long Line

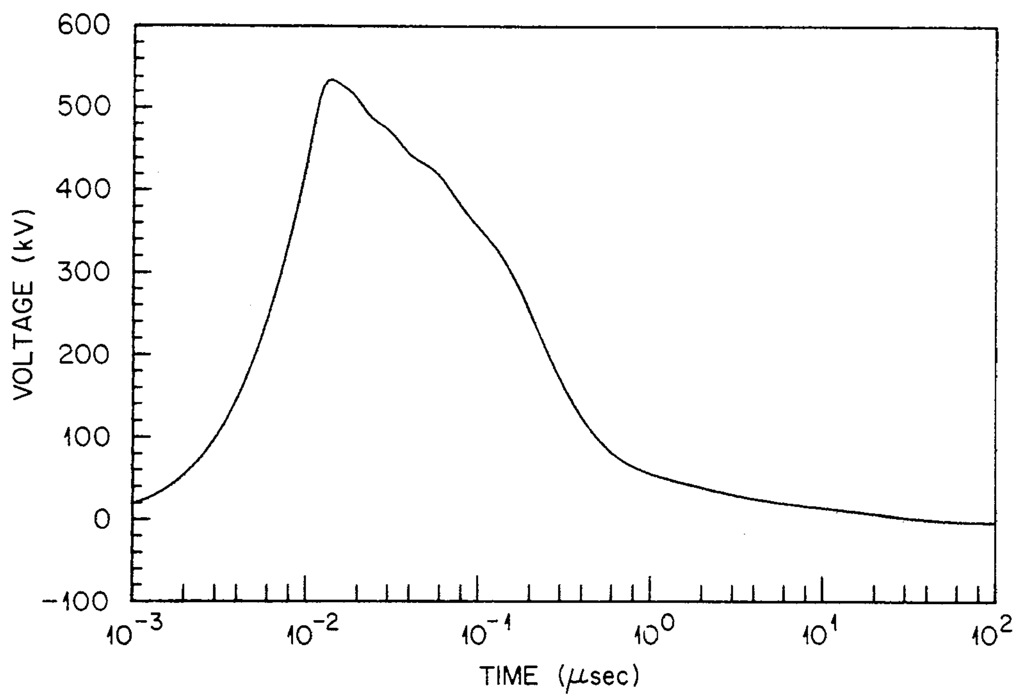
The current induced by EMP on a long line of several miles is similar to that induced on an infinitely long line. The infinitely long line is therefore a convenient model for the single power line that extends several miles in both directions from the point where the surge is calculated.

The current and voltage surges induced on an infinitely long line 10 m above the earth by the representative EMP for various wave incident directions and polarizations are presented in Figs. A1 through A6 of the Appendix. As a representative example, Fig. 2.3 shows the EMP line surges for the incident wave parameters $\theta = 80^\circ$, $\varphi = 30^\circ$, and $\psi = 90^\circ$. The current in Fig. 2.3 has a peak of near 1.2 kA and the induced voltage has a peak of over 500 kV. After one microsecond, the surges have decayed to a relatively low value.

The current waveforms have been calculated from a first-order solution of an infinite wire above the ground. Scattering theory was used to calculate the current response of a wire in free space. The approximate effect of the ground was included by using the total field, incident plus ground-reflected, in the "free space" solution. In this manner the first ground reflection, which is the major effect of the ground, is included in the solution but subsequent wave reflections between the wire and ground are not. The voltage waveforms were calculated from transmission line theory,[6] i.e., the voltage is equal to the product of the current, the cosine of the angle between the line current and the propagation vector, and the characteristic impedance of the transmission line formed by



(*a*) CURRENT SURGE



(*b*) VOLTAGE SURGE

Fig. 2.3. Surges induced on an infinitely long line 10 m above the earth by representative EMP with $\theta = 80°$, $\varphi = 30°$, and $\psi = 90°$.

the line and the earth. The voltage calculated by transmission line theory is called the induced voltage. The induced voltage added to the voltage from the incident field is the total voltage on the line.

2.4 Surges on a Line Terminated by a Transformer

The EMP surges on a long line above the earth terminated by an impedance Z_t can be modeled as a semi-infinite line as shown in Fig. 2.4a. The induced surges can be computed from transmission line theory by employing the current induced on an infinite line as a current source.[3] To determine the impedance of a transformer, consider the mid-frequency model of the distribution transformer as shown in Fig. 2.4b. It is based on the capacitance coupling effect of the transformer; C_c is the primary-to-secondary winding capacitance and C_s is the secondary winding-to-ground capacitance. The transformer termination impedance is approximately the impedance of the capacitive network for the mid-frequency range between several hundred hertz and about 3 MHz.

The surges induced on a semi-infinite line 10 m above the earth terminated by the mid-frequency model of a transformer are shown in Figs. A7 through A13 of the Appendix for a range of incident wave directions and polarizations. A representative example is shown in Fig. 2.5 for $\theta = 80^\circ$, $\varphi = 30^\circ$, and $\psi = 90^\circ$. Current and voltage peaks in Fig. 2.5 are about 2 kA and 600 kV, respectively.

2.5 Short-Circuit Current Surges

The EMP current surges through a short circuit are of interest for specifying the current handling capability of surge arresters. The short-circuit current can be computed by the same method used in subsection 2.4 with $Z_t = 0.0$. The current surges through the short circuit of a semi-infinite line 10 m above the earth are shown in Figs. A14 through A16 of the Appendix for a realistic range of incident wave directions and polarizations. Examples of the short-circuit current surges are shown in Fig. 2.6 for $\theta = 80^\circ$ and $\psi = 90^\circ$. Figure 2.6a shows the surge for $\varphi = 30^\circ$ and Fig. 2.6b shows the surge for $\varphi = 90^\circ$. Note that the peak current for $\varphi = 30^\circ$ is about three times that for $\varphi = 90^\circ$.

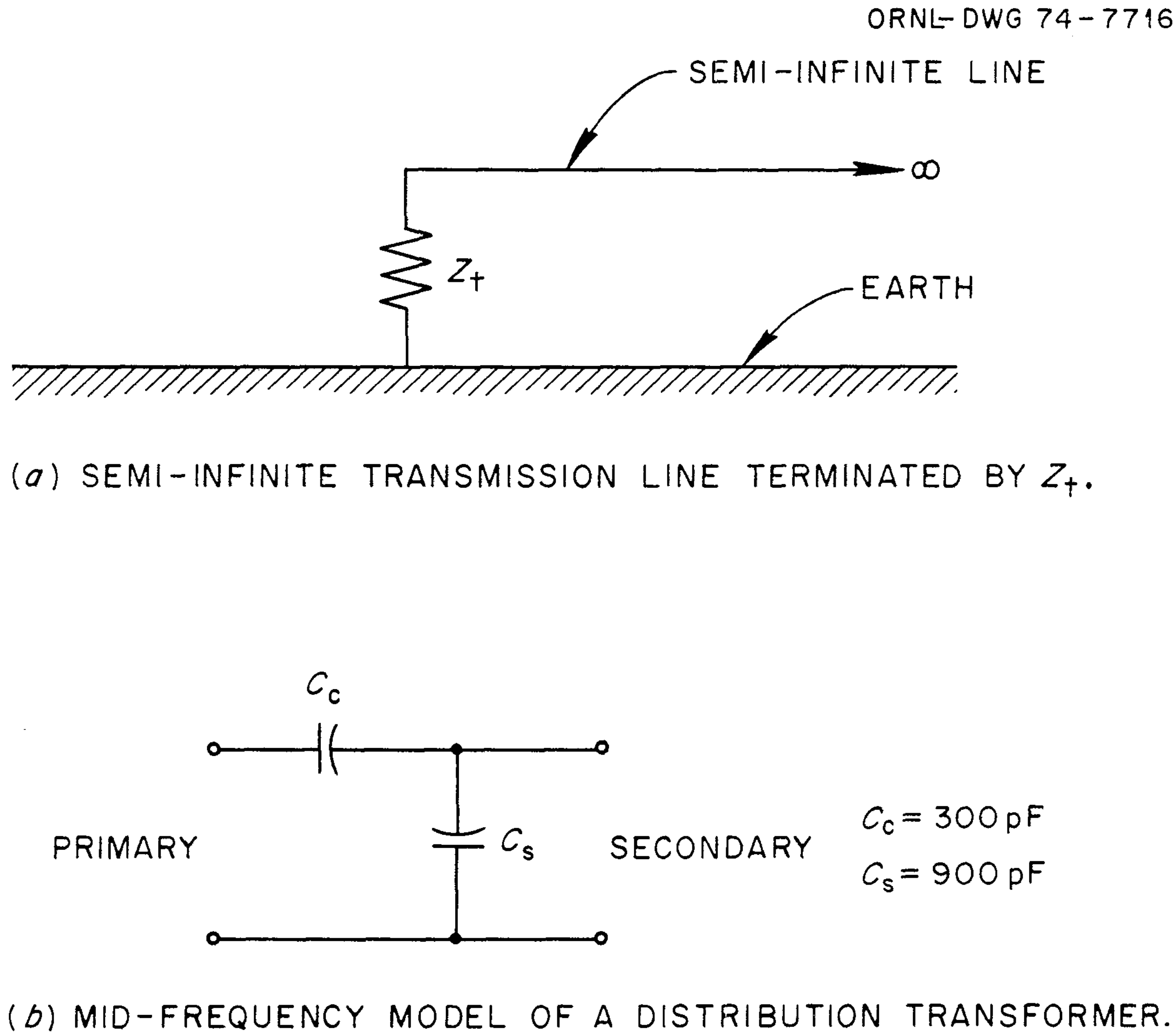


Fig. 2.4. Transmission line and transformer models for the analysis of EMP line surges.

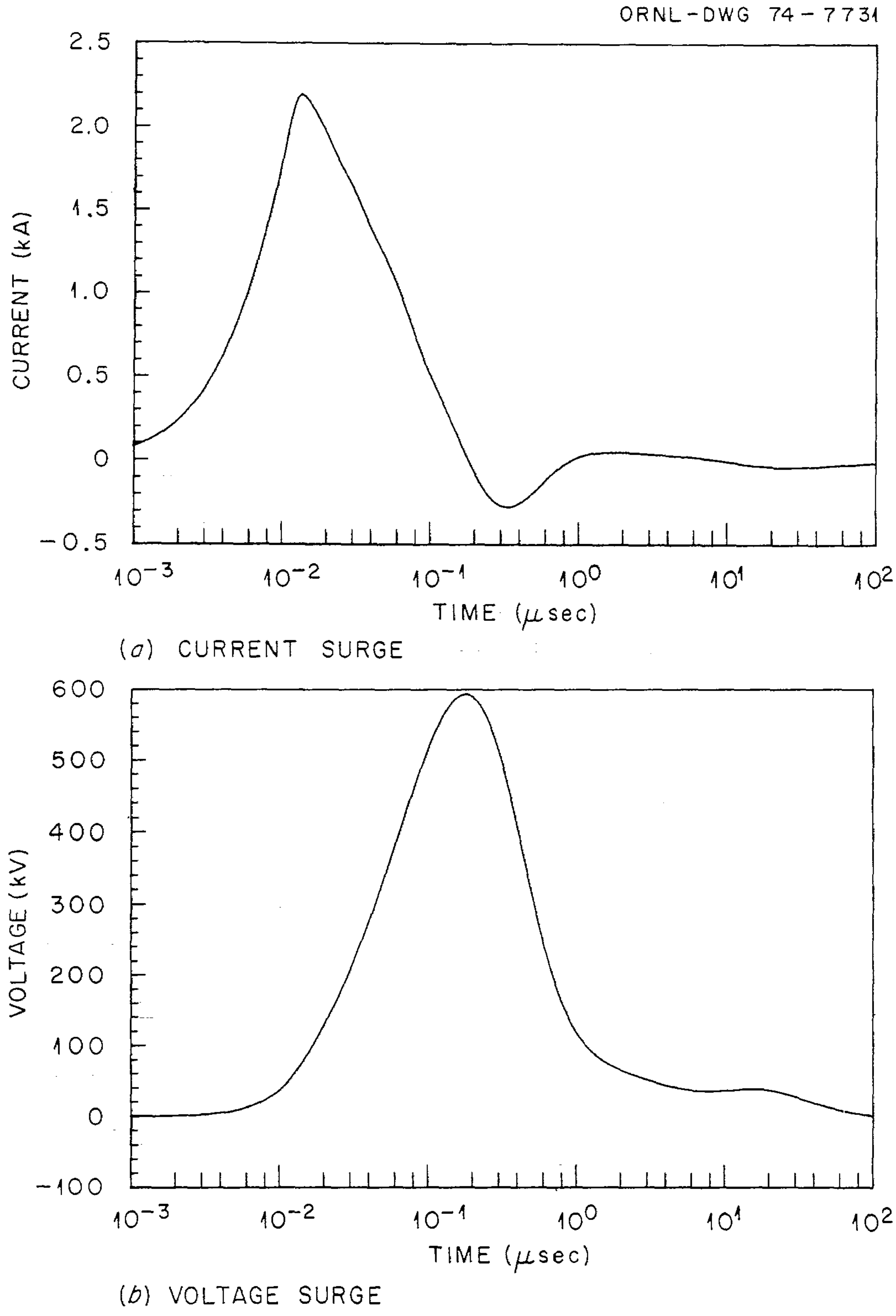
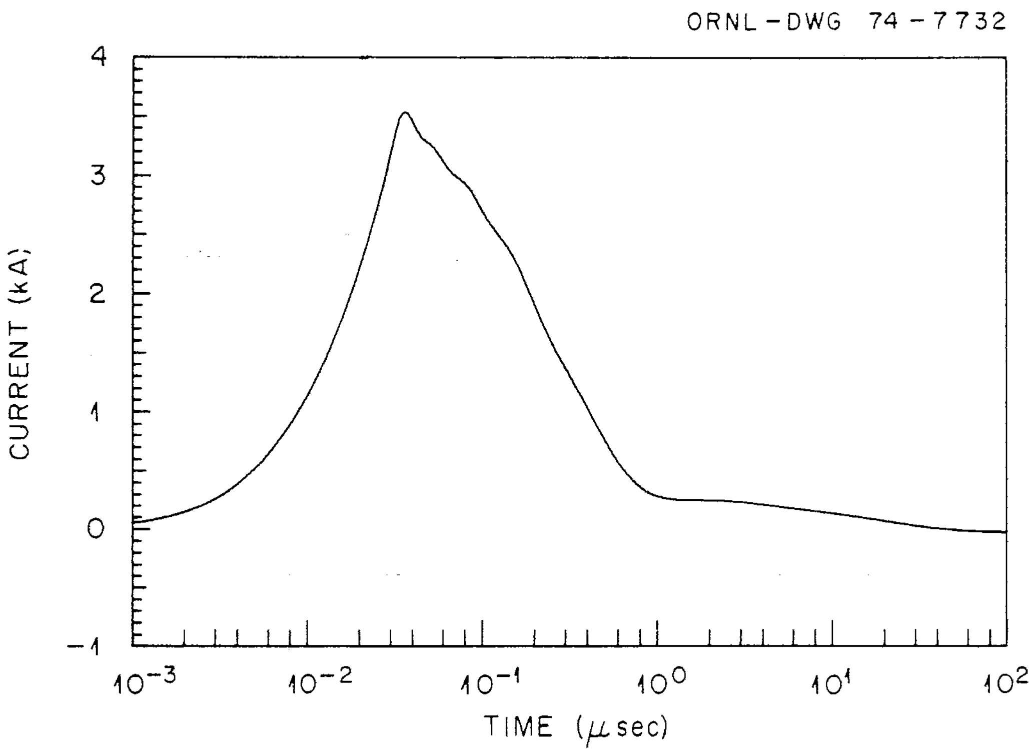
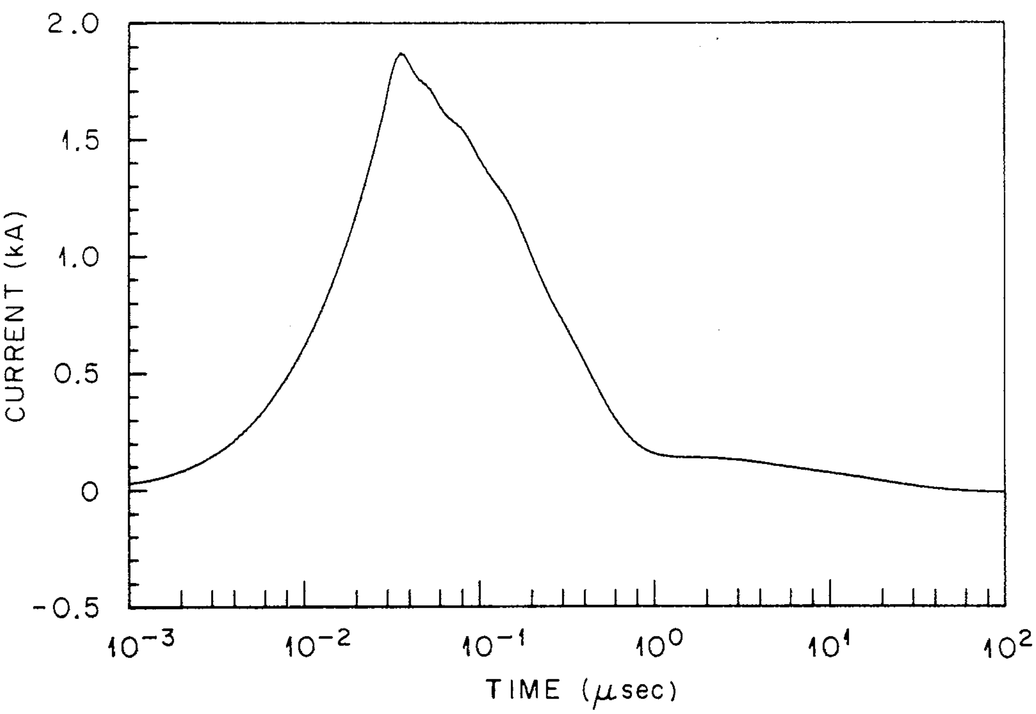


Fig. 2.5. Surges induced on a semi-infinitely long line 10 m above the earth, terminated by a transformer by representative EMP with $\theta = 80^{\circ}$, $\varphi = 30^{\circ}$, and $\psi = 90^{\circ}$.



