Interaction Notes

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EFFECTS OF ELECTROMAGNETIC PULSE (EMP) ON A POWER SYSTEM[*]

J. H. Marable, J. K. Baird and D. B. Nelson

Oak Ridge National Laboratory
Oak Ridge, Tennessee

Abstract

The electromagnetic pulse (EMP), one of the effects of the detonation of a nuclear weapon, consists of a transient wave of intense electric and magnetic fields. These intense fields can cause malfunction or damage to electrical and electronic equipment exposed to EMP. Such malfunction and damage may be widespread if the detonation is at high altitude. In this report are given the results of an investigation of EMP on an electric power distribution system. Only the power circuitry and power components have been considered in this study.

This study is based on numerical and analytical calculations, on discussions with distribution company engineers and power-equipment manufacturer engineers, and on experimental work and field trips. Currents and voltages induced by EMP on distribution circuits as well as those reaching the consumer have been calculated. A comparison with lightning pulses has been made, and the protection presently used against lightning has been explored.

The results of the study indicate that a distribution system should be able to survive a single EMP without extensive damage if it is well protected by lightning arresters. However, extensive lockout of reclosing breakers will occur from multiple detonations, and consumer equipment will be damaged from EMP unless specifically protected. The resulting loss of load has serious implications concerning the system security of the entire power system. The alerting of the power industry and the development of a coordinated program of lightning and EMP protection is recommended.

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CHAPTER I

INTRODUCTION

1.1 BACKGROUND

The detonation of a nuclear weapon releases a large amount of energy, some of which appears in the form of an electromagnetic wave. This wave is characterized by high intensity fields of short duration and is referred to as the electromagnetic pulse (EMP). Experiments, both nuclear and non-nuclear, indicate that EMP can cause damage or malfunction in unprotected electrical or electronic systems. This damage can occur essentially instantaneously over very large areas, possibly crippling vital defense systems.

Previous work[1] on civilian power systems indicates that EMP can induce voltage pulses greater than a megavolt on overhead power lines. These pulses are sufficiently different from lightning pulses and switching surges in shape, geographical distribution, and timing that presently used surge protection may be insufficient. The results can range from short term outage with no significant damage to serious damage of power and control equipment.

This study addresses the problems of understanding the effect of the EMP on power distribution systems, and finding countermeasures for it. Accruing additionally from this study is knowledge of the pulses expected at users equipment connected to the electrical system, as well as information needed for study of power generation and transmission systems.

1.2 OBJECTIVES AND SCOPE

The long term objectives are to assess the threat of EMP to vital civil defense systems and to develop countermeasures for unacceptable damage or malfunction resulting therefrom. The specific objectives and scope of this study were to analyze the EMP effects produced by a thermonuclear attack in a typical local power distribution system and determine (1) if damage or malfunction of the distribution system will cause widespread loss of power to essential users; (2) if pulses induced on power lines will be large enough at users' connections to be damaging to users' equipment; (3) if effects on the distribution system will impair the functioning of the primary generation and transmission system by causing instability or appearing to be a sudden loss of load.

1.3 APPROACH, METHOD AND CONTENT

Previous studies have been largely exploratory in nature with the aim of establishing order of magnitude results. Concern from these studies stimulated this present, more intensive investigation, which includes experimental as well as theoretical methods.

The electric power distribution system has been selected as a basis for this study. This choice was made for a number of reasons. Distribution systems are much simpler than transmission systems and therefore easier to study. They operate at lower voltages so that EMP-induced flashovers are more likely. It is through the distribution system that the EMP as well as the power is delivered to the customers. Hence, a study of the pulse arriving at the consumers terminals necessarily involves a study of the distribution system supplying the consumer. Finally, knowledge of distribution system behavior is necessary if we are to understand EMP effects on generating and transmission systems.

The Knoxville Utilities Board (KUB), which serves the city of Knoxville and a corresponding population of about 300,000 was selected as a representative power distribution system. The choice of KUB for this study was made with the help of TVA on the basis of typicality, size, and proximity. KUB cooperated with us in this study by providing us with information, data, and schematic diagrams of their system.

Power distribution systems are basically networks of current carrying conductors broken by transformers and protected by surge arresters and by current and voltage sensing relays. These elements are largely clustered in areas called substations.

Again, in order to make our study more concrete, a representative substation was chosen, namely, the Dixie substation of the KUB system. This unmanned (as is typical) substation was chosen because it was equipped with a supervisory system for control, indication, telemetry, and recloser blocking. The master of this supervisory system was the Lonsdale dispatching station, a manned substation. These control and supervisory aspects of the system will be studied and presented in a later report.

1.4 EXPERIMENTAL STUDY

As a part of this study, experimental testing of various components of a power system was performed by staff members of the Illinois Institute of Technology Research Institute (IITRI). The objective of this testing was to help evaluate certain aspects of the response of power system components to fast EMP-like pulses. In particular, aspects difficult to idealize were addressed. This experimental effort was of limited scope and was performed to help identify problem areas which might not be readily apparent from purely analytical approaches. The findings of the experimental study are reported in the final Report of IITRI Project E6216, EMP Susceptibility Tests, April 1972 by W. C. Emberson and E. Emerle. Some of the findings of this study are summarized in Appendix A.

CHAPTER II

GENERAL DESCRIPTION OF A DISTRIBUTION SYSTEM

Power systems consist of three basic elements: (1) generation, (2) transmission, and (3) distribution. The generation consists of the generating stations and associated equipment. The transmission consists of (1) step-up transformer stations, (2) transmission lines, (3) switching stations, and (4) major step-down transformer stations.

The basic element with which this study is concerned is the distribution system, which includes those parts of an electric utility system between the power source and consumers' service switches. The power sources may be either generating stations or major step-down transformer stations supplied by transmission lines. KUB has three major stations supplied by TVA at 161 kV.

A distribution system consists of (1) subtransmission circuits which operate at voltages usually between 13 and 66 kV and which deliver energy to the distribution substations, (2) distribution substations which convert the energy to a lower voltage for local distribution and regulate the voltage delivered to load centers, (3) primary circuits which operate between 2.4 and 13.5 kV and supply load to a well-defined geographic area, (4) distribution transformers on poles, on pads, or in vaults near the consumers which convert the energy to utilization voltages, (5) secondary mains, along the street or alley to within a short distance of the users, and (6) service connections which deliver the energy from the secondary mains to consumers' service switches. Figure 2.1 shows a schematic representation of a typical distribution system.

The importance of distribution is indicated by its cost which is an important fraction of the delivered cost of electric power. Approximately 50% of the capital investment in electric power systems in the United States is in the distribution plant.

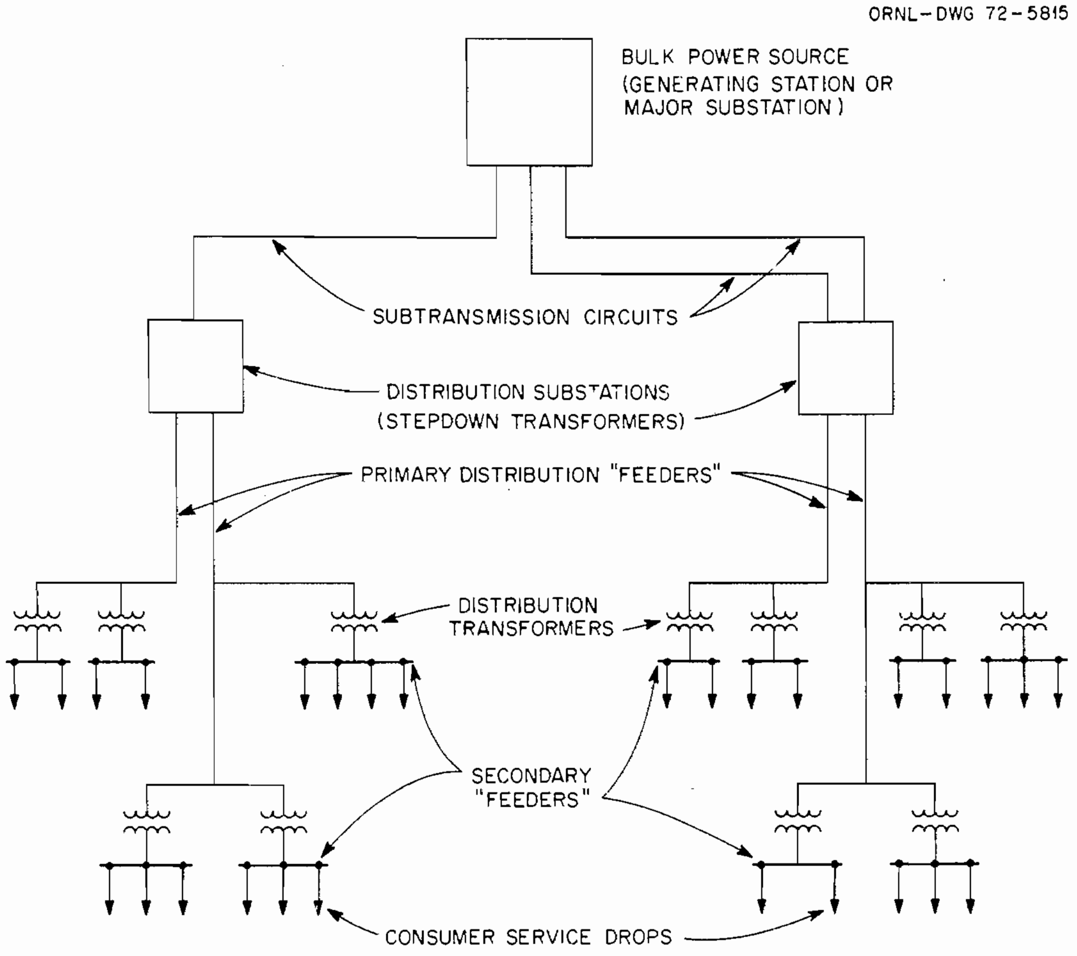

Fig. 2.1. A Typical Distribution System.

2.1 CLASSIFICATION OF DISTRIBUTION SYSTEMS

Distribution systems may be classified in a number of ways. First, they may be classified according to size. Size may refer to the area covered or the total length of the lines of the system. Or size may refer to the electric capacity of the system in kVA. For this study size has significance largely because of its connection with a geographical entity such as a city or a metropolitan area. Thus, the outage of a large part of a distribution system by some cause such as EMP is significant according to (1) the size of the community served and (2) the size of the load lost by the generating and transmission systems serving the distribution systems.

Distribution service may be divided into urban service and rural service. Rural electric service is now available to most rural dwellings because of the vigorous efforts of governmental agencies and cooperatives as well as the utilities themselves. In typical situations there may be only three to five customers per mile of line. This means that rural construction is of the least expensive type consistent with durable and reliable service. Devices on rural systems which might protect against EMP as well as lightning are accordingly held to a minimum.

Urban distribution may itself be divided into overhead and underground distribution. Underground distribution is used in densely built-up sections in spite of a cost penalty of from three to more than seven times that of overhead construction. A recent emphasis on the improving of the appearance of residential areas as well as suburban shopping centers has spurred the development of less costly light-duty underground and semi-underground distribution systems.

Distribution systems may be further classified according to the current (alternating or direct), the voltages on primary and secondary, the type of load, the number of phases, and the number of conductors. Three-phase alternating current is now almost universal for primary distribution. The voltages for these are typically 12.5 and 13.2 kV, older system voltages being somewhat lower. Three-phase four-wire systems are in very general use. The fourth wire of these Y-connected systems is a neutral wire operating at ground potential.

Secondary system voltages supplying general lighting and small power are usually single-phase three-wire mains operating at 120 V line to neutral and 240 V line to line.

2.2 THE RADIAL SYSTEM

The scheme of connection of a distribution circuit may be classified as radial, network, multiple, or series. The radial type of distribution system, such as than shown in Figure 2.1, is the most common. This system gets its name from the fact that the primary feeders radiate from the distribution substations and branch into subfeeders and laterals which extend into all parts of the area served. The radial system is used extensively to serve the light- and medium-density load areas where the primary and secondary circuits are usually carried overhead on poles.

The distribution transformers in this system are connected to the primary feeders, subfeeders, and laterals, usually through fused cutouts, and supply the radial secondary circuits to which the consumers services are connected. Oil circuit breakers arranged for overcurrent tripping are used to connect the radial-primary feeders to the low-voltage bus of their associated substation. When a short-circuit occurs on a feeder, its station breaker opens and interrupts the service to all consumers supplied by the feeder. Manually-operated sectionalizing switches are often installed at the junction of the subfeeders and the main feeder. When trouble on the subfeeder has been located, the faulty section can be isolated by opening the proper switch, and service can be restored to the remainder of the feeder before repairs are made. The purpose of the fuses in the primary leads of the distribution transformers is to open the circuit in case of trouble in a transformer or on its associated secondary lines and prevent a possible shutdown of a considerable portion of the feeder or the entire feeder on such faults.

2.3 SUBSTATIONS

One of the simplest distribution substation designs is shown in Figure 2.2. It consists of a high-voltage disconnecting switch, a transformer bank, and a primary-feeder breaker in the low-voltage leads of the transformer bank. In addition the breaker may be bypassed by a

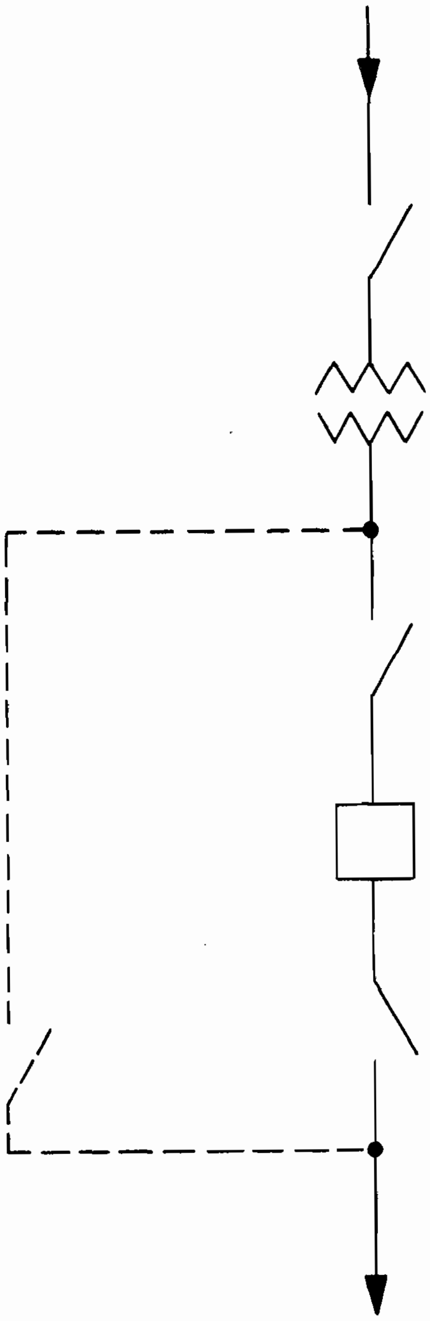

Fig. 2.2. Simple Form of Distribution Substation.

disconnect switch to allow the substation to continue in operation while the breaker is being serviced. In order to permit safe inspection and maintenance of the circuit breaker, disconnect switches are shown on both sides of it.

The single primary-feeder breaker of Figure 2.2 is usually provided with overcurrent relays and automatic reclosing equipment. Its interrupting capacity need be equal only to the maximum fault current through the transformer. The transformer is connected to the supply circuit on its high voltage side through a disconnect switch. The disconnect switch should not be opened under load but should be able to interrupt the transformer exciting current. To prevent accidental opening under load, the switch is interlocked with the primary feeder breaker so that it cannot be opened unless the breaker is open. Likewise, the disconnects on either side of the primary feeder breaker can be interlocked with the breaker such that they cannot open unless the breaker first trips.

2.4 DIXIE SUBSTATION OF THE KNOXVILLE UTILITIES BOARD

Figure 2.3 shows a one-line diagram of the Dixie Substation. The substation is fed by a 66 kV subtransmission line and steps down the voltage to the 13.8 kV primary distribution voltage. Normally, the disconnect on the far right in the high voltage bus is open and the substation is fed through the high voltage breaker. Each transformer feeds a low voltage bus which is in turn connected to the primary distribution system through circuit breakers. The breakers on the low voltage side of two of these transformers are fitted with a transfer bus which permits supply of power to the distribution circuits should one or the other of the low voltage breakers be out of service.