(*a*) PHI EQUAL TO THIRTY DEGREES



(*b*) PHI EQUAL TO NINTY DEGREES

Fig. 2.6. Current surges induced on a semi-infinitely long line 10 m above the earth, terminated by a short circuit by representative EMP with $\theta = 80^{\circ}$ and $\psi = 90^{\circ}$.

2.6 Results of the Parametric Study

The results of the parametric study of EMP line surges are summarized in Table 2.1. The values presented in the table have been estimated from the surge waveform presented in this section and in the Appendix.

The current peaks for an infinitely long line are within the range from 0.75 kA to 10 kA and the line voltage peaks range from 0.0 to 4850 kV. The induced line voltage is zero for cases where the electric field vector is parallel to the wire. The voltage rate of rise, from 10 to 90 percent, of the voltage surges ranges from 0.0 to 36.4 kV/ns. The general effect of the transformer termination is an increase in the peak current and voltage surges and a decrease in the rate of rise of the voltage surge. The transformer voltage rate of rise ranges from 1.72 to 32.8 kV/ns. The short-circuit current surges have peaks that range from 0.75 to 19.5 kA.

The calculations of the EMP-induced line surges presented in this report neglect corona and other discharge mechanisms. (Corona discharge can reduce the EMP surge peaks and rates of rise by 20 percent or more.)[3] These surges are therefore considered as an acceptable and conservative basis for EMP protection requirements.

III. SURGE PROTECTION REQUIREMENTS

3.1 Introduction

Present-day electric power systems use many devices and components for the protection of equipment. These include circuit-opening devices, such as fuses or circuit breakers with protective relay systems, reactors, condensers, regulators, and lightning arresters. The lightning arrester, or more appropriately the surge arrester, is the device that is depended upon to provide protection against surges such as those produced by lightning and EMP. A surge arrester differs from other surge-protective devices such as spark gap in that it is designed for repeated limiting of voltage surges on 50 or 60 hertz power circuits by passing surge current and then automatically interrupting the flow of ac power follow current. Spark gaps do not always interrupt power follow current.

The present standards on surge arresters are based largely on lightning protection requirements. If these devices are to be used for protection against EMP, then the standards must be revised to include EMP protection requirements.

3.2 Present Standards

Surge arresters are designed and manufactured according to American National Standard ANSI C62.1-1971. This is essentially identical to the Institute of Electrical and Electronics Engineers Standard IEEE Std 28-1972 and constitutes, by reference only, an integral part of the National Electrical Manufacturer's Association (NEMA) Standards Publication for Surge Arresters, LA 1.

These standards include: (1) basic definitions applicable to surge arresters, (2) standard service conditions under which an arrester is required to operate successfully, (3) the classification of arresters and the voltage ratings of arresters in each class, (4) construction standards including identification to be included in labeling, mounting, and terminal connections, and (5) various design and conformance tests.

The tests are of nine types:

(1) Surge and power-frequency voltage withstand tests of the arrester insulation with internal parts and external series-gap electrodes removed.

(2) Power-frequency sparkover tests of the arrester to establish that the completely assembled arrester can withstand the rated power-frequency operating voltage with a specified margin of safety.

(3) Tests which determine the impulse sparkover voltage-time characteristics. These characteristics show the relation between impulse sparkover voltage and time to sparkover for specified impulse wave shape which are chosen to be representative of typical lightning and switching surges.

(4) Discharge-voltage tests which show the voltage across the arrester terminals while the arrester is discharging as a function of the discharge current. The standards fix the shape of the current surge and specify several current crest values.

(5) Discharge-current-withstand tests consisting of (a) high-current, short-duration and (b) low-current, long-duration tests. These serve to demonstrate the adequacy of the electrical, mechanical, and thermal design of the arrester.

(6) Duty-cycle tests to establish the ability of the arrester to interrupt follow current successfully and repeatedly under specified conditions.

(7) Radio-influence-voltage test to provide a measure of the high frequency voltage generated by an arrester. Such voltages may cause objectionable communication interference.

(8) Internal-ionization-voltage test to provide a measure of ionization current within the arrester. Such currents may cause deterioration of internal arrester parts.

(9) Pressure-relief tests to demonstrate that failed arresters will withstand ensuing fault current under specified conditions without violent disintegration.

3.3 Recommended Standards for EMP Surge Arresters

An arrester which is to be used for protection against EMP-induced surges as well as for lightning and switching surges should conform not only to the standards set forth in ANSI C62.1-1971 but also to additional or modified standards. These additional standards should reflect the fact that EMP-induced surges have greater rates of rise and shorter times to crest values than do lightning surges. As indicated in the Appendix, the rates of rise may be greater than 30 megavolts per microsecond and the virtual duration of wave fronts (as defined in the ANSI standard) may be as short as 20 nanoseconds. These numbers are not necessarily "worst case" numbers, but they can form a basis for specifying requirements against EMP-induced surges.

In order for a surge arrester to protect a system from high-voltage surges such as those produced by EMP, it is necessary that the arrester act sufficiently fast so that surges capable of producing damage to equipment will be substantially modified by the action of the surge arrester. There will always be an initial part of the surge which escapes the modifying action of the arrester's discharging. This part of the surge passed on must be incapable of damaging the equipment which is being protected or of causing control circuits to malfunction in such a way that performance or operation is interrupted for unacceptably long periods. Otherwise, the arrester is not providing sufficient protection.

With the foregoing statements in mind, and pending the establishment of formal standards by organizations such as IEEE, ANSI, and NEMA, the following additions to ANSI C62.1-1971 are recommended for arresters to be used for EMP- as well as lightning-surge protection.

Impulse tests of arrester insulation withstand test voltages should include, in addition to those given in Table 3 on page 14 of ANSI C62.1-1971, impulse tests using a 0.02 x 1 full wave (see definition 2.29.1 of ANSI C62.1-1971) with crest values of 5 MV or crest values 50 times those given for impulse tests in that table, whichever is smaller.

Additional front-of-wave impulse sparkover tests should be made using nominal rates of rise as follows:

Voltage rating in kilovolts	Nominal rate of rise
Less than 3	500 kV/μs
3 through 48	5 MV/μs for each 12 kV of arrester rating
Above 48	20 MV/μs

The arrester insulation must not flashover during these tests.

The EMP impulse sparkover voltage-time characteristics may be determined as follows. Using a 0.02 x 1 wave shape beginning at a crest voltage below arrester sparkover, the prospective test voltage shall be raised in steps until sparkover occurs. Continue the increase in prospective voltage for at least three steps until the time to sparkover or the rate of rise approaches that of the foregoing additional front-of-wave test. Five tests at each step using that polarity which gives consistently higher sparkover values are sufficient. The arrester insulation must not flashover during these tests.

Discharge voltage characteristics shall be determined for EMP-type surges in addition to those tests given in the standards. For these tests, a 0.16 x 0.4 current waveform shall be used. For each rating of a given arrester design between 1 and 12 kV and of prorated sections for ratings above 12 kV, obtain discharge-voltage time and current-time oscillograms using 1,000, 2,000, and 5,000 ampere crest values. From these, obtain the discharge-voltage-current characteristics for each rating or prorated section.

On each arrester for which the design has been tested according to the above additional EMP standards there shall be firmly attached identification data which includes a statement that the arrester (design) has been tested using EMP-type surge standards.

In summary, a preliminary set of tests and standards has been given for surge arresters, in addition to those specified by the American National Standards Institute. These additional standards are intended to serve as a guide to setting standards for surge arresters to be used for protection against EMP surges as well as against lightning and switching surges.

The usefulness of any standards such as these is limited unless coordinated with similar standards for testing insulation withstand voltages for EMP-type surges. In particular, such standards should be established for transformers and insulators.

Some of the numbers in these preliminary standards are certain to be modified. Nevertheless, the rates of rise, voltage withstand levels, current and voltage crest values, and the wave shape of the proposed standard 0.02 x 1 voltage pulse are sufficiently well established that a great deal of protection against EMP can be assured by using these standards.

3.4 Surge Arresters Presently Available

Modern surge arresters are classified by the IEEE and NEMA standards as station, intermediate, distribution, and secondary arresters. Station arresters are used to protect large and important transformers and switchgear. Intermediate arresters are used to protect smaller or less important transformers and switchgear. Distribution arresters are used to protect distribution transformers and other distribution apparatus. And secondary arresters are used to protect equipment connected to secondary circuits of voltages up to 650 VAC.

Other arrester classifications used by NEMA are protector tubes, gaps, and protective resistors. Protector tubes are used to protect insulators and pole-top switches. Gaps are used to isolate circuits from each other under normal conditions and to provide a path for surges. Protective nonlinear resistors are used to provide a surge shunt for apparatus such as series winding of regulators and generators.

Arresters are rated in terms of ac voltage. Distribution arresters are also rated in terms of current. The voltage ratings of arresters cover different ranges according to type: station arresters range from 3 kV to 684 kV, intermediate arresters range from 3 kV to 120 kV, distribution arresters range from 1 kV to 30 kV, and secondary arresters range from 175 V to 650 V. The minimum crest current standard for an arrester is for a surge current having a (4 to 8) x (10 to 20) waveshape. The crest currents are: 100 kA for station arresters, 65 kA for intermediate and distribution arresters, and 10 kA for secondary arresters.

The impulse sparkover voltage of a station surge arrester rated above 15 kV ranges from two to three times its voltage rating for a surge having a 1.2 kV/ns rate of rise. The maximum discharge voltage also ranges from two to three times the arrester's voltage rating for 10 kA surges. A station arrester rated under 15 kV has a sparkover voltage of about three times its voltage rating for a voltage surge with a rate of rise of 1 kV/ns per 12 kV arrester rating. And the maximum discharge voltage is also about three times its voltage rating for 10 kA surges.

Distribution-type arresters are generally less effective in suppressing surges. Sparkover voltages range from five to seven times the arrester's voltage rating for surges with 1 kV/ns rate of rise per 12 kV of arrester rating. And the maximum discharge voltage is about five times the arrester's voltage rating for 10 kA surges. Secondary arresters have sparkover voltages that range from six to ten times their voltage ratings for a transient with a 0.1 kV/ns rate of rise. The maximum discharge voltage of a secondary arrester is about the same as its sparkover voltage.

The general performance characteristics of arresters for surges with greater than a 1.2 kV/ns rate of rise is not well known since that information is normally not applicable to lightning and switching surges. ORNL and a few other groups[1,2,7] concerned with EMP surges have performed limited tests on a few selected surge arresters. Figure 3.1 shows voltage waveforms recorded by ORNL for a 15 kV station-type Kearney arrester. This arrester is also used as a distribution arrester at Oak Ridge National Laboratory.

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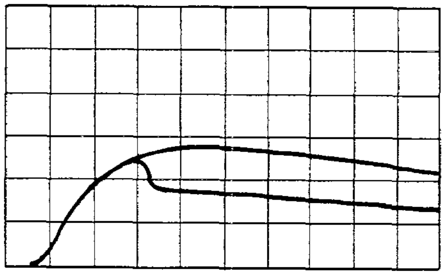
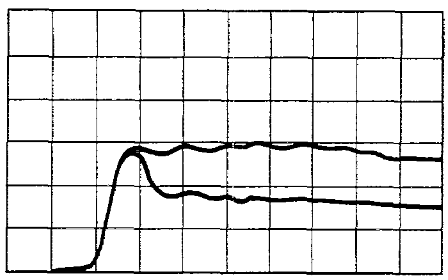


VERTICAL 25 kV/DIV
HORIZONTAL 100 nsec/DIV

(*a*) 0.28 kV/nsec RATE OF RISE

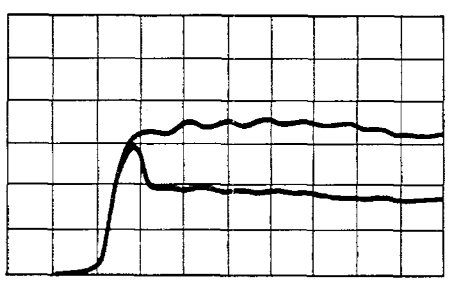
VERTICAL 25 kV/DIV
HORIZONTAL 200 nsec/DIV

(*b*) 0.38 kV/nsec RATE OF RISE



VERTICAL 25 kV/DIV
HORIZONTAL 50 nsec/DIV

(*c*) 2 kV/nsec RATE OF RISE



VERTICAL 25 kV/DIV
HORIZONTAL 50 nsec/DIV

(*d*) 2.33 kV/nsec RATE OF RISE

Fig. 3.1. Measured voltage surge (upper curve) and the voltage across a 15 kV Kearney arrester (lower curve) as a function of rate of rise.

The upper waveform in each graph of Fig. 3.1 is the applied voltage surge with the arrester out of the circuit. The lower curve is the arrester response. The voltage surge was provided by an EMP surge simulator. The surge fall time to half maximum was set for 1 μsec. The rise time and amplitude of the pulse was varied to obtain a range of voltage rates of rise. In Fig. 3.1a, a 0.28 kV/ns rate of rise was applied to the arrester. The arrester fired after about 230 ns. The sparkover voltage is about 60 kV and the maximum discharge voltage is near 40 kV. Figure 3.1b shows the arrester response to a pulse with a 0.38 kV/ns rate of rise. The arrester fired after about 100 ns at near 75 kV sparkover voltage. The maximum discharge voltage for this surge is 50 kV. In Fig. 3.1b, cable reflections can be seen after 1.5 μsec. This corresponds to the round trip transit time in the 500 ft of 50 ohm cable (RG-220/U type) between pulser and load.

In Figs. 3.1c and 3.1d, much faster rate of rise surges are used. The 2 kV/ns surge activates the arrester after 50 ns with a sparkover voltage of 75 kV and a discharge voltage of near 50 kV. In Fig. 3.1d, the 2.33 kV/ns surge fires the arrester after 45 ns. The sparkover voltage is near 80 kV and the maximum discharge voltage is about 55 kV.

The results of the ORNL test are summarized in Fig. 3.2. Results for a 9 kV arrester obtained by SRI[7] are shown in Fig. 3.3. This arrester exhibited a greater increase in breakdown voltage for fast rising pulses than did the one tested at ORNL. Tests on a Dale SPA-100, 120 VAC secondary arrester resulted in a sparkover voltage of 7 kV for 5 kV/ns surges.[8]

These results show that the pulse breakdown voltage of the presently available power line arresters is considerably higher for EMP surges than for lightning surges. For relatively slow rising EMP surges at 2 kV/ns, the sparkover voltage is about twice that due to lightning. More testing with pulses having large rates of rise is needed to determine arrester characteristics in the range required for EMP protection. For a very fast rising surge at 20 kV/ns, the sparkover voltage could be as much as ten times that due to lightning. The effects of arrester lead inductance, which were not investigated in the ORNL test, will further reduce the effectiveness of surge arresters against fast rising pulses.

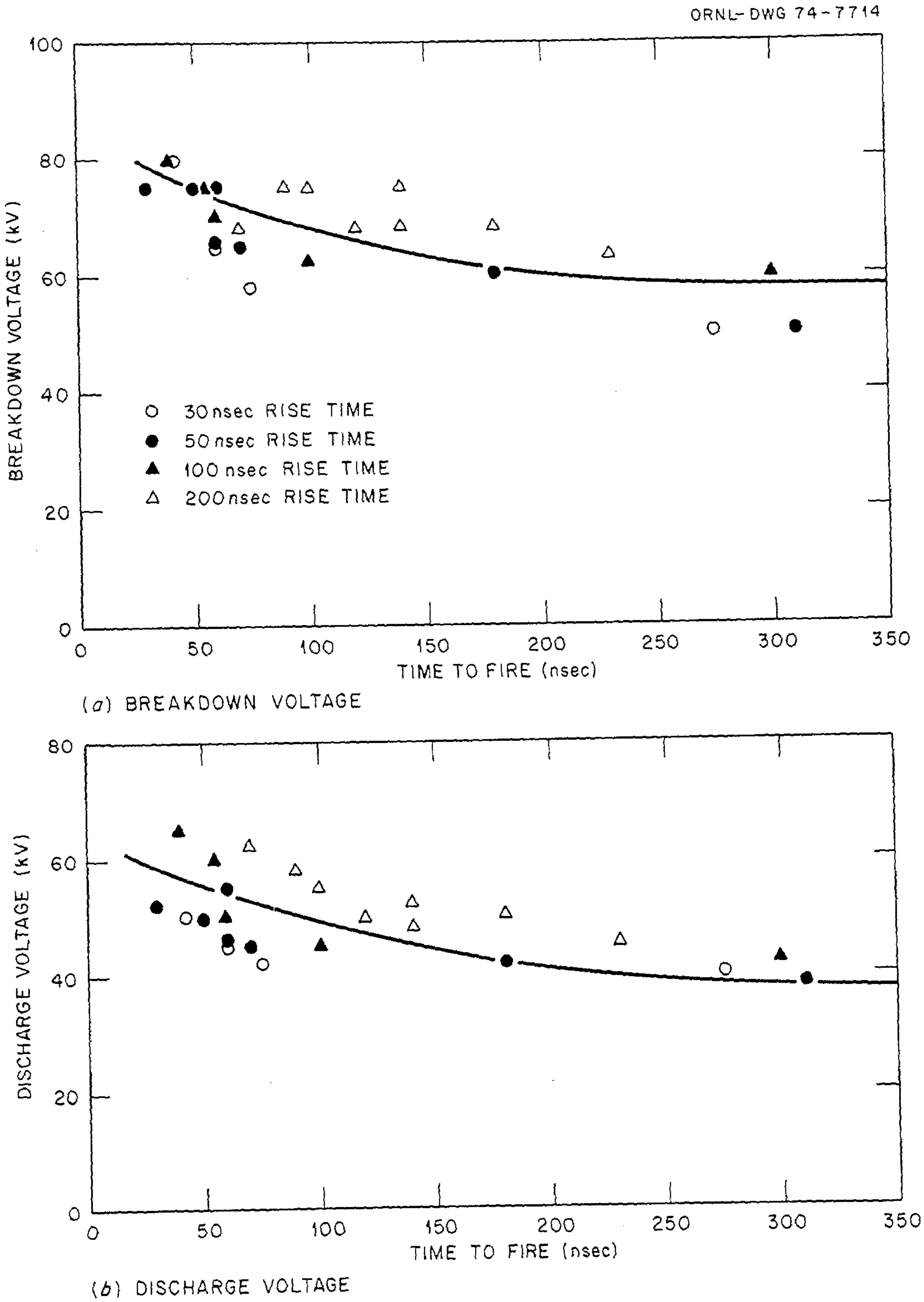


Fig. 3.2. Breakdown and discharge voltages for the 15 kV Kearney arrester.