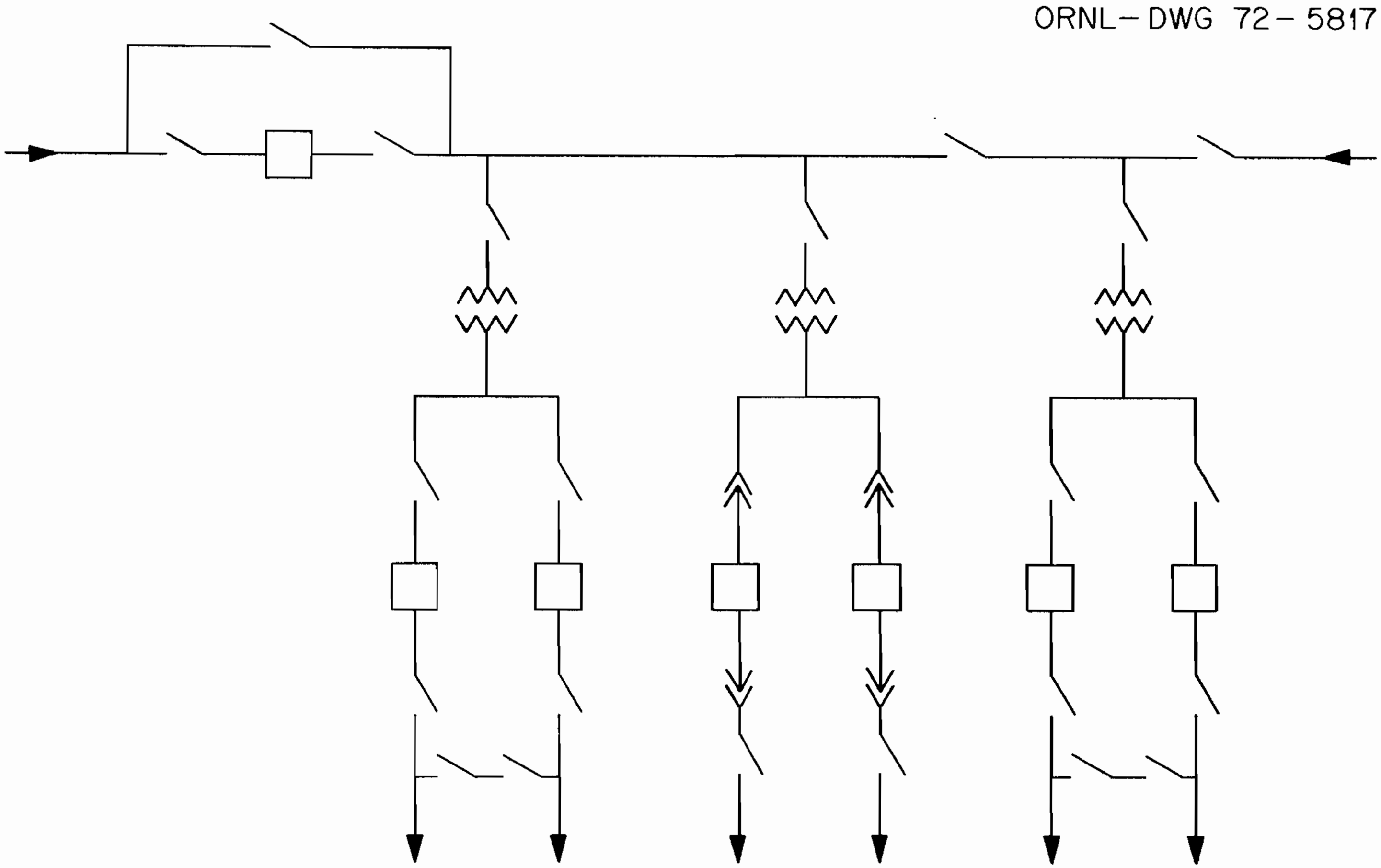

Fig. 2.3. Dixie Substation of the Knoxville Utilities Board.

CHAPTER III

GENERAL CHARACTERISTICS OF EMP

3.1 INTRODUCTION

The characteristics of EMP have been described elsewhere,[2,3] but a description is given here in order to make this report more nearly self-contained, easier to read and to understand, and especially to fix the assumptions under which this study was made.

The concern here is with electromagnetic pulses produced by high altitude nuclear detonations only. Ground and low-altitude bursts produce EMP also; but the EMP fields would not be of prime concern since blast and heat would ordinarily be much more devastating to power systems except within an annular region ranging from a few kilometers to a few tens of kilometers. On the other hand, EMP from a high altitude burst may have an area of coverage of millions of square kilometers, which is a large fraction of the United States.

3.2 TYPICAL CHARACTERISTICS OF EMP FROM A SINGLE HIGH ALTITUDE BURST

An electromagnetic wave, such as EMP, may be described by giving as functions of time the direction in which the wave propagates and the amplitude and direction of the electric field intensity. The direction of the latter is known as the direction of polarization.

The electromagnetic fields produced by a high altitude nuclear explosion will have a direction of propagation and a polarization direction for the electric field which depends upon the location of the burst, the location of the observer, and the direction of the earth's magnetic field. Rules of thumb state (1) that the direction of propagation is radially outward from the point of the burst and (2) that the direction of polarization of the electric field is normal to both the direction of propagation and the earth's magnetic field at the location of the observer.

According to the polarization, the electric intensity may be resolved into two components, one lying in the horizontal plane and the other lying in the vertical plane which contains the direction of propagation. The relative magnitudes of these two components are important for two reasons: (1) the reflection of electromagnetic waves from the earth is different for the two polarization components, (2) the coupling of electromagnetic pulses to horizontal transmission lines depends on the polarization.

Over the state of Tennessee the geomagnetic field has a dip angle of about 67°. This is a fair average of the dip angle over the United States. Using the above rules of thumb, one can easily see that the direction of polarization will be horizontal if the nuclear detonation is north or south of the observer. If the detonation is to the east or to the west, the direction of polarization will be off the horizontal by an angle of about 23° or less, depending on the angle of the burst above the horizon.

The amplitude of the EMP as a function of time, i.e., the wave shape and magnitude, is highly dependent on a number of factors including the height of the burst and the yield of the weapon, as well as the intensity and direction of the geomagnetic field in the upper atmosphere. In order to avoid the complications associated with considering the effects of each of these variables, it is useful and convenient to introduce the concept of a representative pulse. This representative pulse is chosen so that it is somewhat intermediate to what one would expect as an "average" pulse and to what one would reasonably expect as a worst case. Thus, the representative pulse defines an EMP environment which ordinarily would not be exceeded by a significant amount and at the same time would not be much greater than what one might call an average.

This representative pulse is shown in Figure 3.1 and is characterized by three parameters: (1) a peak value for the electric intensity which may be as high as 100 kilovolts, (2) a time to peak value of 2 shakes,* and (3) a time to reduction to half the peak value of 45 shakes.

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*A shake is a unit of time convenient for fast pulse studies. It is defined to be 10^{-8} sec.

Such a pulse can be approximately represented analytically by a sum of two exponential terms of the form

$$E_i(t) = E_o\left(e^{-\alpha t} - e^{-\beta t}\right)$$

where $E_i(t)$ is the amplitude of the incident electric field intensity at time t after the arrival of the front edge of the wave, and E_o, α, and β are constants related to the above three parameters. The values of the constants used in this study are

$$E_o = 5 \times 10^4/.9646 \text{ Volts per meter}$$

$$\alpha = 1.5 \times 10^6 \text{ sec}^{-1}$$

$$\beta = 2.6 \times 10^8 \text{ sec}^{-1}$$

Often it is convenient to regard the pulse as the sum of a continuous distribution of waves, each of which is characterized by an amplitude, a frequency and a phase. The two mathematical tools used for this are (1) the field of complex numbers for treating quantities with amplitude and phase and (2) the Fourier transform for converting from time to frequency.

It has been estimated[2] that for a fairly-typical high-altitude burst, the average EMP energy impinging on an area of ground is less than 3 joules/meter^2. The corresponding energy falling on a house with a floor area of 2,000 square feet would be 0.6 kilowatt-seconds. This EMP energy density is approximately the energy density received from the sun during a time of about two milliseconds. However, the EMP energy is received in something like 0.5 microseconds indicating the EMP has a power density four thousand times greater. Of course, the EMP lies in a different bandwidth with frequencies lying near the broadcast band while the sun's energies lie largely in or near the optical region. This means that the EMP energy is picked up and concentrated in metallic antenna-like structures such as long cables and transmission lines.

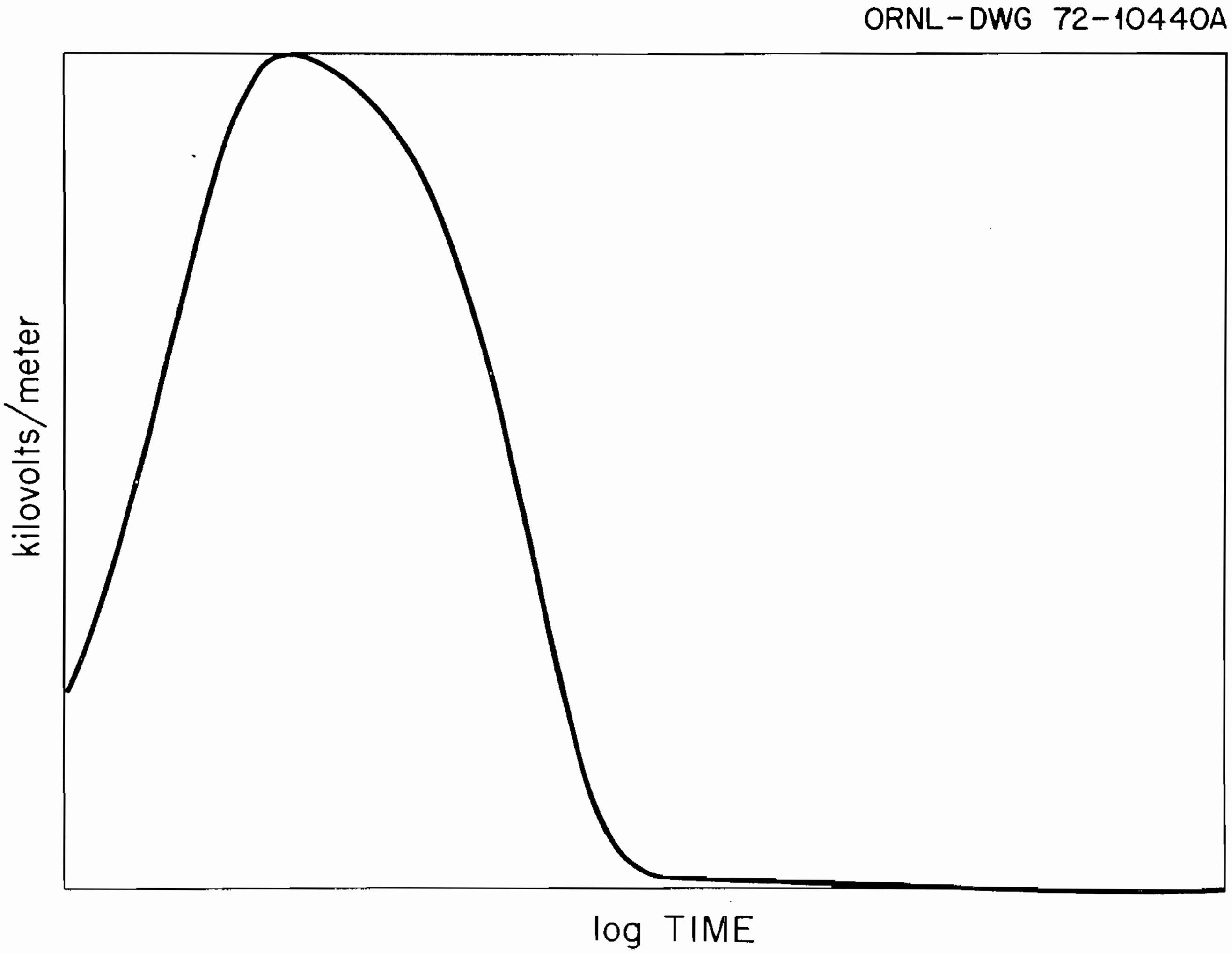

Fig. 3.1. Electric Field Strength as a Function of Time for the Representative EMP.

3.3 MULTIPLE BURSTS

In a nuclear attack, a series of high altitude bursts is not unlikely. The source of these bursts may range from an attacker's offensive missiles detonated explicity to produce EMP effects to our own defensive missiles deployed to intercept offensive missiles. It seems reasonable, then, to expect dozens or perhaps hundreds of high altitude defensive and offensive bursts spread out over a period of a few minutes or an hour.

Since the EMP from each burst is distributed over most of the country, the effects of many pulses must be considered and evaluated regardless of the location of the observer. Such an effect might manifest itself as a source of instability in a large electric power network due, for example, to repeated malfunctioning of various control elements. Another effect of multiple pulses would be associated with the failure of components. Here, one may consider the probability of damage to a single individual component as well as the expected total number of components failing in a system.

Of particular concern is the effect of multiple bursts on reclosers and circuit breakers which lock open after having interrupted several defected faults within certain prescribed time limits of the order of a minute. In the KUB system a recloser locks out if four faults are detected in about three minutes.

3.4 CURRENTS AND VOLTAGES INDUCED BY EMP

The EMP will cause current and voltage surges to appear in the components of a distribution system. The most important mechanism for this is the coupling through the transmission and distribution lines. The currents and voltages induced directly in components, such as transformers, is assumed negligible because of the size and because of the shielding ordinarily furnished by the equipments metallic case.

Since it is not possible to calculate the current and voltage induced by the EMP for all possible situations and geometries, only a few cases have been selected. These selections have been made in order to establish some upper limits and some reasonable "average-type" pulses.

In addition, two methods of calculation have been used in order to provide a check.

A description of the coupling calculations used is as follows. First there was assumed an incoming EMP with polarization and propagation directions which depend on the location of the line and the point of detonation as described in section 2.2. This wave was decomposed, or transformed, into its frequency components. To these components were added the contributions from ground reflection. Next, mathematical models of the lines and the associated equipment, such as transformers, were applied in order to calculate the currents and voltages at various points in the network as a function of frequency. Finally, these frequency components were added (the inverse transform) to reconstitute the voltage and current pulses as functions of time.

The calculation of the ground-reflected frequency components involved: (1) the decomposition of the polarization vector into two components, one lying in the plane of incidence, the other horizontal, (2) the selection of a low-frequency conductivity for the ground with corresponding experimentally determined frequency-dependent conductivity and dielectic constant,[4] (3) the application of Fresnel's reflection formulae.[5]

An example of the combination of the incident field plus the reflected field is shown in Figure 3.2. Note the more rapid drop (and even a negative part) of the combined field as compared with the incident field alone in Figure 3.1. This example assumes the incident field is sweeping in from ten degrees above the wire with a polarization in the vertical plane containing the wire. Fields sweeping in from higher angles and with horizontal polarization show an even more rapid drop in the combined field.

EMP-induced current pulses have been calculated on the basis of two theories: (1) scattering theory, and (2) transmission line theory. Scattering theory is based rigorously and directly on Maxwell's equation and is directly associated with the geometry and basic physical parameters of the systems. However, the mathematical analysis and computation needed are difficult except for the simplest and most ideal situations.