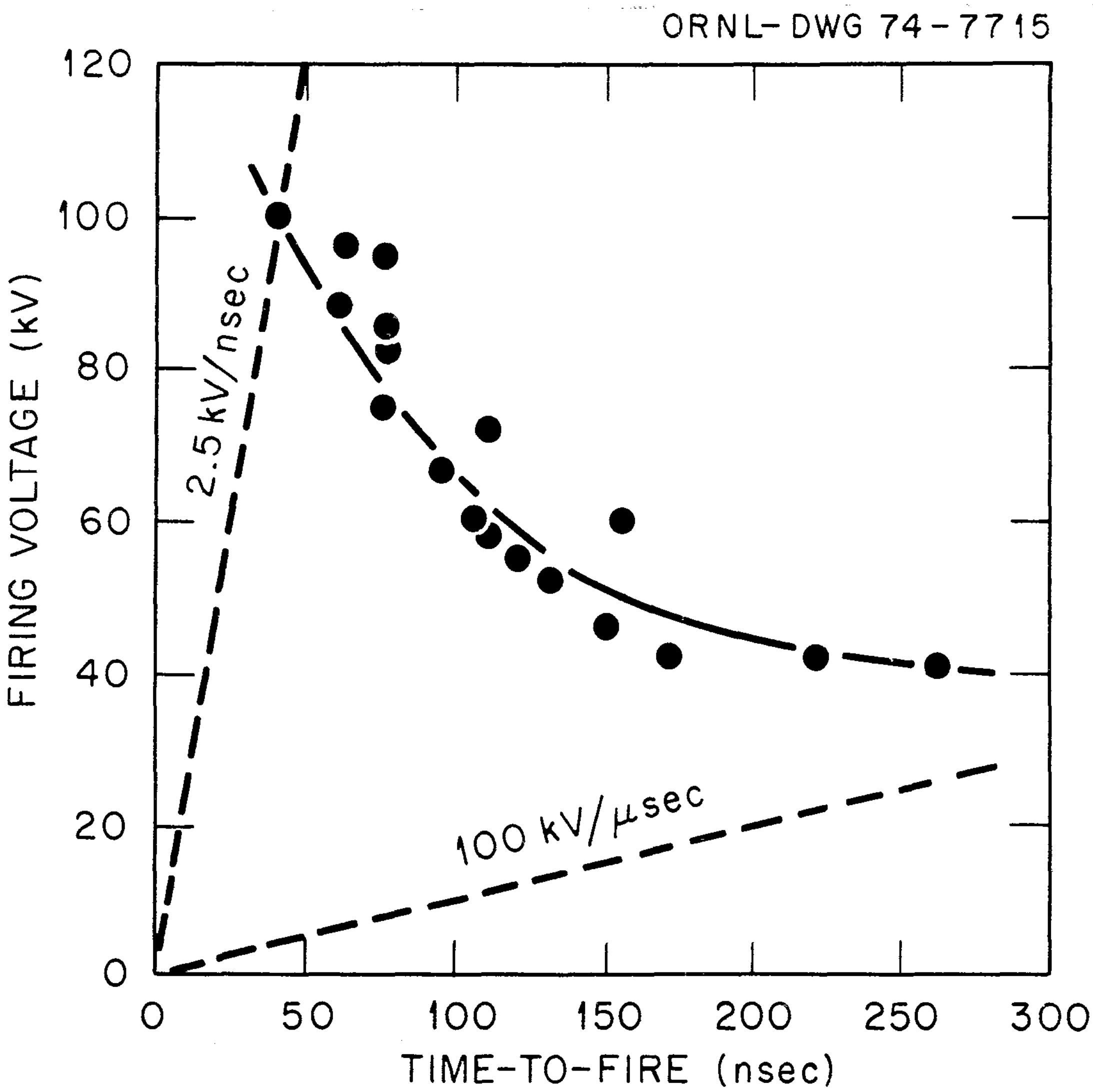


Fig. 3.3. Breakdown voltage for a 9 kV arrester.

The large EMP surge sparkover and discharge voltages could have serious consequences for power equipment. Insulation breakdown could occur on internal equipment wiring, resulting in damage by ac power follow. To prevent equipment damage, important equipment should be protected by an arrester which can effectively suppress EMP, lightning, and switching surges. Presently available power line arresters should be further tested with the recommended EMP standards to determine their effectiveness in protecting equipment against EMP surges.

IV. PROTECTIVE ACTIONS AND PROCEDURES

4.1 Review of Expected EMP Effects on Electric Power Systems

Preceding sections have made clear that surge voltages induced by EMP in the electric power lines exceed the basic insulation level on most above-ground power distribution lines. Similar surges, but reduced in magnitude depending upon the amount of shielding present, will also be induced in underground power cables, control lines, telephone cables, power supplies, and other conductors associated with electric power generation, transmission, distribution, and control.

The probable disturbances resulting from these surges have been described in other reports;[9-12] here we consider aspects relevant to preventative or corrective action possible just before or after high-altitude nuclear detonations.

4.1.1 Flashover and Power Follow

Depending upon height of burst, the area of coverage of EMP from a single high-altitude detonation can easily be most of the United States and within this area substantially uniform EMP field strengths will occur. Thus, entire power systems will be impacted simultaneously. If there are several detonations over the U.S., each point in the U.S. will be affected by the EMP's from all high-altitude detonations.

The EMP-induced surges on distribution lines are expected to cause flashover at points of impedance change, corners or ends of lines, and locations of reduced insulation level, as well as across lightning arresters. Discharges through lightning arresters will be extinguished, but a fraction of those across insulators will be sustained by power follow, initiating circuit breaker operation. If three of more high-altitude detonations occur within two or three minutes (with some variation depending upon breaker design) repeated flashover can cause circuit breaker lockout, necessitating manual reclosure. Consequently, the distribution system load would be removed from the transmission network.

4.1.2 Transient Stability[5]

Multiple faulting (flashovers) over a large geographical area accompanied by a loss of load due to circuit breaker openings could induce transient instability and wide-area power blackouts. To investigate this possibility, Manweiler recently modeled EMP-induced perturbations using the computer transient stability program developed by Philadelphia Electric Company. A network base case supplied by the Tennessee Valley Authority represented more than 1500 busses (generators, tie points, and loads) and provided a good transient stability model of the southeastern United States.

In the study, EMP flashovers on the distribution system were modeled by faulting distribution (not transmission) lines serving between five and thirty percent of the connected load in the affected area. Many studies were run for different fault densities, sizes of perturbed area, and impedances between the faulted distribution lines and the connecting lines. Calculations were done for both a single set of multiple faults, as would occur from a single nuclear detonation, and multiple fault sets modeling multiple detonations occurring within a short period of time.

In general, the multiple fault perturbations affected the entire network in the following manner. First, within the perturbed area most generators accelerated together. However, for a large fault density, many machines lost synchronism within the perturbed area. These machines would thus be removed from the network. A second effect of the EMP disturbance was an interference between the perturbed and unperturbed areas through the transmission tie lines, which seemed to exacerbate the instability, particularly within the perturbed area. In order to determine whether this interference between perturbed and unperturbed areas was indeed disruptive, the major tie lines between the faulted and unfaulted areas were opened before the simulated EMP was applied. In this case, transient instability was less likely to occur; generators in the faulted area still accelerated, but remained in synchronization with each other.

Repeated detonations, which were modeled by applying a second simulated EMP about 0.5 second after the first perturbation, greatly increased the likelihood of transient instability at even a low fault density. Major instability was likely when only a few percent of load was faulted.

In making conclusions from this study, one must remember that the study is but a first attempt to determine the effects of EMP perturbations on the transmission system's stability, which is a very difficult problem. Although the model of the power system is quite accurate in some respects, there were several limitations to the study. If the number of EMP bursts were increased beyond even two, the perturbation would be much more severe. No malfunction of the transmission system was included, although line surges were studied to see if circuit breakers on the transmission system would open. (Section 4.1.3 of this report discusses possible effects on transmission system components which could increase the probability of instability.) Furthermore, only the transient time period (up to 1.5 seconds following flashover) was considered. Dynamic instability, which is a very important component of the total EMP effect, and which occurs after the transient period, cannot be modeled by the existing program. Since the omitted effects will tend to encourage instability, we must conclude that loss of synchronization and resultant power blackout are very likely. On the time scale of a minute to a few hours, it is possible that human intervention could reduce the severity of a blackout.

4.1.3 Communication and Control Circuit Damage and Malfunction

EMP will induce large surge currents and voltages in the communication and control circuits of power systems. These surges can cause faulty operation of logic circuits and can burn out components, especially semiconductor diodes, transistors, and integrated circuits. Malfunction of control circuits can result in erroneous breaker operation, false telemetry of data, and general scrambling of the control function. Semiconductor burnout can be difficult to repair, particularly if spare parts and test equipment are not readily available. Power may be available even if control circuits are damaged, but without such important functions as protective relaying, the power components are very vulnerable to damage by transients, faults, etc.

4.1.4 Power Component Damage

While less likely than control circuit damage, damage to power components such as transformer windings, bushings, or other insulation cannot be excluded. There are at least two reasons for this. The first is that the rise time for EMP surges is much shorter than that for lightning. Insulation levels may not be adequately coordinated for these fast rising pulses; consequently, there is no assurance that protective devices will fire before flashover occurs in components. Even though the energy in an EMP surge is considerably less than in direct lightning strikes, power follow from the power line voltage can damage equipment by sustaining an arc initiated by EMP. The second reason is that, in low lightning areas, much power equipment is not protected by lightning arresters.[12] In unprotected equipment, power follow after EMP flashover may cause serious damage to transformers. Fortunately the trend in power systems is toward increased protection, even in low lightning areas.

4.1.5 Damage to Customers' Equipment

Surges induced in electric power lines will propagate through transformers and enter customers' equipment, possibly causing damage or malfunction. Resultant faults or loss of load can exacerbate the instability problems of the power system.

Customers with standby power can avoid entry of these surges by disconnecting themselves from commercial power and going to standby power if attack warning is available before the first high-altitude detonation. Fast acting primary and secondary lightning arresters may also help to avoid damage. Transformers attenuate surges somewhat and lengthen their rise time, increasing the chance that secondary arresters will be able to dissipate them successfully. Long runs of above-ground wire following the transformer will have surges induced on them which negate the effectiveness of the transformer and lightning arresters.

4.2 Protective Action Before or During Attack

4.2.1 Need for Protective Action

It is expected that high-altitude detonations will occur at the beginning of an attack, possibly through use of our own Spartan anti-ballistic missiles. Large parts of the country might experience no other direct effects of nuclear detonations, being remote from probable targets. Under such circumstances there are cogent reasons for trying to maintain or restore electric power. These include the desirability of light and ventilation for fallout shelters, the need for traffic signals and gasoline pumps for evacuation, time required for orderly shutdown of factories and chemical process plants, light and power for hospitals, police and fire departments, pumps for water, gas, and sewer utilities, and general comfort and aid to the population. If EMP were a local phenomenon occurring with blast or heat, the additional effects ascribable to it would be minimal. As a nationwide effect, it is worthwhile to counter the disruptive impact of EMP.

4.2.2 Preparation in Advance of Nuclear Attack

Because little time would be available after attack warning, it is essential that some steps be taken in advance. Since damage to solid state communications and control equipment may occur, spare parts, test equipment, and trained repairmen should be available. Plans should be made for possible cannibalization of redundant equipment in the event that insufficient spare parts are available.

Disruption of communications through equipment damage is also possible. For distribution systems the most important communications links are: first within the system itself, second with the transmission system (if this is a separate entity), and finally with essential customers. At present, it is quite feasible to provide sufficient EMP protection to assure survival of a minimal radio communications system in the UHF and VHF bands.[3] However, it is necessary in advance of warning to establish radio nets and common frequencies and to position transceivers, if this is necessary.

Finally, maintenance and dispatch personnel must be trained to know what to expect and what corrective actions are available. For example, if a dispatcher observes breaker operation and false telemetry, advance training may give him the ability to respond more quickly to avoid loss of power through instability.

4.2.3 Actions upon Receipt of Attack Warning

Assuming that power companies have planned their response in advance, attack warning should trigger the execution of these plans. Maintenance vehicles should be prepared for dispatch in event of damage, breaker lock-out, or loss of telemetry. Test equipment and spare parts should be made available, and maintenance personnel alerted. Pre-planned radio nets for backup communications with other power companies, other utilities, and essential customers should be activated. Customers with standby power, whose equipment could be damaged by EMP conducted through power lines, should be alerted to disconnect from commercial power and go to standby power. The customer may still be in danger from EMP surges induced on his own lines, unless he has adequate surge protection. Chemical plants, oil refineries, aluminum plants, and other customers requiring time for orderly shutodwn should be warned that power failure may be imminent. Dispatchers should review generation on line and ready whatever spinning reserve is available for possible energizing should some generators lose synchronization.

The study reviewed in Section (4.1.2) indicated that transient instability was somewhat less likely if tie lines between the affected area and surrounding areas were opened prior to the occurrence of EMP. However, we do not recommend sectionalizing power grids on receipt of attack warning, because it will be impossible to determine in advance the boundary between affected and unaffected areas. Further the preliminary nature of this study would make it foolhardy to ignore recent power system experience indicating that strong interconnections help to prevent blackout. The matter of grid sectionalizing requires considerably more study before it can be recommended as a protective measure against EMP-caused blackout.

4.2.4 Actions during Attack

We exclude, as beyond the scope of this report, other more localized weapons effects. Obviously, blast and fire will be much more important in target areas than will EMP. Furthermore, in these areas repair or restoration attempts will be severely hampered by the inadvisability of leaving shelter. However, most of the country's area will not suffer direct effects under any conceivable attack, and in these locations power maintenance, restoration, and repair activities are feasible. We do not know enough about the occurrence of EMP effects to give detailed instructions for how to carry out these activities. Preceding sections have indicated the kinds of disturbances likely to occur; we must leave to the ingenuity of power company personnel the preferred response.

An obvious possibility will be loss of voltage at some location in the power system, reported by telemetry, telephone, or the backup radio communication net. The dispatcher must then decide whether this is due to loss of feed from the transmission system or a malfunction within the distribution system. If the former, he should report this to the transmission system dispatcher (who should already know), and ascertain how long power is likely to be out. If the latter, he should localize the disturbance and either try to restore power by remote reclosing of breakers or else dispatch maintenance crews to diagnose and repair any damage.

This scenario fails if a large amount of damage occurs, for the maintenance crews will be overwhelmed. However, EMP tests of communications and control systems analogous in some respects with power systems have indicated that massive damage to equipment is not likely. The most common form of damage occurs to semiconductor devices tightly coupled to long cables. If we consider the example of a protective relay, this would imply concern for the power supply (connected to 115 V power) and input and output circuits (connected to sensing wires and control lines). Tests have also shown that failure does not occur in all seemingly identical equipment. EMP-caused damage tends to be probabilistic rather than deterministic. Power engineers are familiar with this phenomenon in lightning damage, where perhaps only one unit out of several similarly struck by lightning will require repair. If maintenance crews are instructed to look first for damage in the most likely circuits, then the repair and restoration process can be considerably accelerated.

Another scenario requiring exceedingly fast action by dispatchers is incipient blackout due to EMP-caused flashover. Many of the plans developed by the Electric Reliability Councils will be useful in combating this. Rapid load shedding, bringing up of spinning reserve, and as a last resort sectionalizing should be considered.

Dispatchers must be prepared to drop either generation or load very quickly. Events on a few seconds time scale are beyond human intervention; but even one-half minute allows for dispatcher response if he is aware of what is going on.

4.2.5 Action Following Attack

During this period the primary concern will be for power restoration and repair of damage. Unfortunately, semiconductor devices, the components most likely to be damaged, cannot be repaired. They must be replaced from spares. If insufficient spares are available, some control functions must be dropped, or else electromechanical backup equipment substituted. Fortunately, electromechanical components are much less vulnerable to EMP damage than are solid state, so these should be available for replacement.

V. EMP PROTECTIVE PROGRAM FOR POWER DISTRIBUTORS

5.1 Introduction

It is not possible to develop a single unique, completely detailed plan for upgrading a power distribution system with respect to its hardness to EMP. There are a number of reasons for this.

Not all is known about EMP effects. Much of what we know about possible EMP effects is based on combined theoretical calculations and limited experimental information. High-altitude testing of nuclear weapons is, of course, banned. However, laboratory experiments and simulator testing tend to confirm the theoretical models used.[13]

Protective devices presently used for protection against lightning on transmission, subtransmission, and primary distribution lines have not been designed or systematically tested for surges such as those induced by EMP. However, a number of manufacturers are offering devices for protecting secondary distribution lines against EMP-type surges. Standards such as those introduced in Chapter III for surge arresters have not yet been set for protective gear and equipment.

Furthermore, each electric power distributor has its own inherent problems and situations. The amount of protection already available, the extent to which the distributor depends on supervisory control and automatic substations, the amount of lightning protection assumed by overhead ground wires, the isokeraunic level, the company's policy regarding the use of technical staff, etc. all point to the fact that the individual distributor can best develop a detailed plan to fit its own unique needs in an economic and cost-effective manner.