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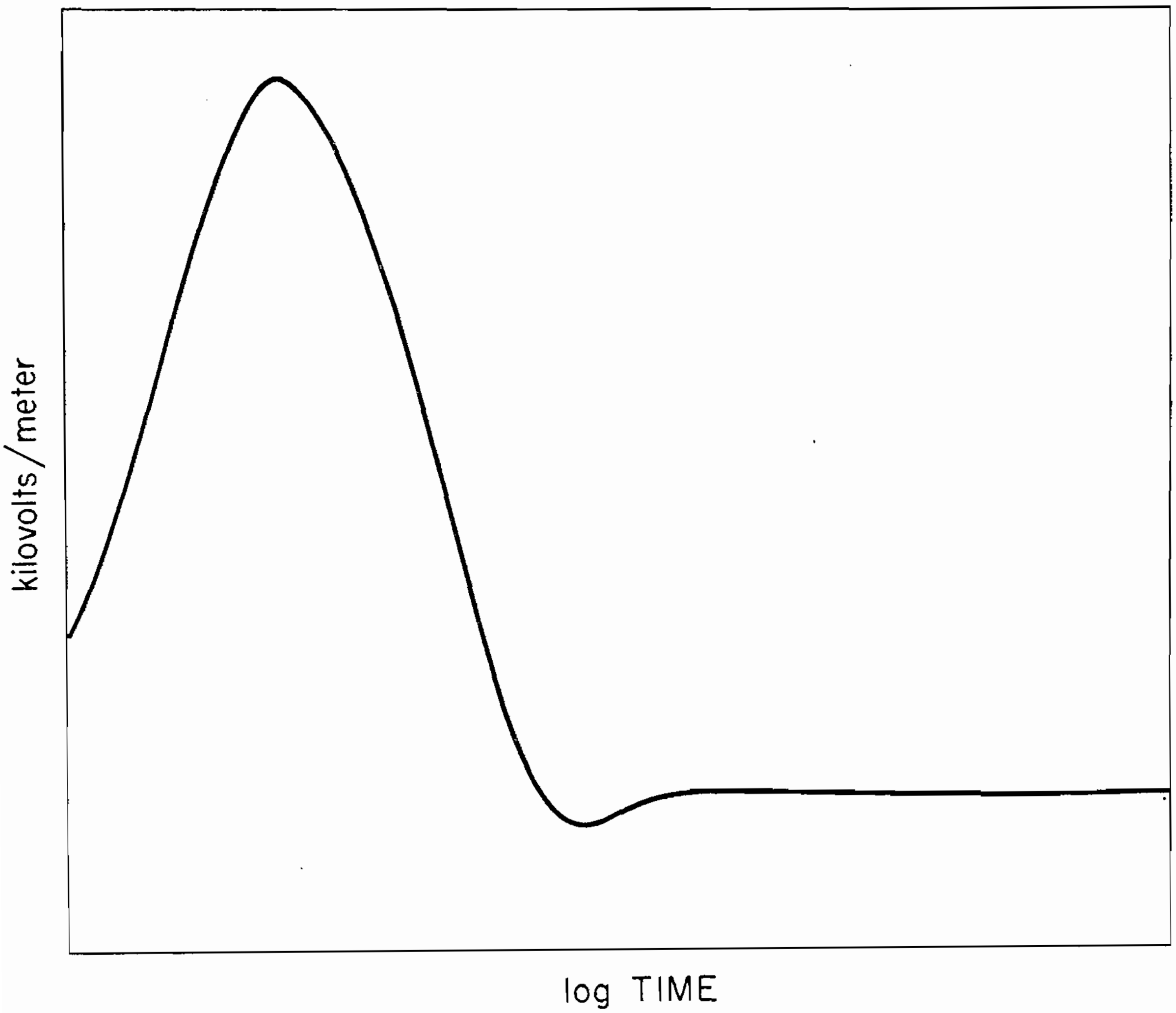

Fig. 3.2. The Horizontal Component of Electric Field of the Combined Incident and Ground-Reflected Fields at a Height of 10 Meters.

Transmission line theory requires for its validity the correct choice of certain "line parameters" such as the characteristic impedance and propagation constant. These parameters are not fixed but depend on the manner or mode in which the current and voltage are traveling. However, there are standard formulae for calculating these line parameters which have been shown to be valid for most of the cases of practical interest.

For this study both methods have been applied. The scattering theory has been applied to the calculation of current pulses in infinite perfectly-conducting wires. Transmission line theory has been applied to these cases as well as to networks of wires of finite length and finite conductivity with different directions and connected by transformers.

In particular, the case in which the incident wave of EMP comes in from a direction along the wire and ten degrees above the horizon has been selected as a test for comparing the two methods. The electric polarization was chosen to lie in the vertical plane formed by the incoming wave direction and the direction of the wire. The wire was assumed to be a perfect conductor with no resistivity.

The current for this case according to scattering theory is shown in Figure 3.3. The current according to transmission line theory is shown in Figure 3.4. A comparison of these two figures shows that transmission line theory gives a reasonable basis on which to make estimates of the effects of EMP on lines.

This case, which will be referred to as Case A, is unrealistic for several reasons. First, the resistance in the wire has been neglected. This resistance will be seen to be of some importance. Second, the electric polarization chosen is possible only for EMP near the earth's magnetic equator. Nevertheless, this case has been selected in order to represent a reasonable upper bound to the range of possible voltage and current pulses to be expected from EMP.

In order to apply transmission line theory to the problem of EMP coupling to finite electrical networks the following relations have been developed and used:

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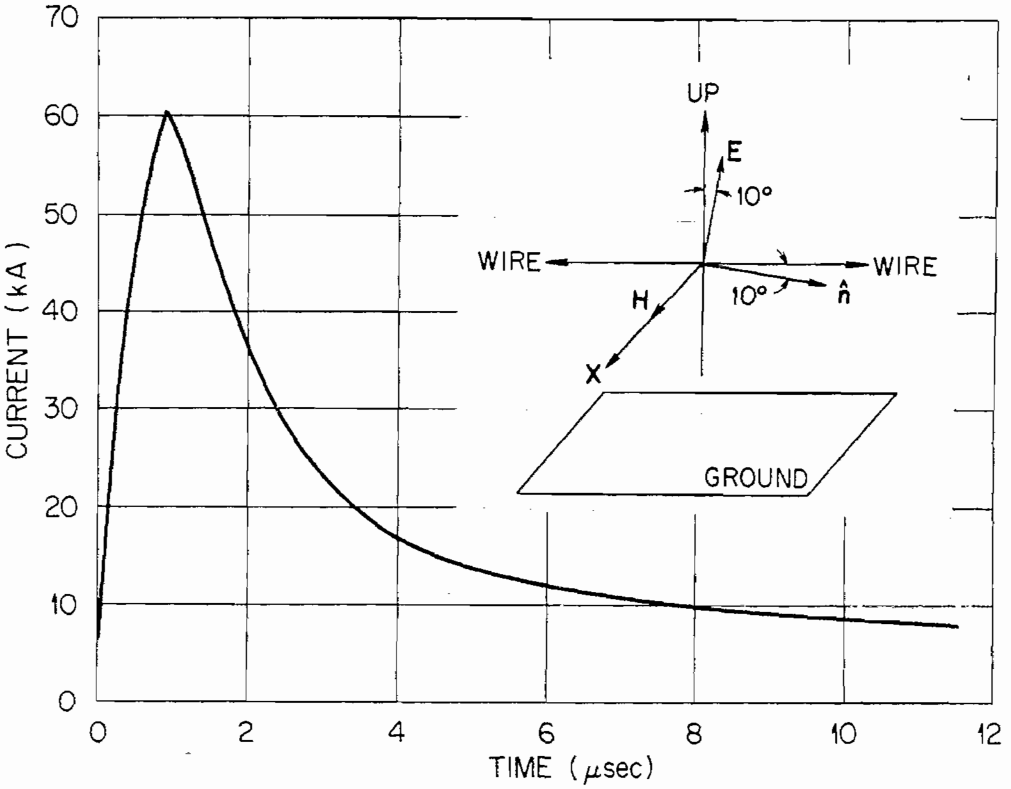

Fig. 3.3. Pulse Incident along the Wire, 80° with Respect to Vertical (Source 10° above Horizon). Electric Field Vertically Polarized. Infinitely-Long Perfect Conductor. Conductivity and Dielectric Constant of Ground Independent of Frequency.