5.2 Training of Personnel

The need for protecting transmission and distribution lines and associated equipment from lightning has been recognized from the inception of the electric power industry. The necessity for protection against switching surges has been recognized more recently as transmission voltages have increased. The importance of and need for protecting the electric power system against EMP surges have yet to be recognized by much of the industry.

Because of this lack of recognition of the EMP protection problem, the first step a distribution system should take in order to upgrade itself with respect to EMP vulnerability is to provide its personnel with information and training regarding EMP problems. Only with an informed management and technical staff will a power distribution company be able to provide EMP protection in a coordinated and economic manner.

It is not unusual for electric power companies to provide training for their employees. Many power companies provide both on-the-job training courses as well as after-hours courses of the self-improvement type. Such courses include subjects such as management principles, safety, driver's training, basic electricity, etc.

Some states provide funds for the purpose of upgrading the technical capabilities of employees. To provide state or federal funds for sponsoring EMP courses for power distribution company personnel may well be in the national interest, and should be seriously considered.

The personnel of a power distribution company who need knowledge of EMP include both managerial personnel and engineering personnel. The managerial personnel need EMP knowledge as background information to make sound decisions for planning for future systems and operations. The engineering personnel need information concerning EMP in order to assess specific engineering and design details in the coordination of EMP protection with lightning and other protection.

Accordingly, personnel training for EMP protection should be divided into two groups: (1) management training and (2) technical and engineering training. Training courses should be provided to each group.

The purpose of the training course for management personnel is to provide them with basic facts regarding EMP and its consequent implications and problems. This information is required to make responsible management decisions concerning EMP-related problems.

The outline of such a managerial course on EMP is given below. It consists of a seven-hour presentation. Note that two hours of the course are devoted to civil defense. This discussion of civil defense includes reviews of Russian, Chinese, Swedish, and Swiss civil defense systems as well as a review of civil defense goals and requirements in the United States. Without such background material in civil defense, the concepts of EMP vulnerability and protection are meaningless.

EMP Course Outline
(for Management Personnel)

			Hours
I.	Civil Defense Primer		
	A.	Review of Russian, Chinese, Swiss, and Swedish Civil Defense Programs	3/4
	B.	U.S. Civil Defense requirements	3/4
	C.	The reliability of electric power during a crisis	1/2
II.	EMP Origins		
	A.	High-altitude EMP production	1/2
	B.	Pulse characteristics and range	1/2
III.	Effects of EMP		
	A.	EMP-induced current and voltage surges in cables and equipment	1/2

		Hours
B.	Effects on materials, components, and equipment	1
C.	Systems effects	1/2
	(1) Distribution system effects	
	(2) Stability of the power grid	
IV.	EMP Protective Measures	
A.	Shielding and Wiring Practices	1
B.	Protective devices	1
	Total	7

The course for engineering personnel is designed for those who have a B.S. in engineering or the equivalent. Again, a review of civil defense is included. Technical details omitted in the course for management have been included. The number of lecture hours is 21. This is academically equivalent to a two quarter-hour course. The outline is as follows.

EMP Course Outline
(for Engineering Personnel)

		Hours
I.	Civil Defense Primer	
A.	Review of Russian, Chinese, Swiss, and Swedish Civil Defense Programs	3/4
B.	U.S. Civil Defense Requirements	3/4
C.	The Reliability of Electric Power during a Crisis	1/2
II.	Origins of EMP	
A.	Mechanism of EMP Production	1/2
B.	Pulse Characteristics and Range of High-Altitude EMP	1/2
III.	Effects of EMP	
A.	Interaction and Coupling Mechanisms	2
B.	Common Mode and Differential Mode on Aerial and Underground Cables	2
C.	EMP-Induced Surge Characteristics, Peak Values, Time Response, Examples	2
D.	Characteristics of Equipment and Components Subjected to Fast EMP-Type Surges; Insulation, Transformers, Meters, Relays, Transistors, Solid State Devices, Supervisory Control Equipment, Cables, Computers, etc.	3

		Hours
E.	Systems Effects	1
	1. Lock-Out of Circuit Breakers	
	2. Transient Stability Effects	
IV.	<u>Protection Against EMP Effects</u>	
	A. EMP Shielding Principles - Conduits, Undergrounding	1
	B. Wiring Practices - Grounding	1
	C. Protective Devices - Spark Gaps, Arresters, Filters	3
	D. Coordination of Protection	3
	Total	21

In addition to the two course presentations outlined above, two corresponding manuals should be available covering the same material. These can be used as supplementary texts for the above courses, or they can be used as the basis for self study for employees of those distribution companies that are unable to give the above course presentations.

5.3 Upgrading System Components

Power distribution companies may upgrade their physical facilities with respect to EMP hardness in two respects: (1) increase the hardness of the power lines and power apparatus especially with respect to arcing or flashover with attendant power follow and consequent opening of breakers and possible lockout; (2) increase the EMP hardness of automatic control and supervisory control systems, especially by the use of low voltage arresters, gaps, and filters.

The problem of lightning surges on power lines has been largely solved through the combined use of arresters, overhead ground wires, and relay-operated circuit breakers. Overhead ground wires give little or no protection against EMP. Reclosing circuit breakers give protection against power follow caused by EMP-induced flashover and arcing, but the occurrence of several surges in a few minutes can cause the reclosures to lock out. Hence, there is but one possibility for EMP protection of the power lines: the arresters must be in sufficient number and of proper location so that little or no flashover will appear in the system.

As pointed out in Ref. (12), the best locations for an arrester are at sharp corners, terminals, dead ends, and points of discontinuity.

Protection of control circuitry is discussed in Ref. (4). Many of the measures which have been applied to suppress interference by switching surges in Extra High Voltage substations are also useful against EMP.

Protection of a segment of the distribution system against EMP should receive a priority in accordance with the importance of that segment. Thus high-voltage subtransmission lines should be the first to be protected, since all power must first flow through these lines. Similarly, those primary distribution lines which serve critical industries, utilities, and hospitals should be protected before other primary circuits. Of course, facilities which have adequate emergency standby power generation capability need not be included in such considerations.

Accordingly, the following priority-ordered protection plan is recommended.

Protection Plan

1. Harden high-voltage subtransmission system. Place surge arrester at all points of discontinuity, end points, terminals, corners, (especially those formed with acute angles), and entrances to substations.

2. Harden the automatic control circuitry associated with high-voltage subtransmission system. Transistors and other solid state devices must be protected by proper selection of fast-acting spark gaps, or metal oxide varistors.

3. Harden that portion of the primary distribution system which serves vital industries. Place surge arresters at all points of discontinuity, end points, terminals, corners, and entrances to substations.

4. Harden the automatic control circuitry associated with the above vital portion of the primary distribution lines. Protect transistors and solid state devices by proper selection of spark gaps and/or metal oxide varistors.

5. Harden selected portions of the remaining primary, secondary, and control circuitry. In the choice of what protection should be provided in the final step, the distribution company should consider the following points and how they apply to the company's particular situation:

(a) Protect that type of equipment which is occasionally observed to undergo failure or malfunction from "normal" transients, such as those from lightning and switching operations.

(b) Combine EMP protection with other requirements.

(c) Make use of the electromagnetic shielding provided by well grounded metallic enclosure with a minimum of openings.

(d) Specify EMP hardness requirements when ordering new equipment.

In formulating the above priority-ordered protection plan, it is recognized that each distribution company must make some modifications of the plan in order to adapt it to the company's own peculiar requirements in a cost-effective manner.

The following is an example of cost-effective methods of combining protection against EMP with other operational requirements. The Knoxville Utility Board has eliminated windows in metal control buildings at unmanned substations. This decision was made in order to give better insulation so that temperature variations inside the building can be controlled through the use of a heat pump. Window breakage, through vandalism or natural causes, was of particular concern. Eliminating the windows solved that problem, and at the same time gave an all metal building with improved EMP attenuation properties.

In any national emergency in which the power industry is involved, it is important that good communications between the various segments of the industry be maintained. Startup and shutdown of plants, operational adjustments, and maintenance require a combination of telemetering and voice-communications circuits. Such circuits may be accomplished using microwave, UHF, or VHF radio links, leased telephone lines, or power-line carrier low-frequency carrier systems.

Any of these communications circuits may be damaged by EMP unless they are adequately hardened. In particular, it is a simple matter to protect UHF and VHF radio systems against the effects of EMP, and specific hardening procedures are given in Ref. (3).

It is therefore recommended that all communications facilities between the various segments of the electric power industry be backed up by an EMP-hardened VHF or UHF radio system.

5.4 Plans for Emergency Action

Many electrical distributors have formed cooperative pools in order to coordinate their activities. One of the purposes of such a pool is to set up means and channels for providing aid to members in case of a natural disaster or other emergency. The pool organization helps the member distributors in the development of emergency plans and procedures that will result in the availability of personnel and equipment in sufficient amounts when a disaster occurs. Information relating to other neighboring distributors is made available and communications procedures are established.

A typical form for information provided by each distributor and made available to the neighboring member distributor is shown in Figs. 5.1 and 5.2. Information of particular concern is that relating to means of communication, namely radio frequencies used, call letters, and the name, call sign, etc. of a local amateur radio operator. The amateur operator should be informed of EMP effects and should have EMP protection on his equipment. A similar form should be made out and filed for local electrical contractors.

Each distributor should prepare and have ready: (1) an emergency procedure plan and (2) an organizational setup for handling a major disaster on its system. Such an emergency plan should include plans for EMP's wide-spread surge effects as well as for natural disasters, including wind, sleet, ice storms, floods, hurricanes, and tornadoes. This plan should consist of complete, tailor-made details for handling the work and arrangements. Emergency procedures for EMP should include consideration of the following points:

1. Radioactive fallout levels should be followed closely. The local civil defense unit is the source for information regarding existing levels as well as expected future levels. Distribution companies should acquire some instrumentation of their own for measuring fallout levels. Maximum doses should be fixed in the plan, and these should be used in determining emergency work schedules.

One person should be assigned the responsibility of following the schedules of the various crews and the corresponding accumulated doses.

ORNL-DWG 74-9409

INFORMATION TO UPDATE DISTRIBUTOR EMERGENCY WORK PLAN

Name of Distributor ______________________________

Address ______________________________

Phone Number ______________________________

Manager's Name ______________________________

Manager's Home Address ______________________________

Manager's Home Phone ______________________________

Name of Alternate Contacts:

(1) ______________________________

Home Phone ______________________________

Home Address ______________________________

(2) ______________________________

Home Phone ______________________________

Home Address ______________________________

Radio Frequency
or Frequencies ______________ Call Letters ______________

Number of Personnel Available ________ Union ______________

System Voltages ______________________________

Primary Conductors ______________________________

____

Secondary Conductors ______________________________

Splicing Sleeves Used ______________________________

Sleeving Tools Used ______________________________

Name of Local Amateur Radio Operator ______________________________

Location ______________ Telephone ______________

Station Call Sign ______________ Emergency Net or CD Net ______________

Has Emergency Power Source? ________ Equipment EMP Hardened? ______________

Fig. 5.1. Distribution emergency data sheet.

ORNL-DWG 74-9410

SPARE SUBSTATION TRANSFORMERS

Number	Voltage	Capacity	Impedance	Mfg.	Polarity
______	______	______	______	______	______
______	______	______	______	______	______
______	______	______	______	______	______

TYPICAL PERSONNEL AVAILABLE IN AN EMERGENCY

Lineman No. ______ Groundmen No. ______ Supervisory Personnel ______

TYPICAL EQUIPMENT AVAILABLE IN AN EMERGENCY

	Number	Personnel on Each
Service Trucks	______	______

	Number	Size	Special Equipment
Heavy Trucks	______	______	______
	______	______	______
	______	______	______

SPECIAL FACILITIES

Boat with motor No. ______ H.P. ______ Without motor No. ______

Chain saw No. ______ Size ______ Air Compressor ______

Spotlights No. ______ Size ______ Power Source ______

Walkie-Talkie sets No. ______

Generator No. ______ Size ______ Hot Line Trailer Sets ______

4-wheel drive vehicles (kind) ______

Crawl Tractor (no. & size) ______
(clearing & cutting blade)

Other material or services which may be helpful: ______

______

______

Fig. 5.2. Distribution emergency data sheet (continued).

The recommendations of the National Committee on Radiation Protection and of the International Committee on Radiological Protection concerning maximum permissible radiation exposures should be observed. In particular, their recommendations concerning accidental or emergency doses should be noted. Figure 5.3 is a map of the United States showing four-day dose levels due to fallout from a hypothetical nuclear attack. The map is given here only to indicate the order of magnitude of radiation levels from fallout. Weapons sizes have increased since the data for this map were accumulated. Actual fallout dose levels are affected by many factors including weather and seasonal effects.

2. An initial survey of the extent of damage, malfunctions, and mis-operations should be made as soon as possible. Time is likely to be very precious, thereby giving this preliminary survey great urgency.

3. If additional outside help is needed, this should be determined as soon as possible and communicated to the local civil defense headquarters and the district manager for the power pool. Help from neighboring electric utilities is not likely since they will probably be plagued with similar EMP problems of their own, but this source should not be overlooked. Local electrical contractors are valuable sources for help. Each distributor should compile and maintain a list of contractors available in his area.

4. One person should be in charge of delegating work (e.g., the construction superintendent) to all outside help brought in. Of course, all work may be seriously limited by fallout.

5. The person in charge should verify that all personnel brought in to help are informed of and understand minimal safety practices. The following basic safety rules are typical: (a) all substation switching shall be done by the electric distributor's employees only and through orders of the dispatcher only. (b) If a line controlled by an Oil Circuit Reclosure (O.C.R.) is to be worked or de-energized, the handle must be in an off-position and both leads must be removed from line. Local personnel only shall operate an O.C.R., and line number and O.C.R. number shall be given to the dispatcher before O.C.R. is opened or closed. No O.C.R. shall be operated without the use of hot sticks. (c) All lines are to be grounded while making repairs.

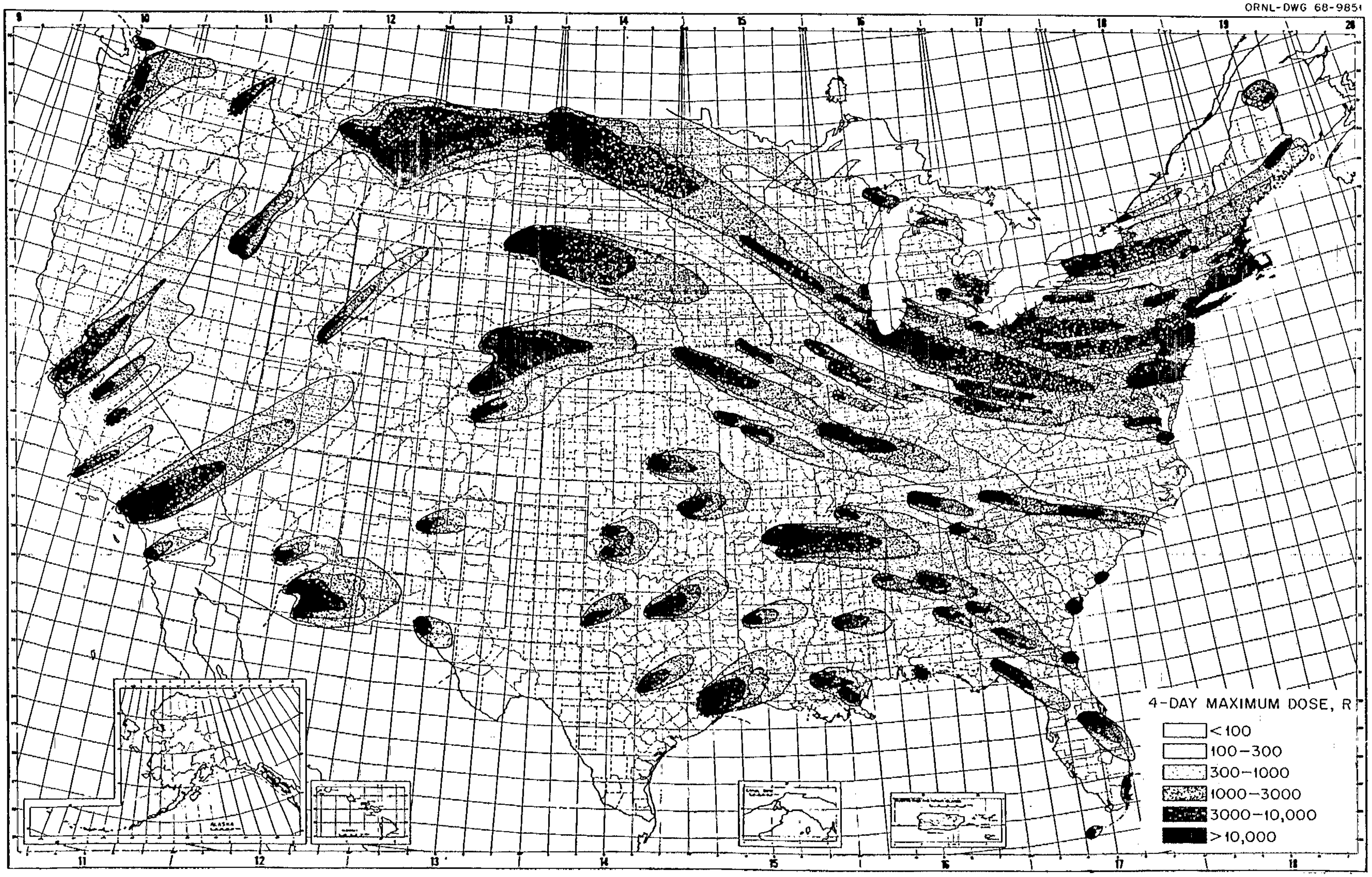


Fig. 5.3. Fallout pattern from UNCLEX attack.