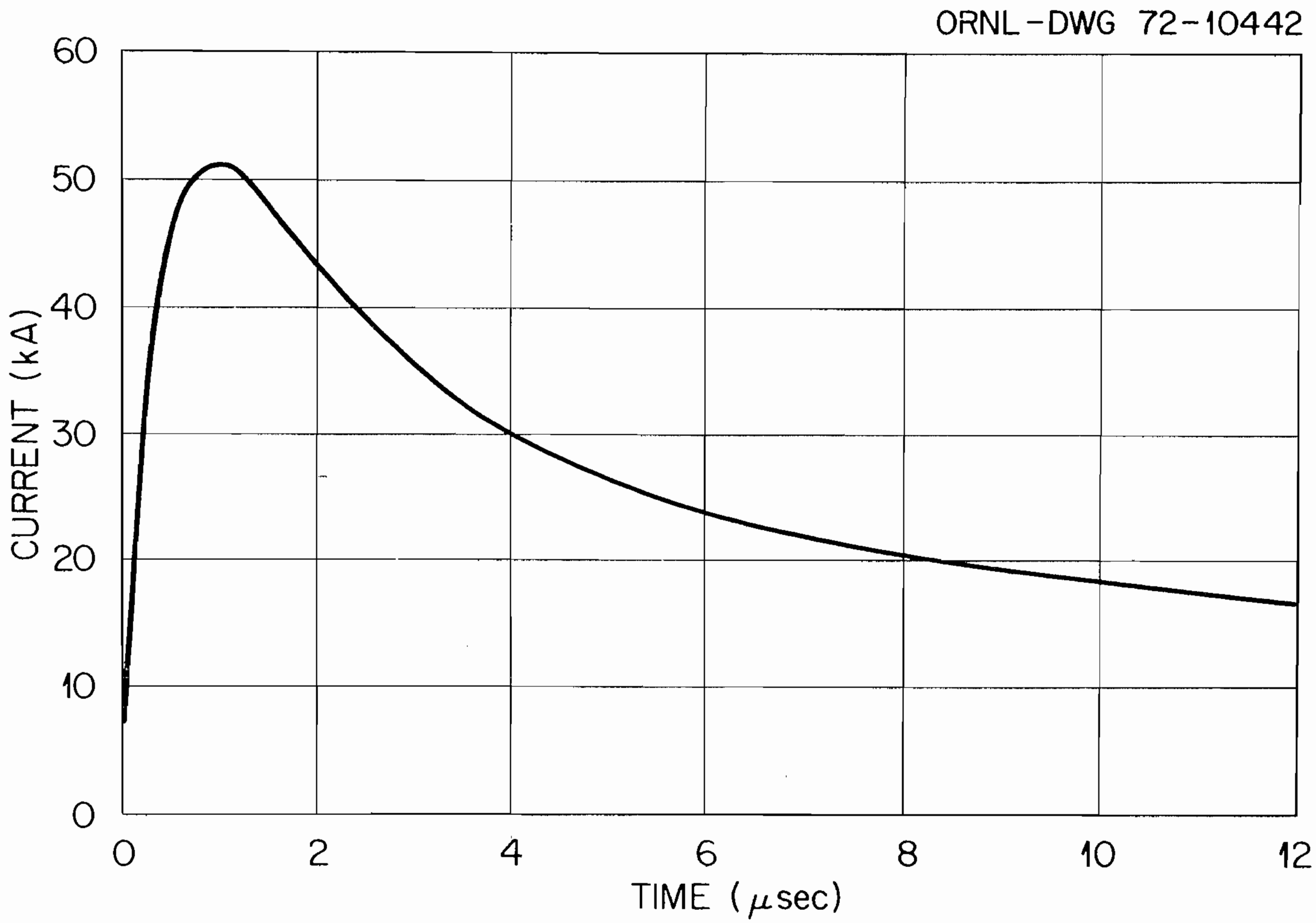

Fig. 3.4 The Current for the Same Situation as Described Under Fig. 3.3 According to Transmission Line Theory with no Resistive Element in the Line or Ground.

$$V(\ell) - V_\infty(\ell) = \cosh(\Gamma\ell)(V(o) - V_\infty(o)) - Z_o \sinh(\Gamma\ell)(I(o) - I_\infty(o))$$

$$I(\ell) - I_\infty(\ell) = \frac{\sinh(\Gamma\ell)}{Z_o}(V(o) - V_\infty(o)) + \cosh(\Gamma\ell)(I(o)) - I_\infty(o))$$

The quantity $V(\ell) - V_\infty(\ell)$ is the difference between the actual voltage $V(\ell)$ at a point a distance ℓ down the line and the voltage $V_\infty(\ell)$ that would appear at that point if the line extended to infinity in both directions. Similar interpretations hold for the other differences. Thus, the above equations relate the voltage and current differences at a point ℓ (one end of the line) to the voltage and current differences at point o (the other end). The relations involve, in addition to the line length ℓ, the line parameters, Γ and Z, which are the propagation constant and the characteristic impedance of the line, respectively.

The line parameters are calculated according to the method given by Sunde.[6] The "source voltages and currents, V_∞ and I_∞, are calculated according to studies reported previously.[7]

The line segments of an electrical distribution system may be joined directly or may be connected by various equipment. Transformers, in particular, which connect lines of different voltage ratings, are of concern for two reasons: (1) the possibility of coupling the pulses from primary to secondary as well as the modifying of the pulse shapes and (2) the possibility of EMP damaging the transformers. Here we are concerned with the first possibility, the following chapter is concerned with the second.

3.5 TRANSFORMER MODELING FOR EMP SURGES

The impedance and transfer characteristics of three-phase transformers subject to fast surges is a very complicated and involved subject. As a start, we have represented three-phase transformers by a bank of three similar single-phase transformers. The model of each single-phase transformer in the bank is represented by the schematic diagram shown in Figure 3.5. This model includes effects of interwinding capacitance, series capacitances, and capacitances to ground.

The parameters are obtained from a variety of sources. Transformer name-plate information provides the kilovolt ratings, kV_1 and kV_2, of

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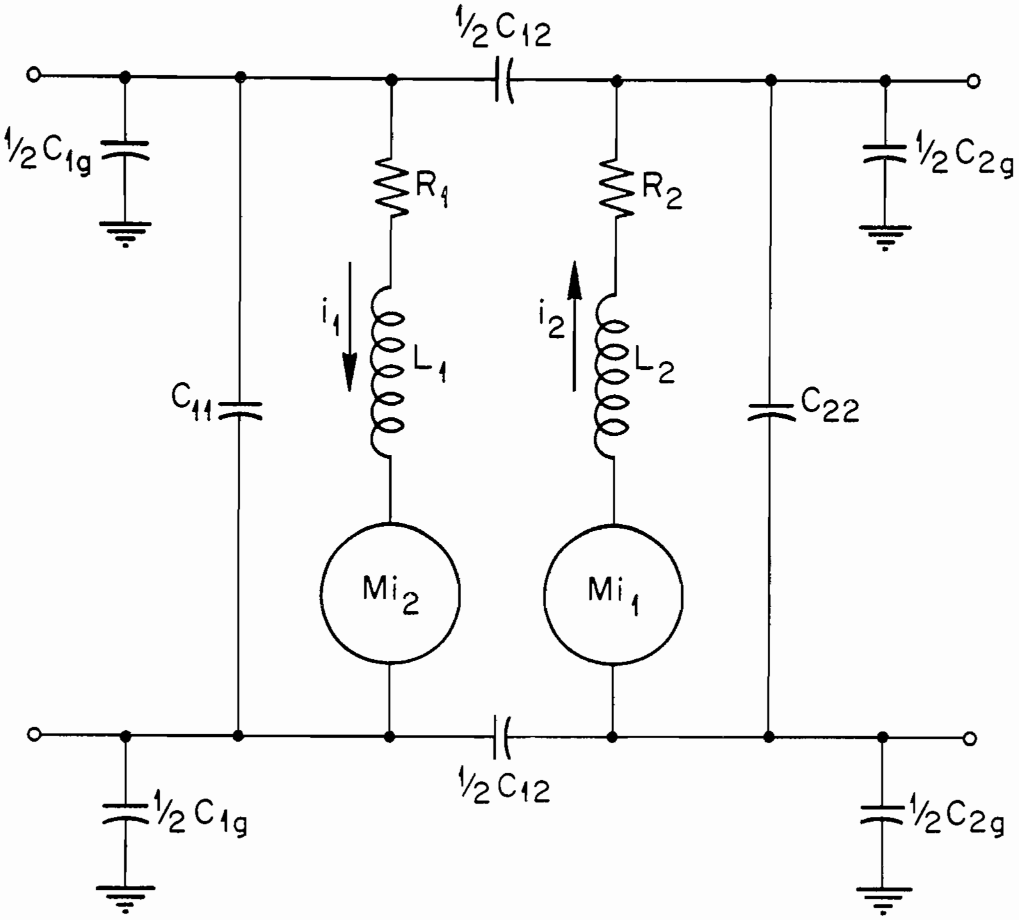

Fig. 3.5. Single-Phase Transformer Model which Includes Shunt Capacitances C_{11} and C_{22}, Interwinding Capacitance C_{12}, and Capacitances to Ground C_{1g} and C_{2g}, as well as Inductive and Series Resistive Elements.

primary and secondary, respectively, as well as the per unit leakage reactance X_{pu} and the power rating MVA. A leakage inductance

$$L' = \frac{1}{2} \frac{X_{pu}}{2\pi 60} \frac{kV_1 \cdot kV_2}{MVA}$$

and an effective turns ratio

$$n = kV_1/kV_2$$

are calculated from this information.