(d) Rubber gloves must be worn when operating any type of switch which is normally hand operated and which is energized at over 750 volts.

5.5 Summary

In summary, the recommendations for upgrading a power distribution system for EMP protection include the following:

1. Designate one person to be responsible for EMP technical matters.

2. Train personnel in EMP -- both in the management area and in the technical engineering area.

3. Prepare an emergency procedure plan and organizational setup for natural disasters and emergencies which include EMP civil defense measures.

4. Review communication links to local civil defense headquarters and to the dispatcher and the district manager of the bulk power source. Be sure there is an EMP-hard line of communication to each of these.

5. Establish a policy of continued EMP awareness and a program of continually increasing the hardness of the power equipment, and of the supervisory control circuitry.

APPENDIX

PARAMETRIC STUDY OF EMP LINE SURGES

PARAMETRIC STUDY OF EMP LINE SURGES

The following figures show the current and voltage surges induced by representative EMP on a long copper power line located 10 m above a finitely conducting earth. The incident wave parameters θ, φ, and ψ are varied over realistic ranges. Three line terminations are used: no termination (i.e., infinitely long line case), mid-frequency model of a transformer, and a short circuit.

A list of the figures that follow is given below.

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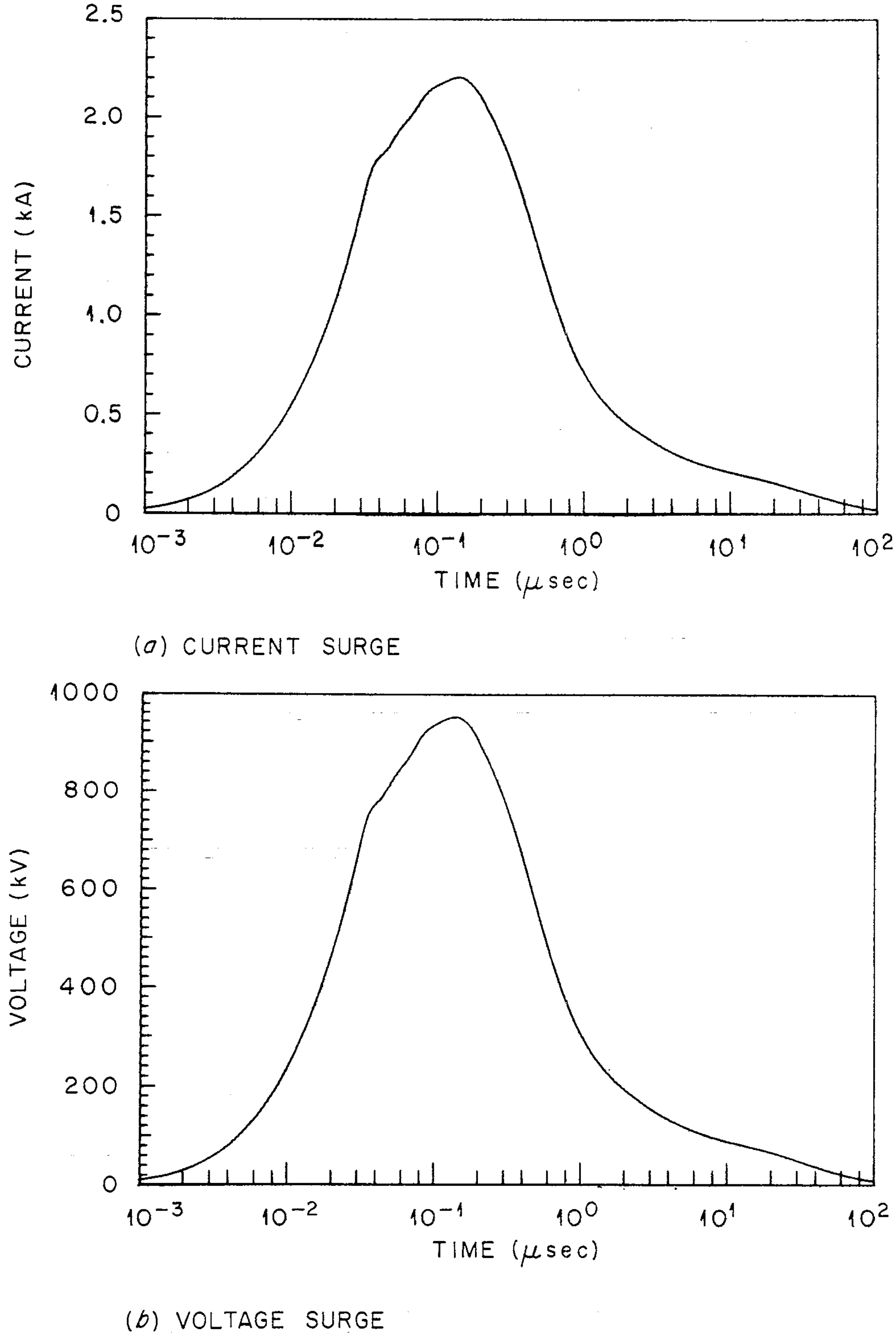
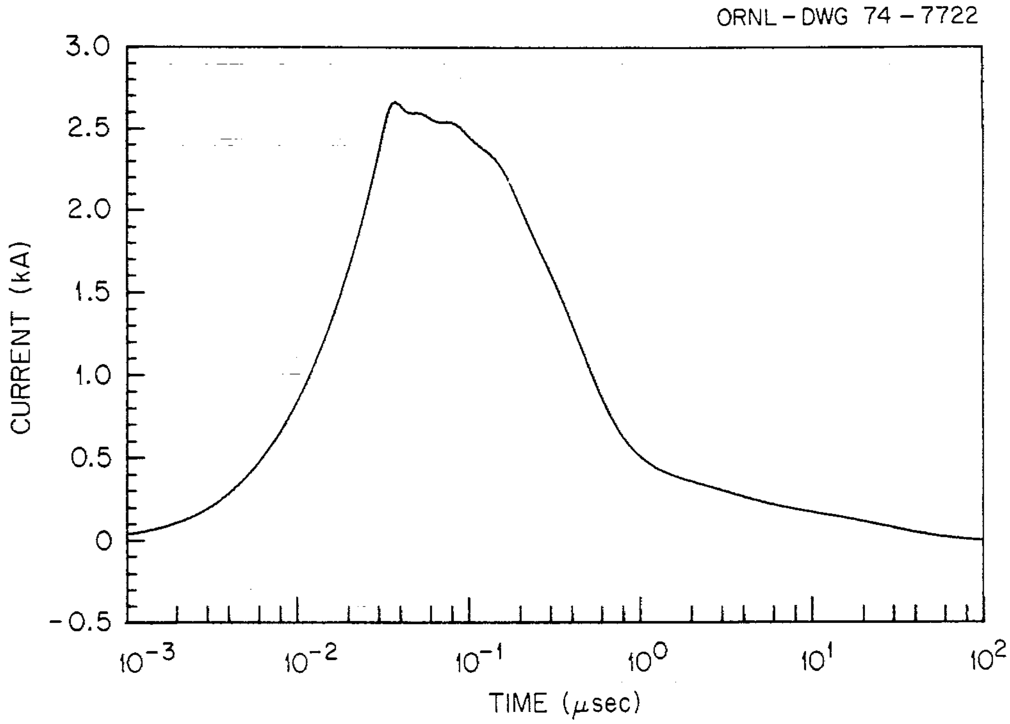
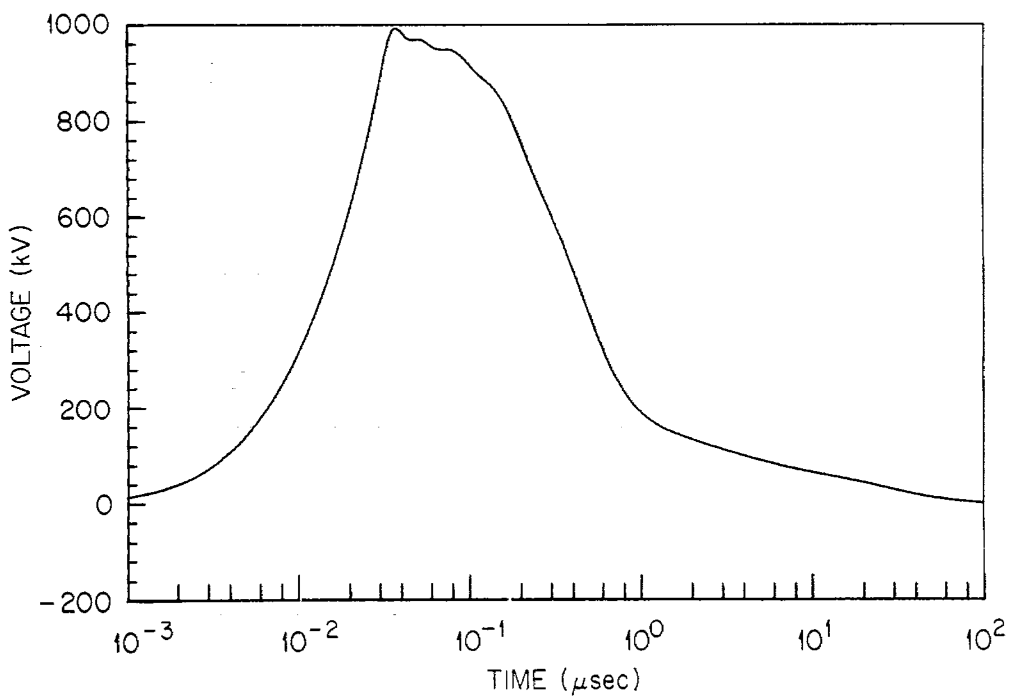


Fig. A-1. Surges induced on an infinite line for $\theta = 60^{\circ}$, $\varphi = 0^{\circ}$, and $\psi = 60^{\circ}$.



(*a*) CURRENT SURGE



(*b*) VOLTAGE SURGE

Fig. A-2. Surges induced on an infinite line for $\theta = 60°$, $\varphi = 30°$, and $\psi = 60°$.

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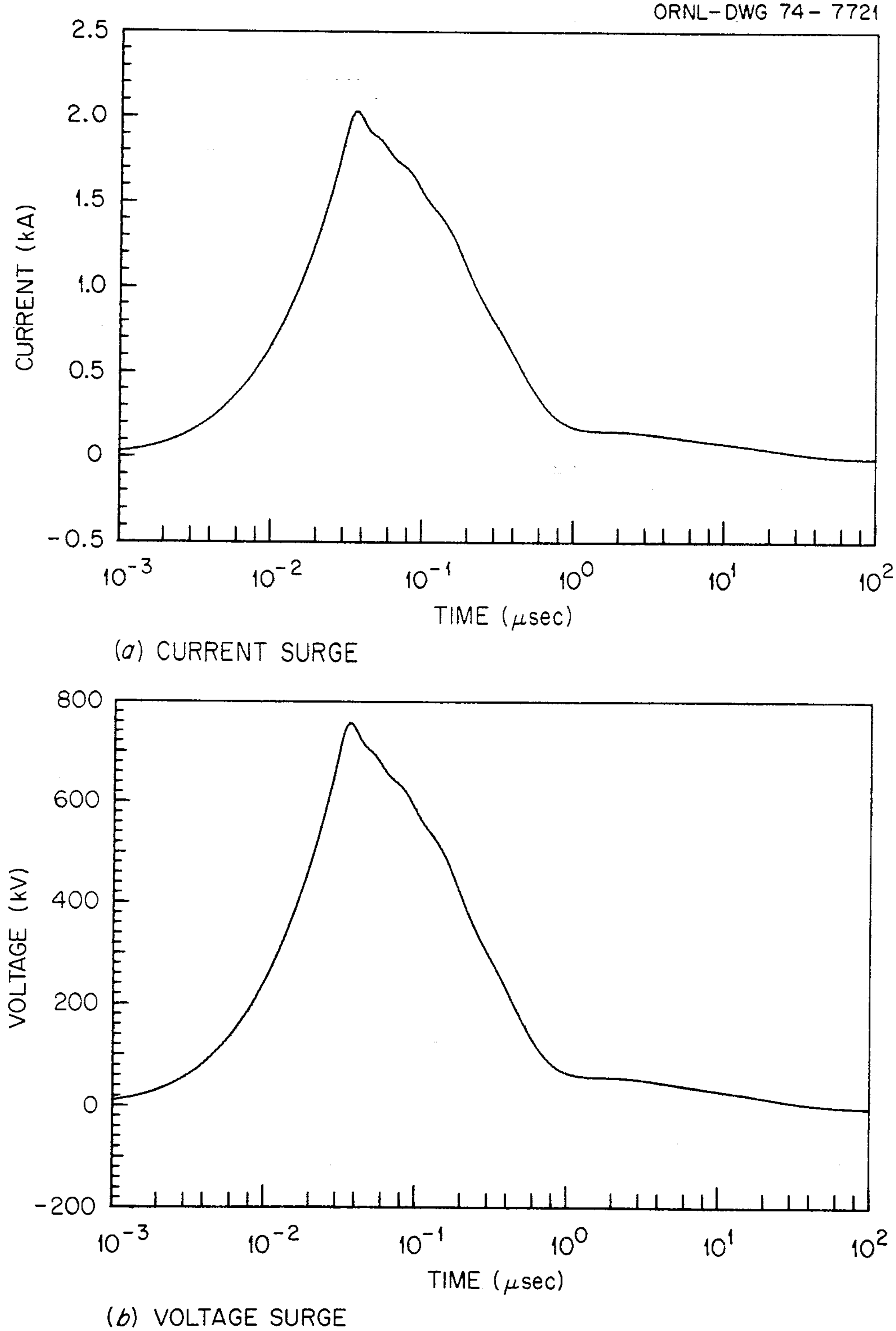


Fig. A-3. Surges induced on an infinite line for $\theta = 60°$, $\varphi = 30°$, and $\psi = 90°$.

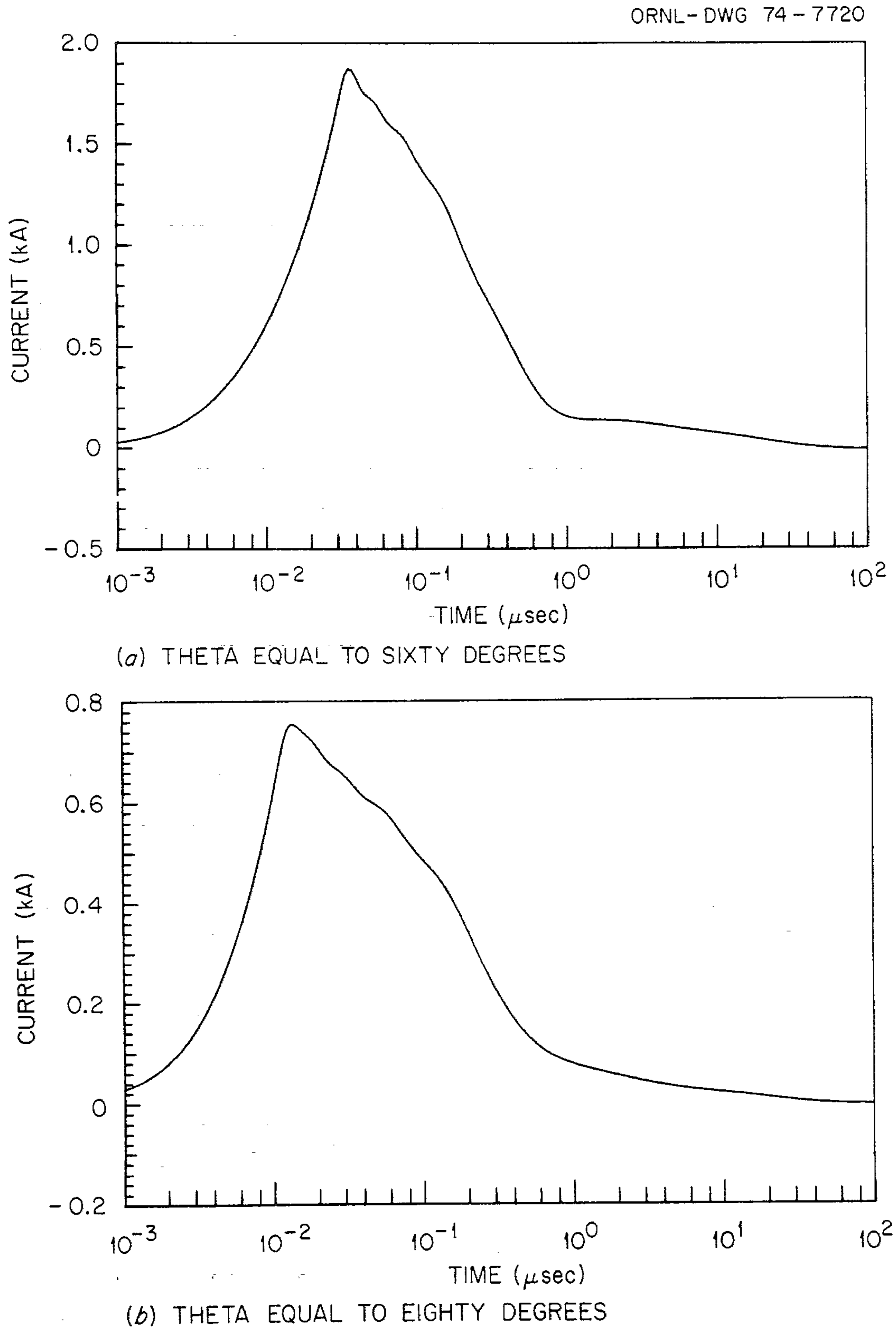
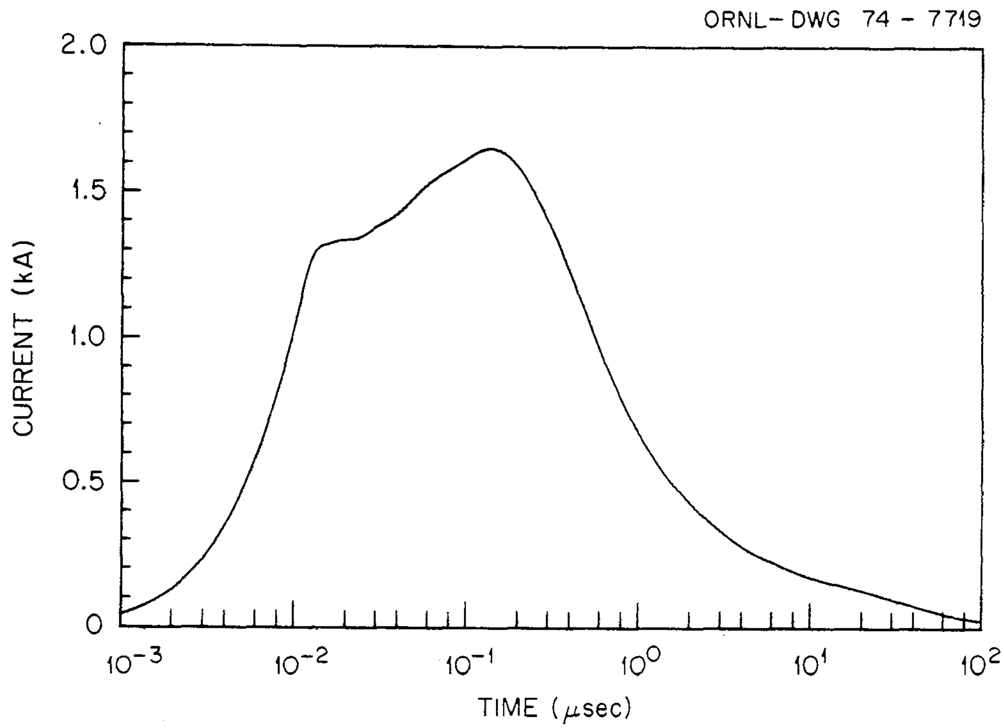
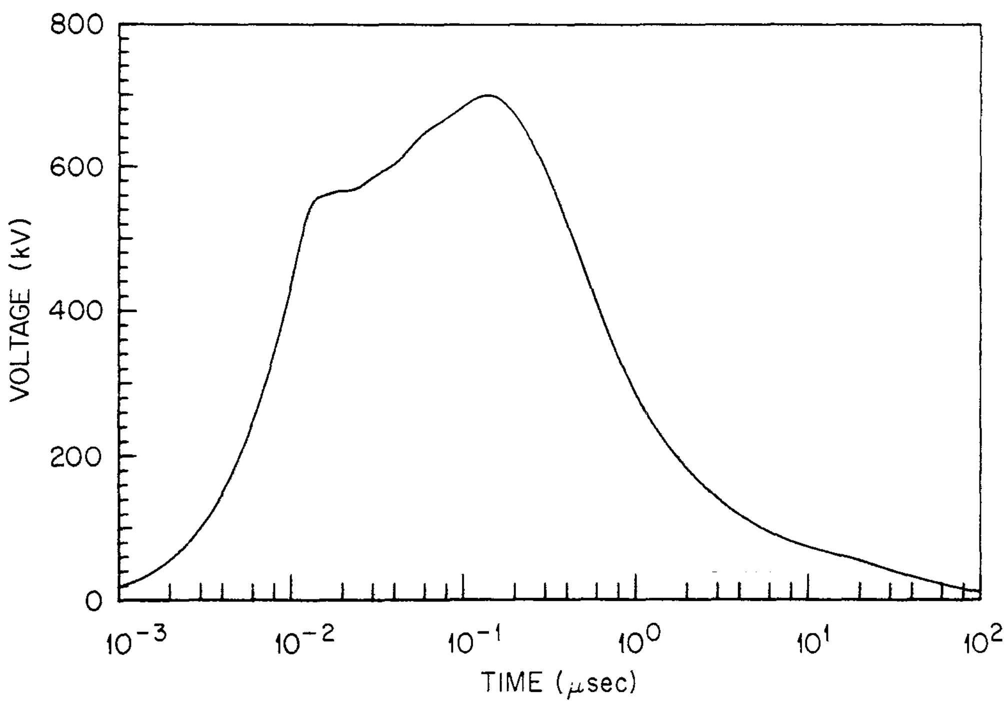


Fig. A-4. Current surges induced on an infinitely long line 10 m above the earth by representative EMP with $\varphi = 90^\circ$ and $\psi = 90^\circ$.



(a) CURRENT SURGE



(b) VOLTAGE SURGE

Fig. A-5. Surges induced on an infinite line for $\theta = 60^\circ$, $\varphi = 30^\circ$, and $\psi = 60^\circ$.

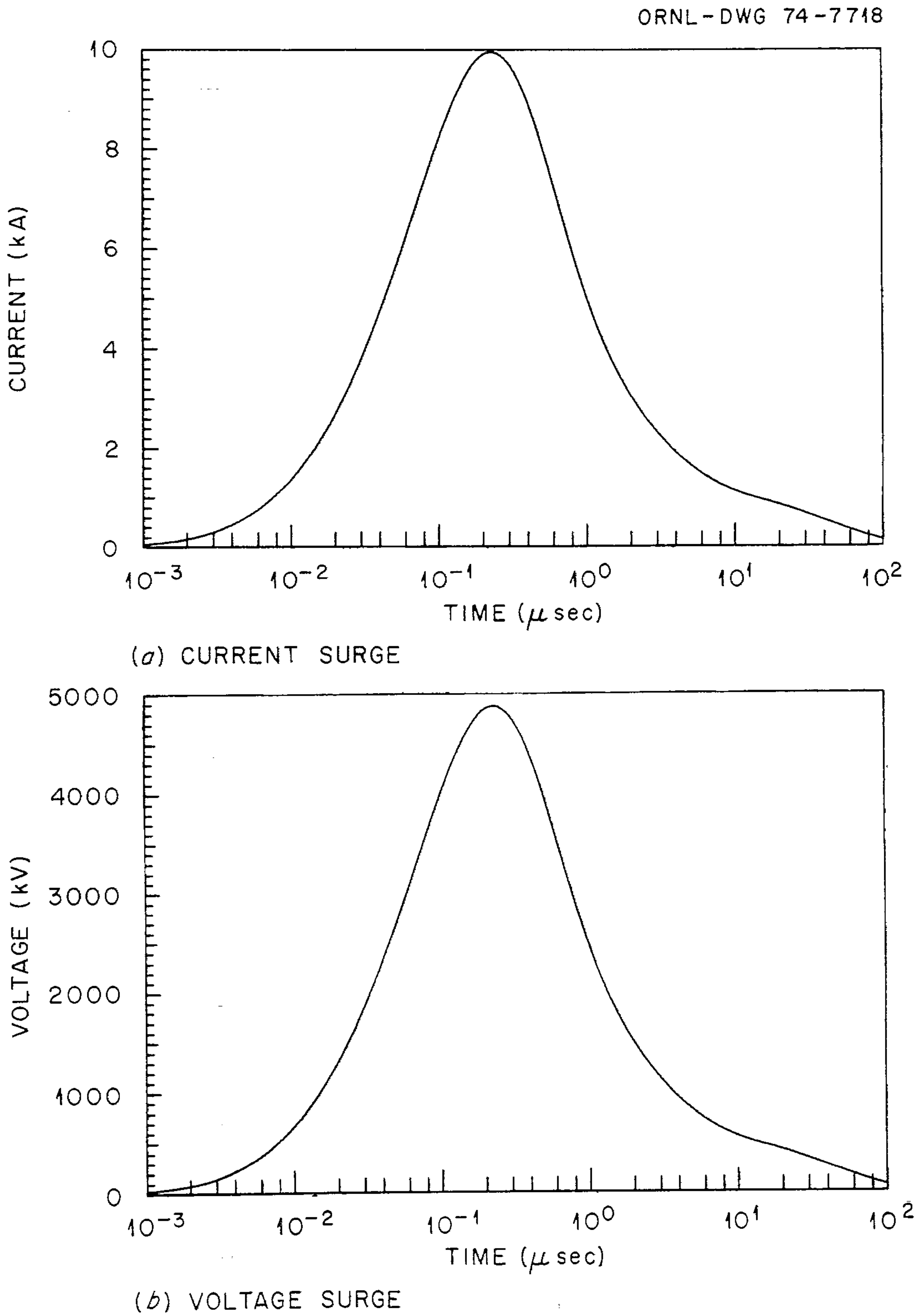


Fig. A-6. Surges induced on an infinite line for $\theta = 80^\circ$, $\varphi = 0^\circ$, and $\psi = 60^\circ$.

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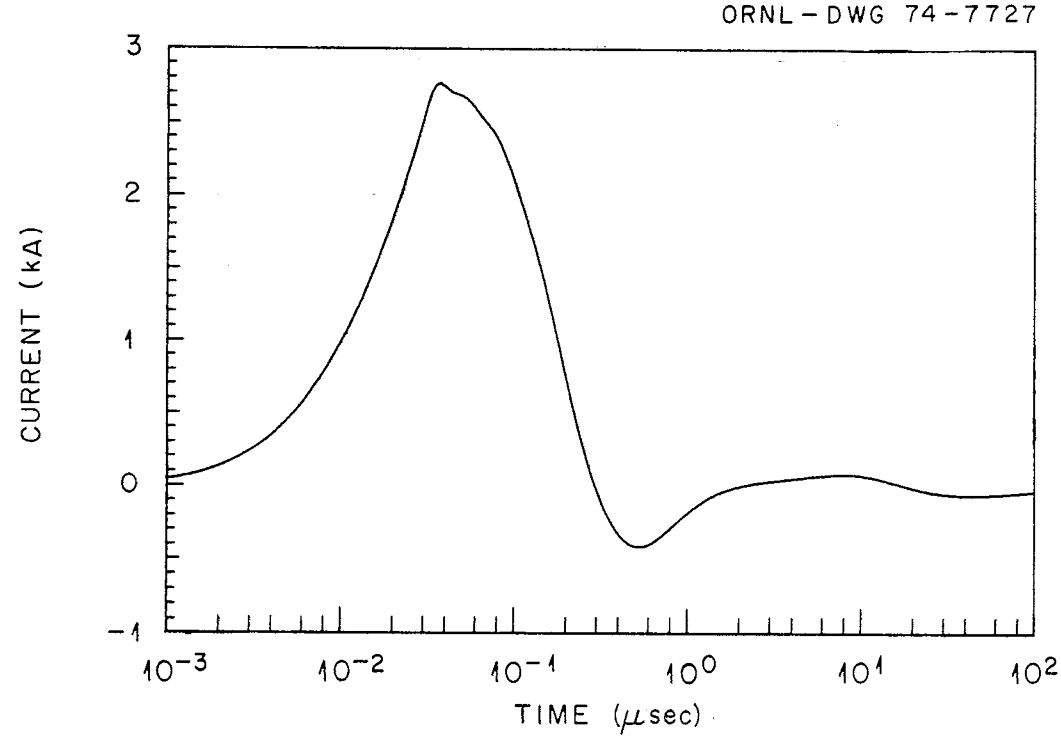
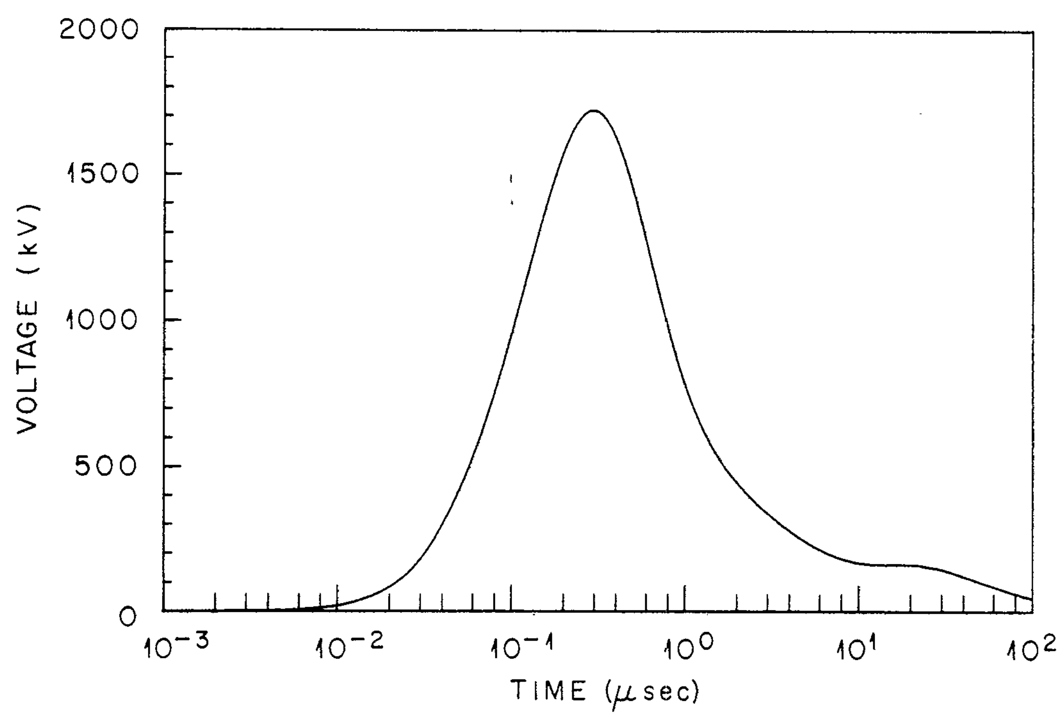


(a) CURRENT SURGE



(b) VOLTAGE SURGE

Fig. A-7. Surges induced on a semi-infinite line terminated by a transformer for $\theta = 60^\circ$, $\varphi = 0^\circ$, and $\psi = 60^\circ$.

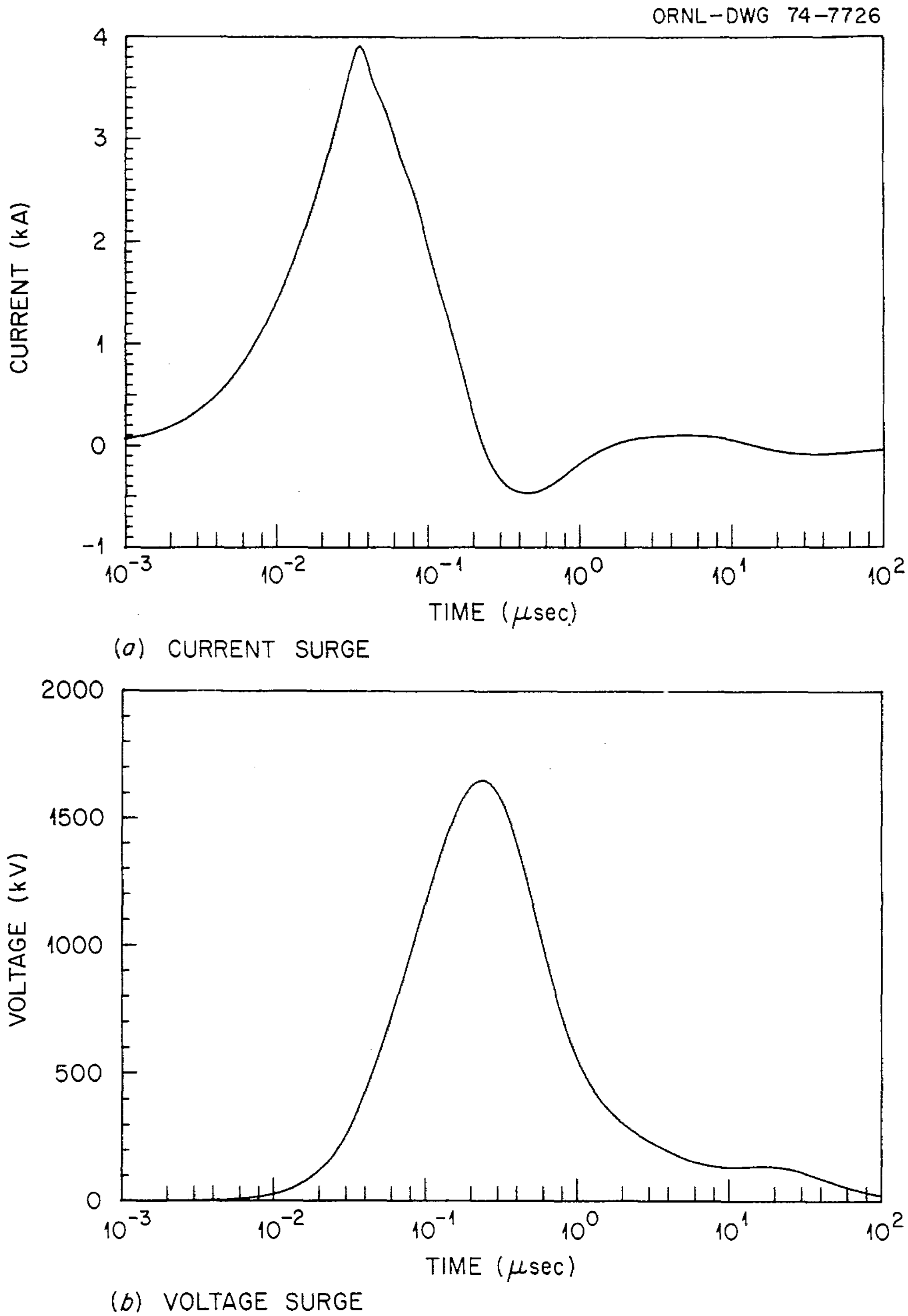


Fig. A-8. Surges induced on a semi-infinite line terminated by a transformer for $\theta = 60^\circ$, $\varphi = 30^\circ$, and $\psi = 60^\circ$.