A typical transformer iron has a flux penetration characterized by a time constant[8]

$$T_1 = 6.5\mu\,\text{sec.}$$

The mutual inductance is then given as a function of frequency by

$$M(s) = M_o \frac{\tanh \pi \sqrt{sT_1}}{\pi \sqrt{sT_1}}$$

where M_o is the mutual inductance at low frequencies and is related to the size and shape of the transformer by

$$M_o = \mu N_1 N_2 A/\ell$$

where μ is the permeability of the iron, A is the cross-sectional area of the iron, ℓ is the length of the flux path in the iron, and N_1 and N_2 are the number of turns of primary and secondary, respectively.

The corresponding self inductance of the primary is

$$L_1(s) = n(M(s) + L'),$$

and of the secondary,

$$L_2(s) = \frac{1}{n}(M(s) + L') .$$

The effective resistance of the windings was obtained from engineering tables[9] on the basis of MVA rating and was apportioned to primary and secondary on the basis of equal heat production.

The capacitance values were obtained in part from tabulations[8] and from reasonable guesses based on transformer construction. These capacitance values, or, rather, particular ratios of these values are of special importance since the transformer often looks like a capacitance voltage divider for pulses traveling in the common mode (all three lines have equal currents in phase).

The passage of surges through three-phase transformer banks depends on the type of transformer connection as well as the type of mode of the surge. We have calculated the coupling matrix for common-mode surges passing through delta-delta, delta-grounded Y, delta-ungrounded Y, grounded Y-grounded Y, grounded Y-ungrounded Y, ungrounded Y-ungrounded Y. Each of these transformer connections looks very much like a capacitance voltage divider for common mode pulses; the delta-delta connection, in particular, is exactly this, since there is no voltage across the windings in common mode.

The surge voltage ratio μ of secondary to primary in the delta-delta connection is given by

$$\mu = \frac{C_{12}}{C_{12} + C_{2g}}$$

where C_{12} is the interwinding capacitance and C_{2g} is the secondary to ground capacitance. Since the primary is at a much higher voltage than the secondary, the insulation between primary and secondary is greater than that between secondary and ground. Hence, C_{2g} is ordinarily several times greater than C_{12}, and μ is typically of the order of one-fourth. This has been demonstrated experimentally at IITRI using very fast pulses.[10] Lightning experience also bears this out.[11]

Pulses coupled onto the secondary will pass through the transformer onto the primary according to the above equation with C_{2g} replaced by C_{1g}. Typically, C_{1g} is of the same order of magnitude as C_{12} and μ is of the order of one-half.

This equation suggests two ways in which to reduce the surge passed by transformers. The first is to reduce the value of the interwinding capacitance C_{12} by modifying the design of the transformer. The second is to increase the value of the secondary to ground capacitance C_{2g}. This may be effectively accomplished without redesigning the transformer by simply adding an external capacitance to ground on the secondary transformer terminals.

3.6 QUALITATIVE COMPARISON OF EMP WITH LIGHTNING

An EMP is often compared to lightning. The principal reason for this comparison is to get some understanding of the extent to which lightning protection devices will protect equipment against the EMP. Another reason is to scale and measure the EMP along the lines of a phenomena with which we are more familiar.

In this comparison it is important to understand the differences between the EMP and lightning. Here we are not concerned so much with the differences in the origins and causes of the two phenomena but with the differences in the voltages and currents produced by them. It is the voltage (the gradient of the voltage, to be more accurate) which causes flashover and the breakdown of insulation. It is the current, however, which is detected through the use of current transformers for the operation of circuit breakers (potential transformers are also sometimes used).

Before we discuss the characteristics of the voltage pulses induced by lightning or an EMP we must be clear what is meant by voltage since the electric field is not conservative. In this report voltage refers to the integral (a line integral from ground to wire) of that component of the electric field normal to the wire and the ground. This is the component which ordinarily will be responsible for the breakdown of insulation, etc. In non-mathematical terms, we are using those electric forces pointing from the wire to the ground to define the voltage and not those forces pointing along the wire.

A direct lightning stroke may be regarded as an electric charge injection process. This charge, which appears at a point on the line, creates a voltage and must travel by whatever paths are available to ground if the line is to become electrically neutral. Ordinarily the charge travels away from the stroke point in opposite directions along the line forming a current and an associated voltage. In ordinary aerial transmission lines the ratio of the voltage to current in such pulses is of the order of 300-500 ohms. This ratio, called the surge impedance or characteristic impedance, is slightly frequency dependent.

In contrast to lightning, the EMP is not a local charge injection process carrying its own electrostatic field with it. On the contrary, it is a continuous current induction process. That is, current is induced continuously, uniformly, and unidirectionally along a segment of a transmission line.

The manner of current generation depends on the angle between the incoming wave and the transmission wire. If the wave comes in at right angles to the wire, the current is generated simultaneously at all points in the wire. If the wave comes in at some direction nearly along the wire then the current is generated at the point of intersection of the wave and the wire. This point of current generation moves along the wire with a speed faster than the speed of light. This speed is actually the speed of light divided by the cosine of the angle between the propagation direction and the wire.

As this angle becomes smaller the speed of the point of current generation decreases and becomes more nearly the speed of light. The current generated correspondingly becomes more successful in trying to keep up with the point of generation. Hence, the peak current induced is larger in magnitude for smaller angles of incidence on the wire.

There is another important effect dependent on the angle of incidence. This is associated with the buildup of charge and voltage along the transmission line which may be considered by conceptually thinking of an instantaneous photograph of the current along the wire.

If the EMP comes in at right angles to an infinitely long wire, then the current is the same all along the wire and there is no net charge or voltage. If the wire is finite in length, then the same statement is valid until charge and voltage buildup at the ends causing a reflected pulse to be launched back along the wire. In this case of perpendicular incidence there is no voltage until the current is reflected. The reflected voltage V_r is related to the reflected current I_r by

$$V_r = ZI_r$$

where Z is the characteristic impedance.

If the EMP comes in at angle θ with the line then it can be shown that the voltage in an infinite line is related to the current by

$$V = ZI \cos \theta$$

where Z is the characteristic impedance of the line. If the line is finite then the latter of the two equations applies up until the current is reflected at the ends, and then the reflected voltage and current satisfy the first equation.

3.7 CHARACTERISTIC EMP-INDUCED CURRENTS AND VOLTAGES

Voltages and currents for a number of typical geometries are shown in Figures 3.5 through 3.10. The captions are self-explanatory.

These results may be modified by a phenomenon which has not yet been taken into account, namely that due to corona. Sunde has shown that the effect of corona is to delay or chop off the front of the voltage pulse as shown in Figure 3.11. Since EMP voltage pulses are induced continuously along a line right up to a terminal, such coronal distortion may well be less for EMP than for local charge injection processes, such as lightning, for which the pulse must travel some distance to a terminal. In any case, this difficult question of corona effects on EMP pulses requires further study and research for its resolution. It is not anticipated that corona will alter the principal findings of this study.

3.8 QUANTITATIVE COMPARISON OF EMP AND LIGHTNING

The current and voltage of Figures 3.7 and 3.8 represent a typical large pulse which can be induced by an EMP on transmission and distribution lines. This is not an absolute limit but only a reasonable representative of the largest pulses to be expected.