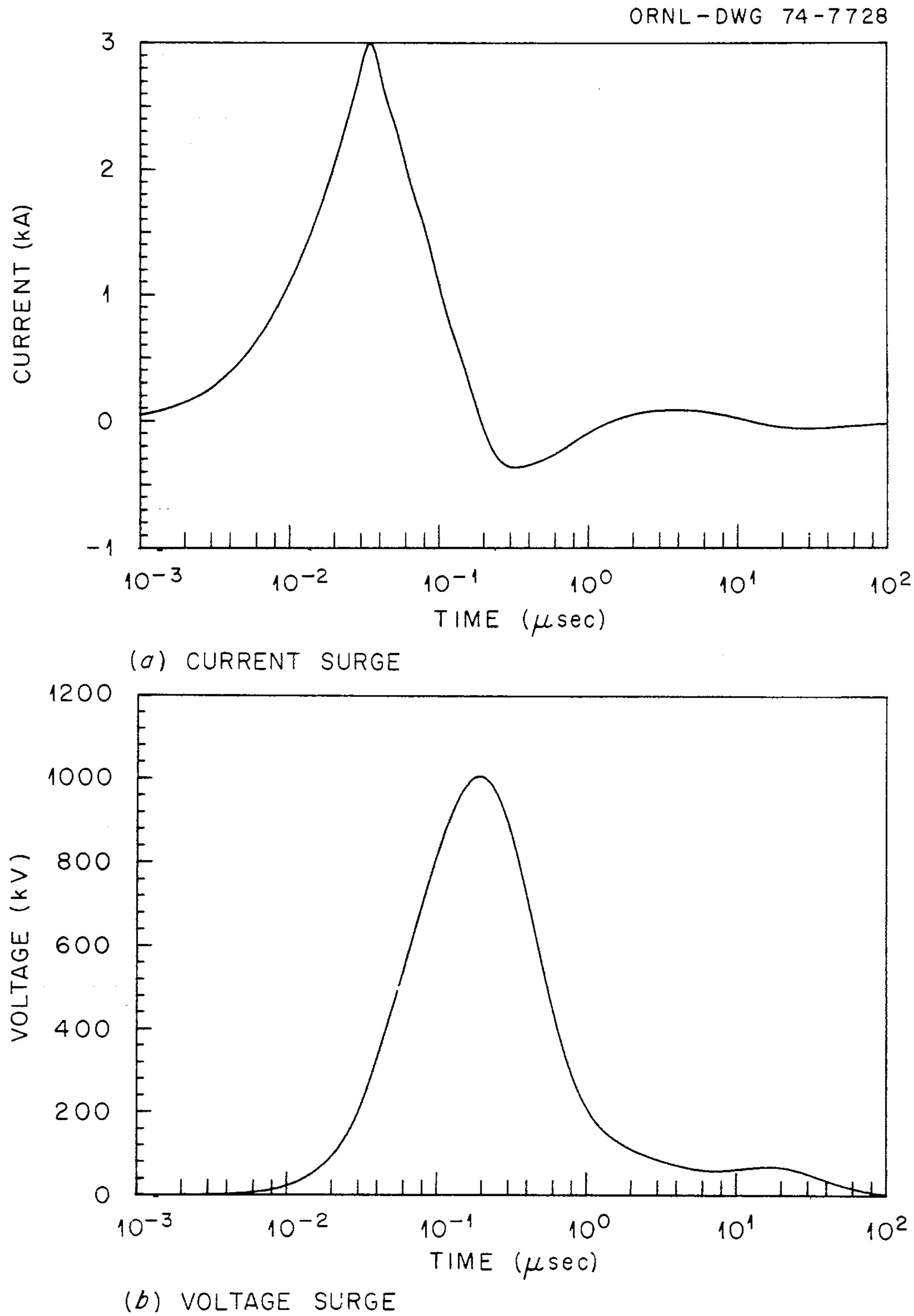


Fig. A-9. Surges induced on a semi-infinite line terminated by a transformer for $\theta = 60^\circ$, $\varphi = 30^\circ$, and $\psi = 90^\circ$.

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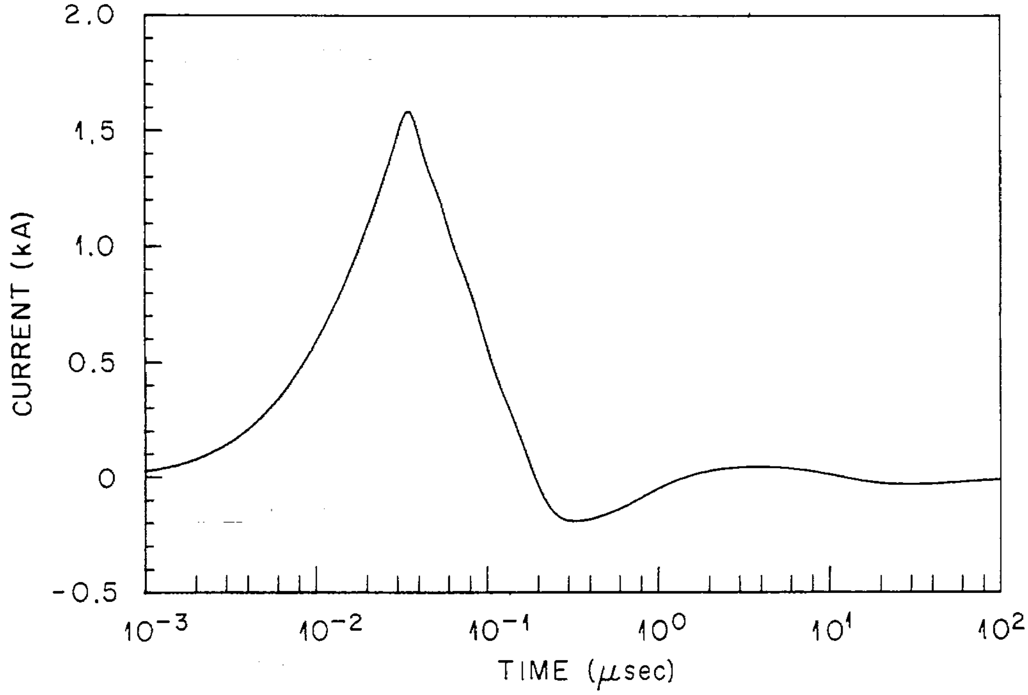
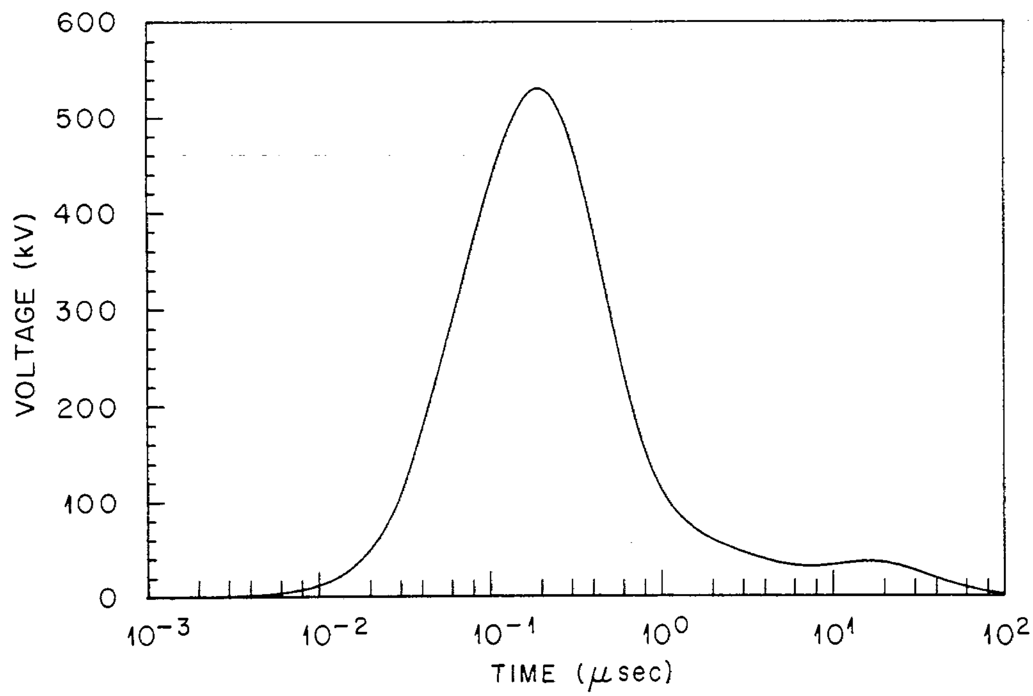
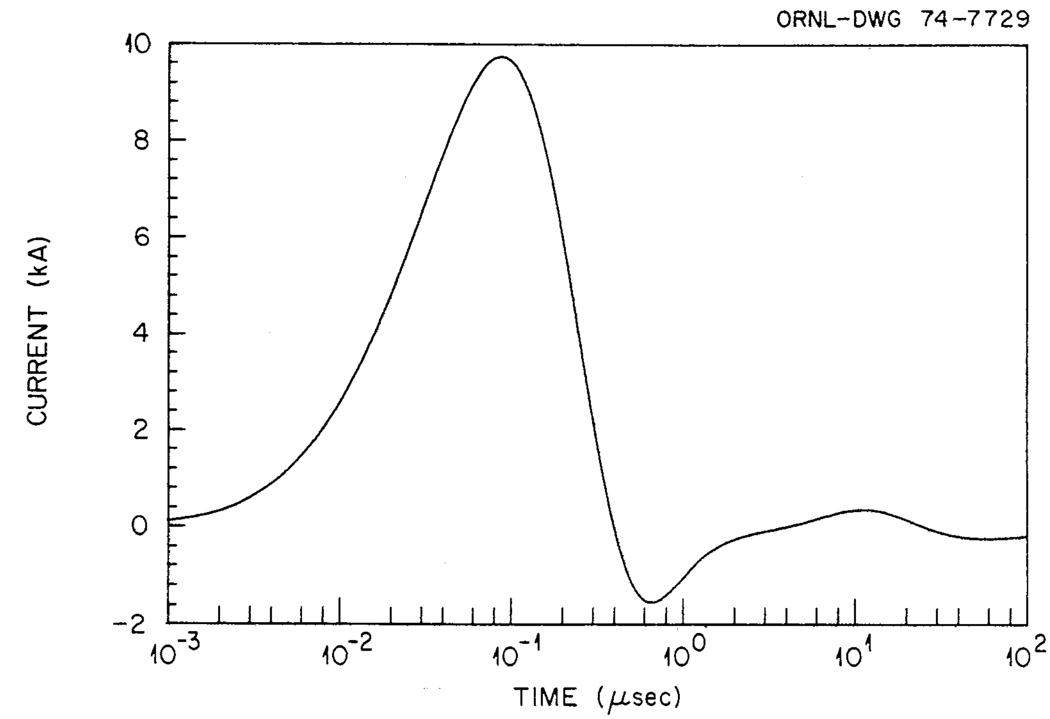


(*a*) CURRENT SURGE

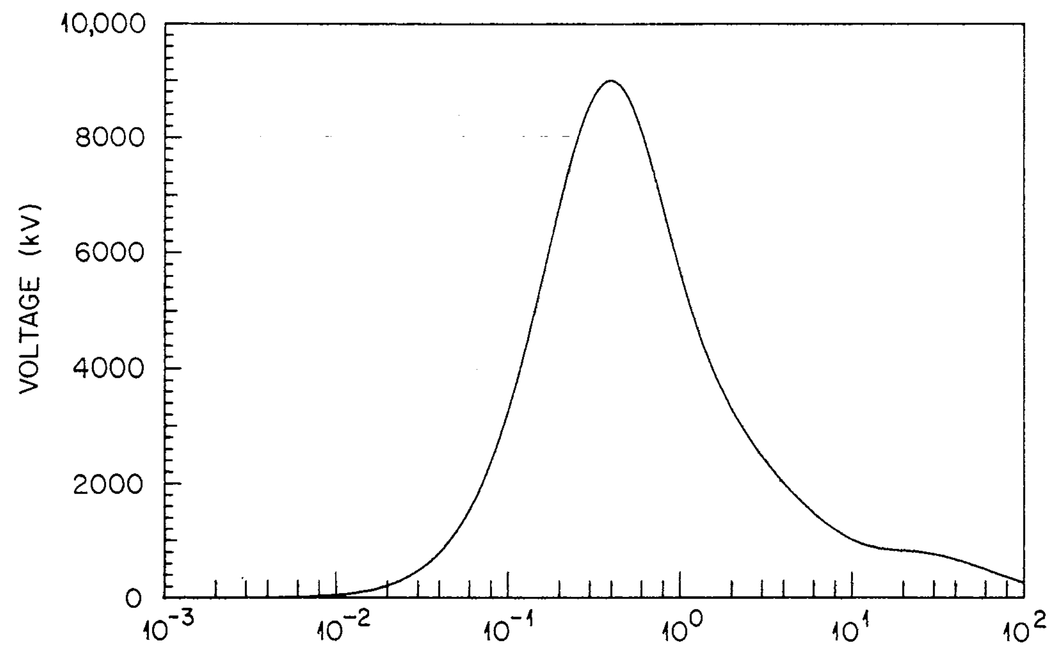


(*b*) VOLTAGE SURGE

Fig. A-10. Surges induced on a semi-infinite line terminated by a transformer for $\theta = 60^\circ$, $\varphi = 90^\circ$, and $\psi = 90^\circ$.



(*a*) CURRENT SURGE



(*b*) VOLTAGE SURGE

Fig. A-11. Surges induced on a semi-infinitely long line 10 m above the earth, terminated by a transformer by representative EMP with $\theta = 80^\circ$, $\varphi = 0^\circ$, and $\psi = 60^\circ$.

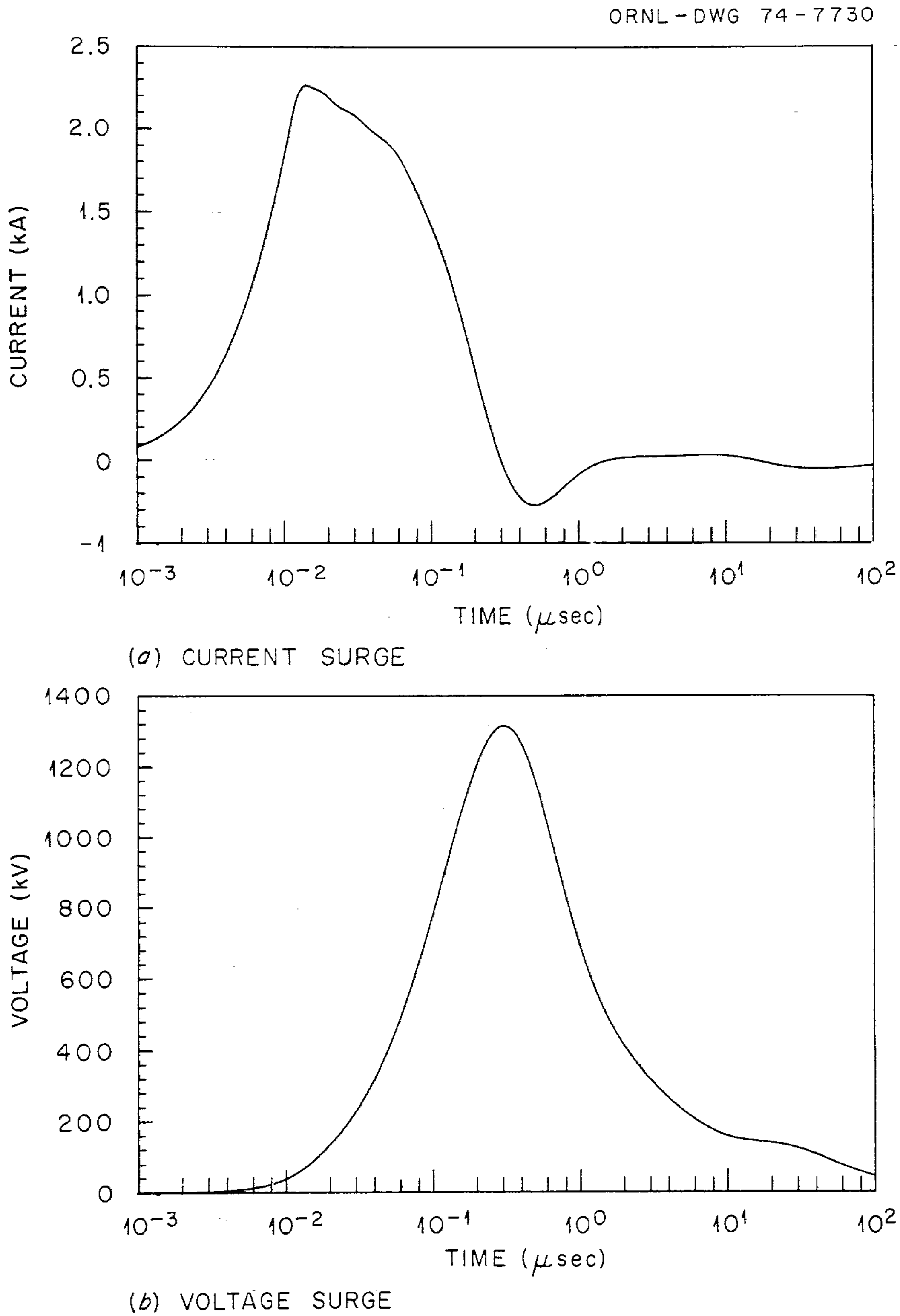


Fig. A-12. Surges induced on a semi-infinitely long line 10 m above the earth, terminated by a transformer by representative EMP with $\theta = 80^{\circ}$, $\varphi = 30^{\circ}$, and $\psi = 60^{\circ}$.

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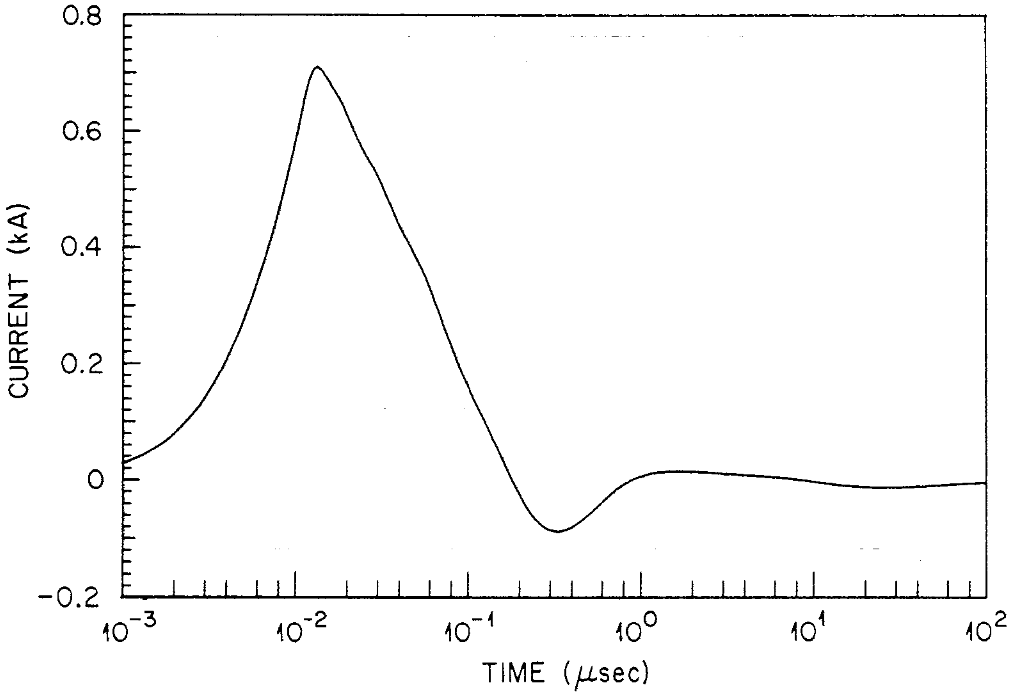
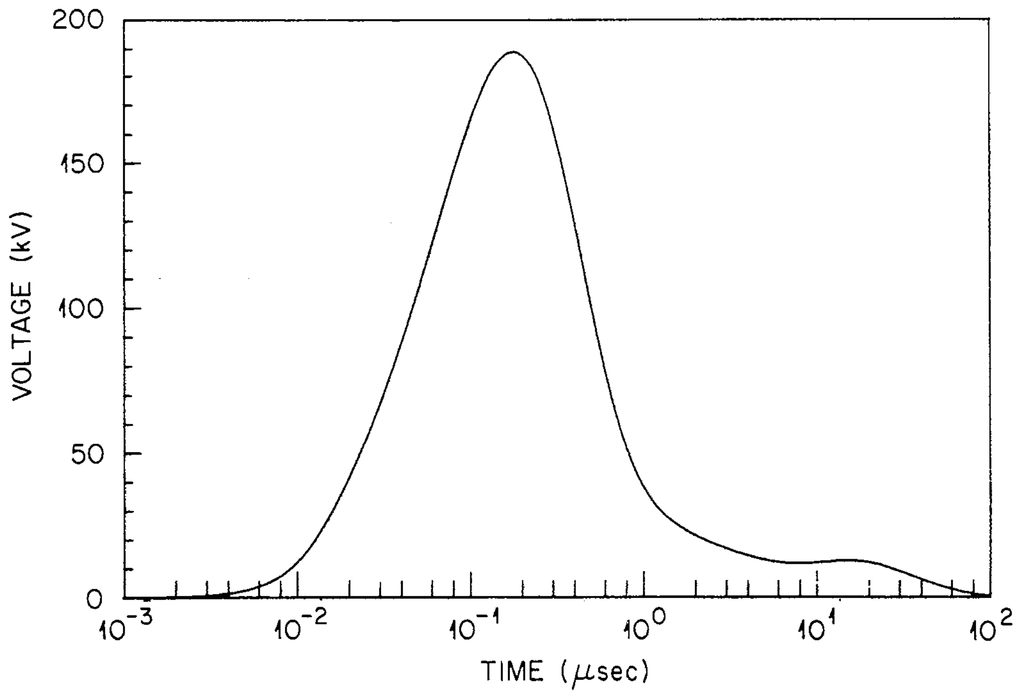
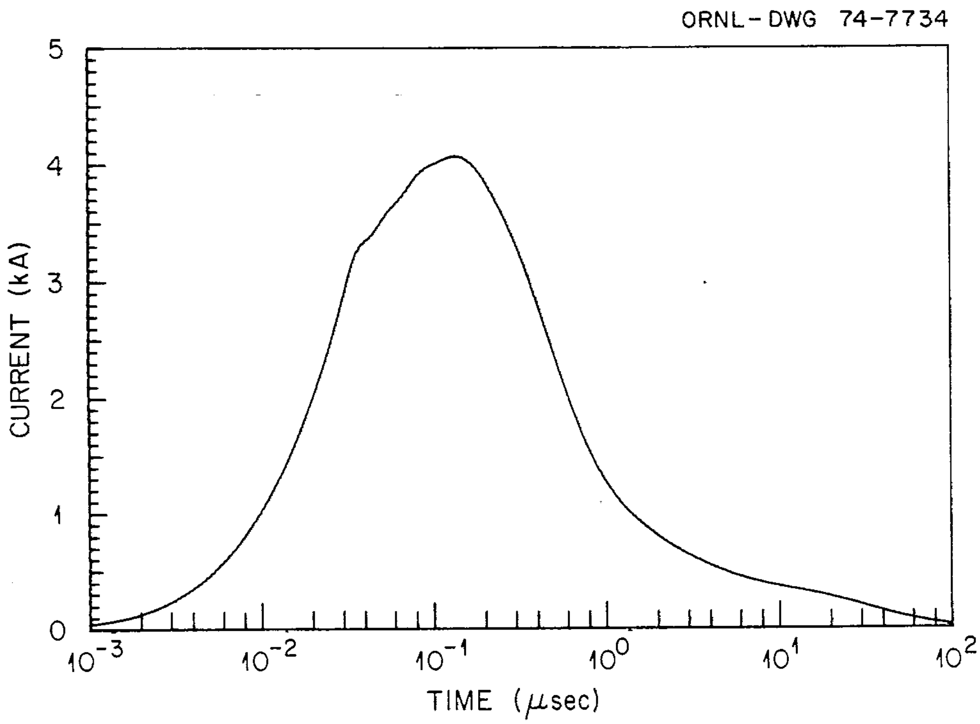


(*a*) CURRENT SURGE

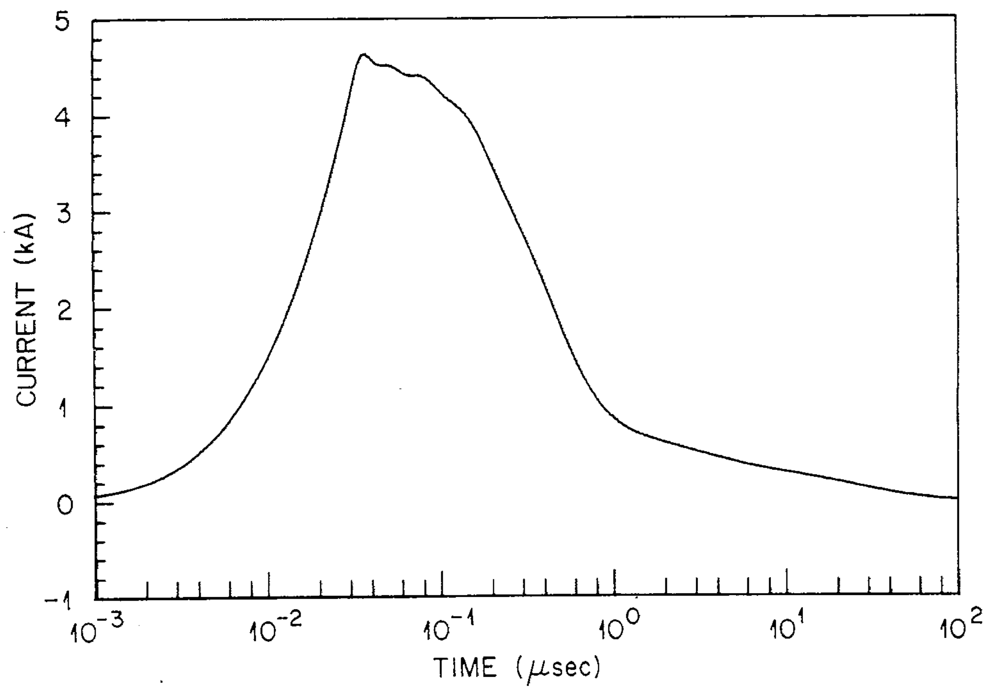


(*b*) VOLTAGE SURGE

Fig. A-13. Surges induced on a semi-infinitely long line 10 m above the earth, terminated by a transformer by representative EMP with $\theta = 30^{\circ}$, $\varphi = 90^{\circ}$, and $\psi = 90^{\circ}$.



(*a*) PHI EQUAL TO ZERO DEGREES



(*b*) PHI EQUAL TO THIRTY DEGREES

Fig. A-14. Current surges induced on a semi-infinitely long line 10 m above the earth, terminated by a short circuit by representative EMP with $\theta = 60^\circ$ and $\psi = 60^\circ$.

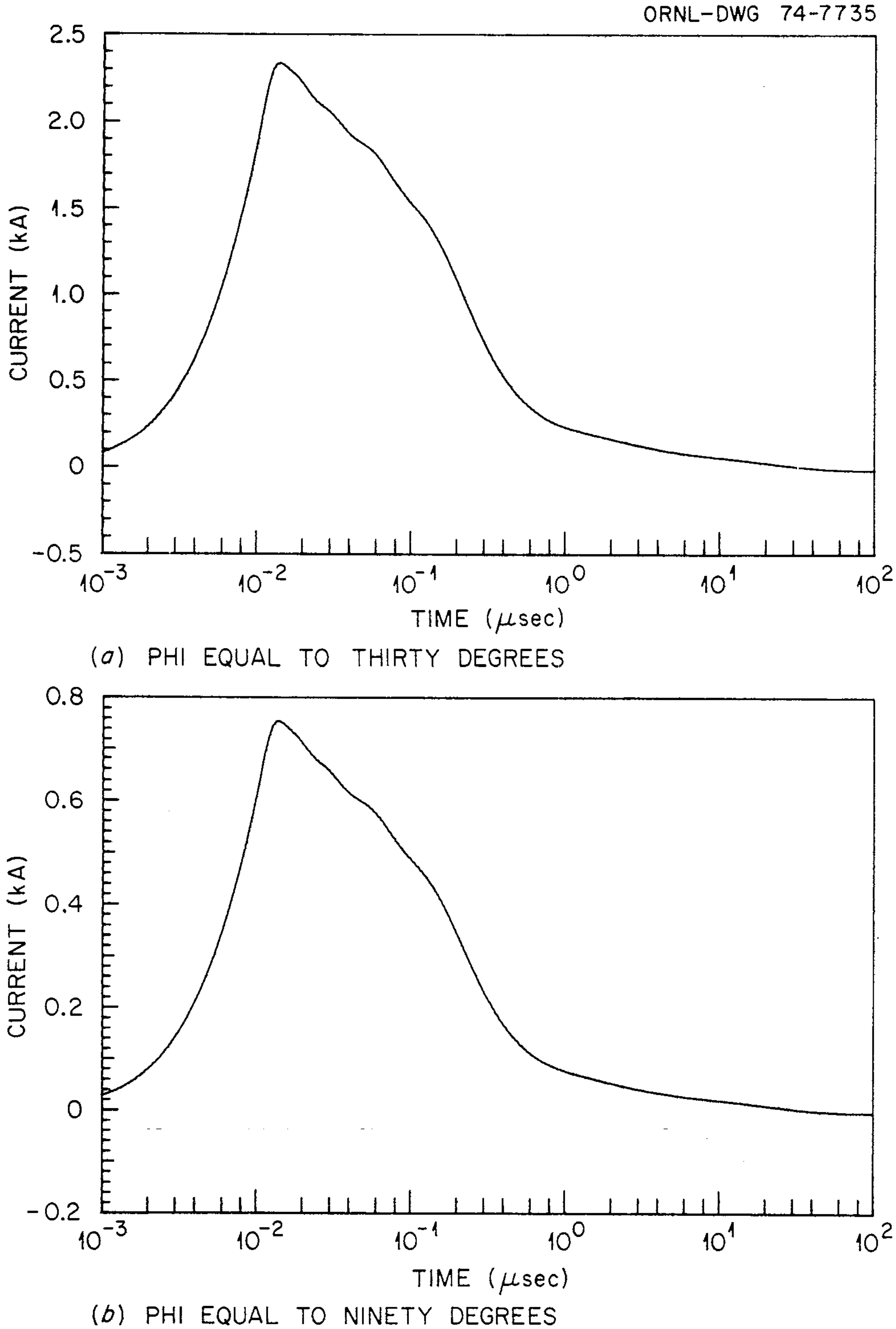


Fig. A-15. Current surges induced on a semi-infinitely long line 10 m above the earth, terminated by a short circuit by representative EMP with $\theta = 60^{\circ}$ and $\psi = 90^{\circ}$.

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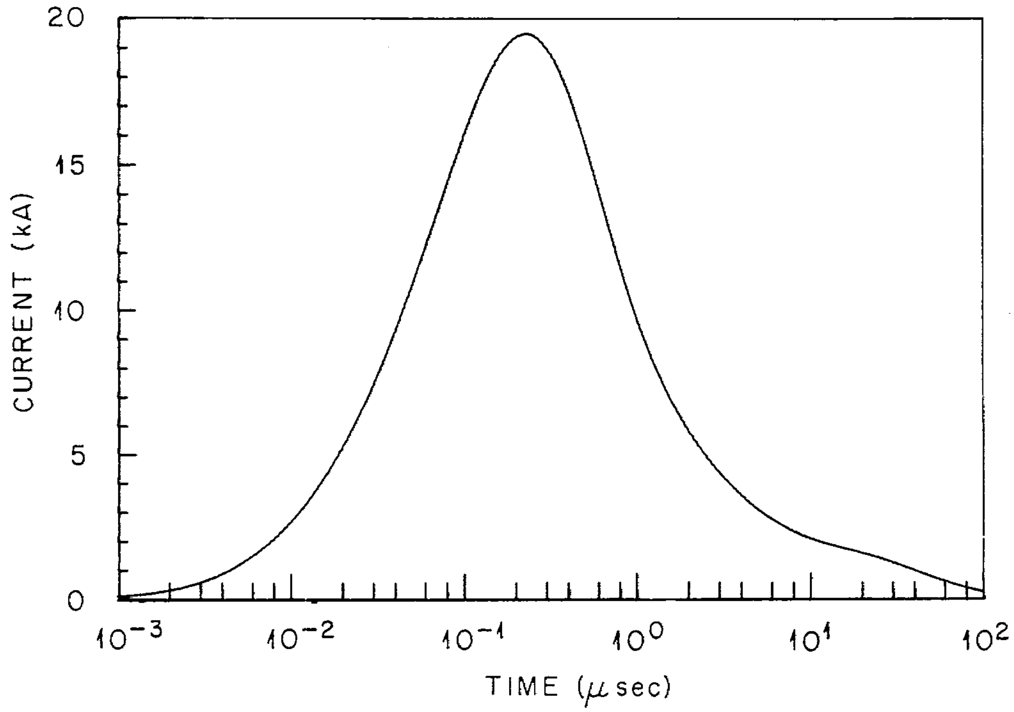
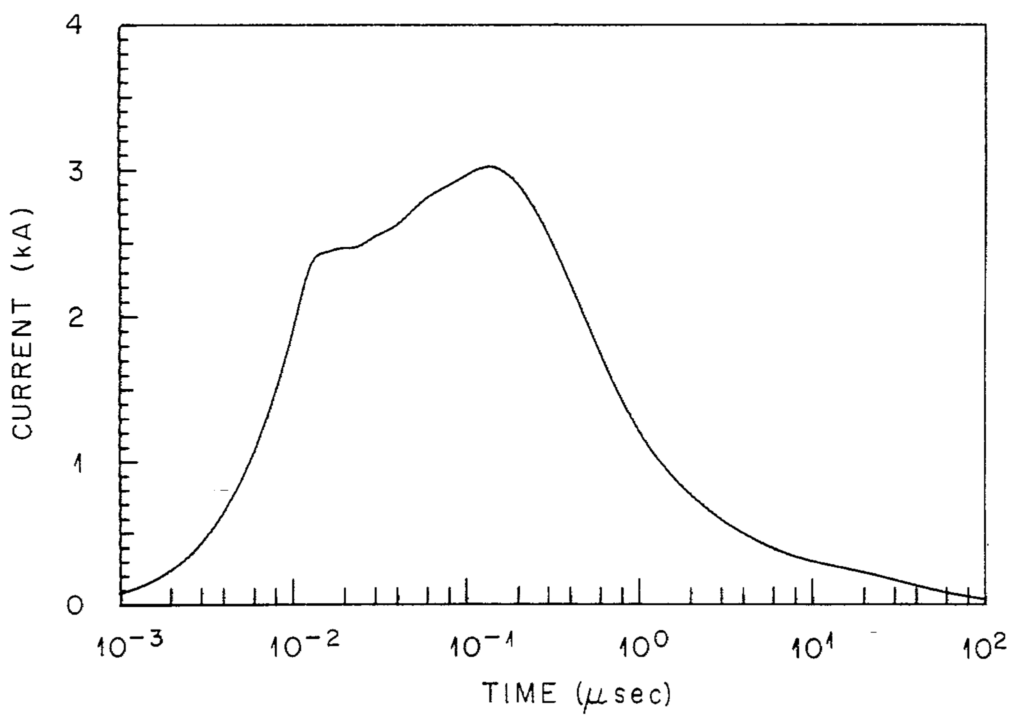


(*a*) PHI EQUAL TO ZERO DEGREES



(*b*) PHI EQUAL TO THIRTY DEGREES

Fig. A-16. Current surges induced on a semi-infinitely long line 10 m above the earth, terminated by a short circuit by representative EMP with $\theta = 80^{\circ}$ and $\psi = 60^{\circ}$.

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