It is interesting and informative to compare this large EMP pulse with lightning pulses. Figure 3.12 shows a cathode-ray oscillogram of the highest lightning voltage recorded on a transmission line.[12] This pulse reached a crest of 5,000 kV in less than two microseconds. The maximum rate of rise was of the order of 4,000 kV per microsecond. Because the lightning struck four miles up the line from the oscillograph

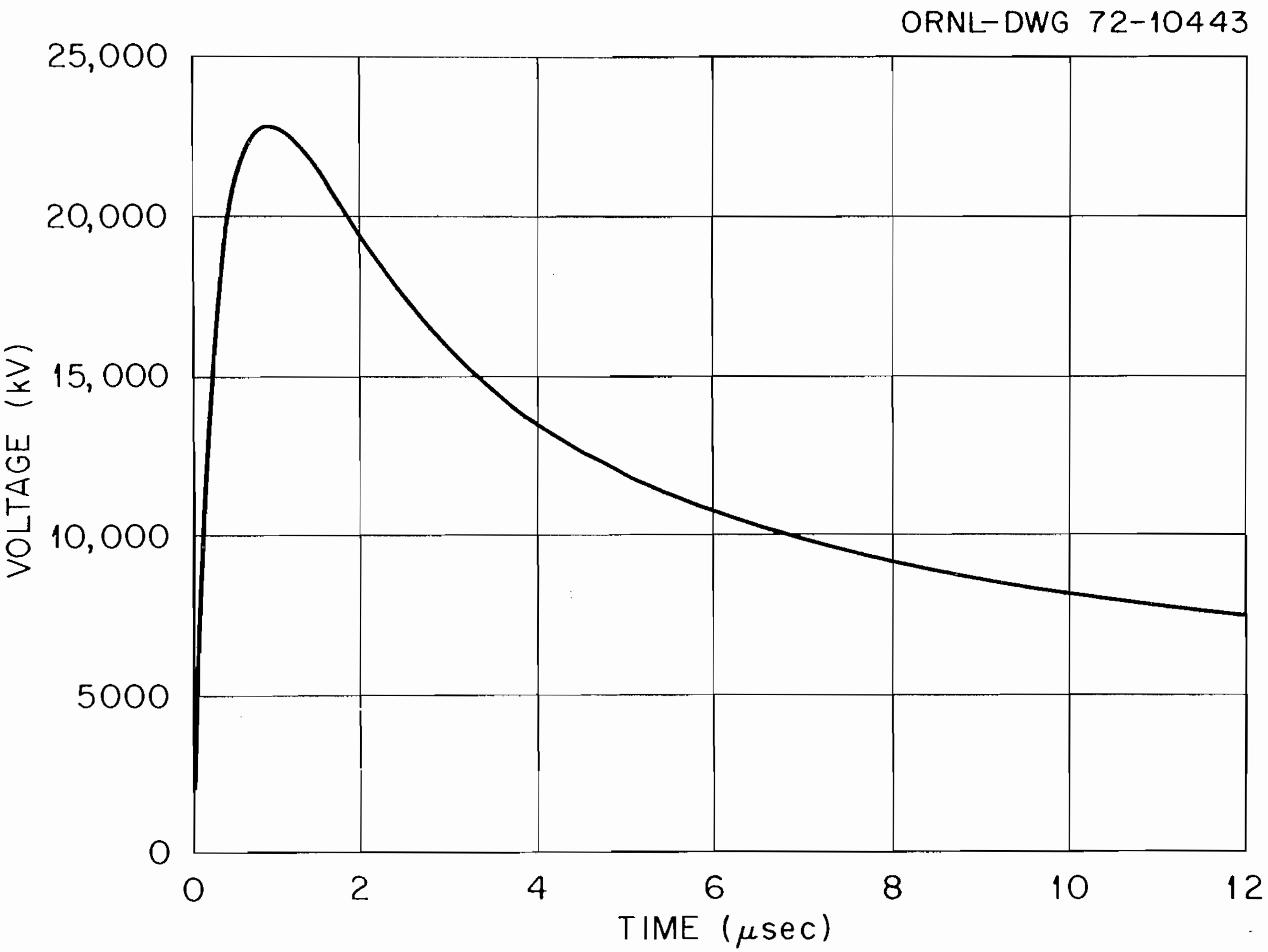

Fig. 3.6. The Voltage Corresponding to Fig. 3.4.

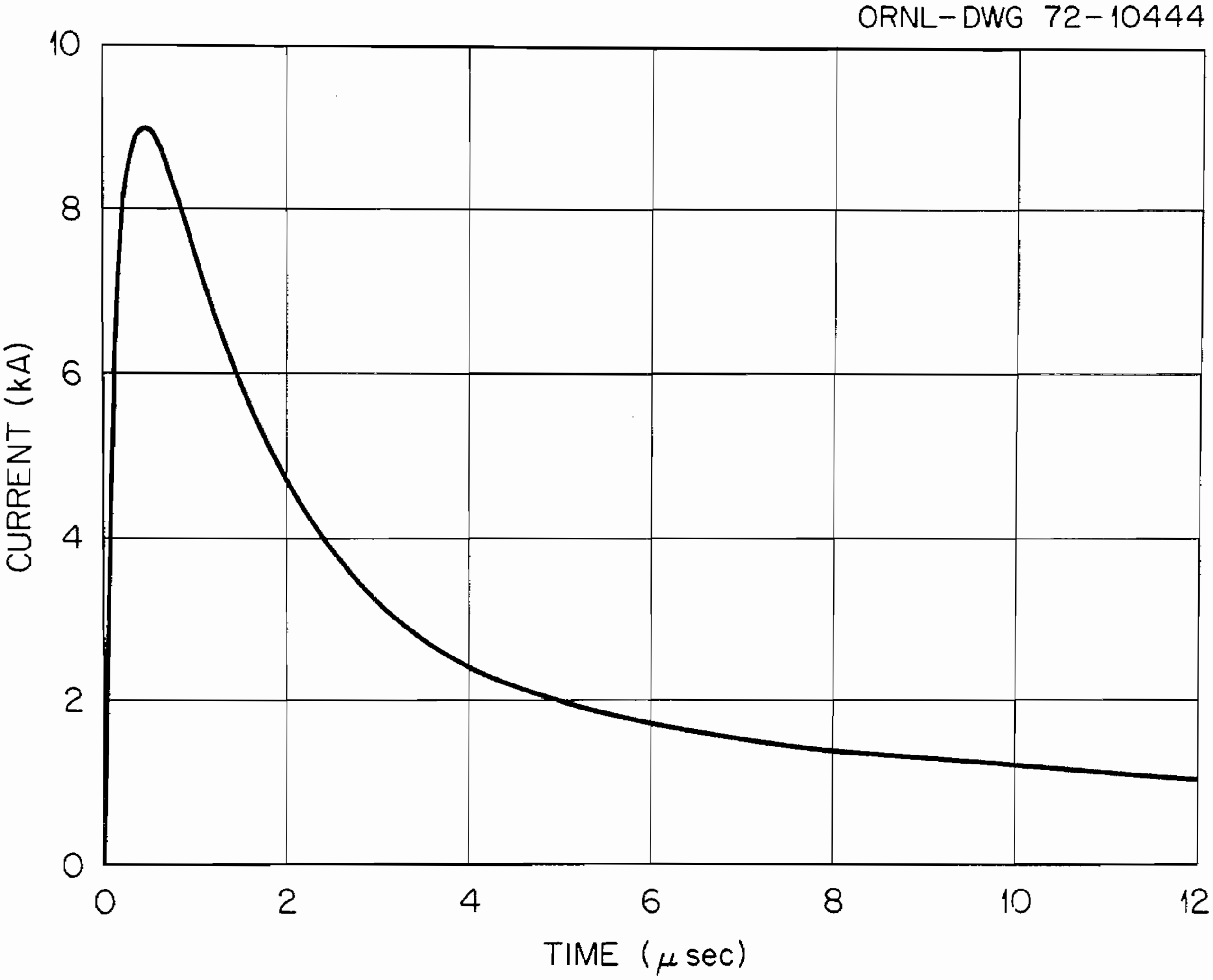

Fig. 3.7. The Current as Described in Fig. 3.4 but with Frequency Dependent Resistance Included in Line and Ground.

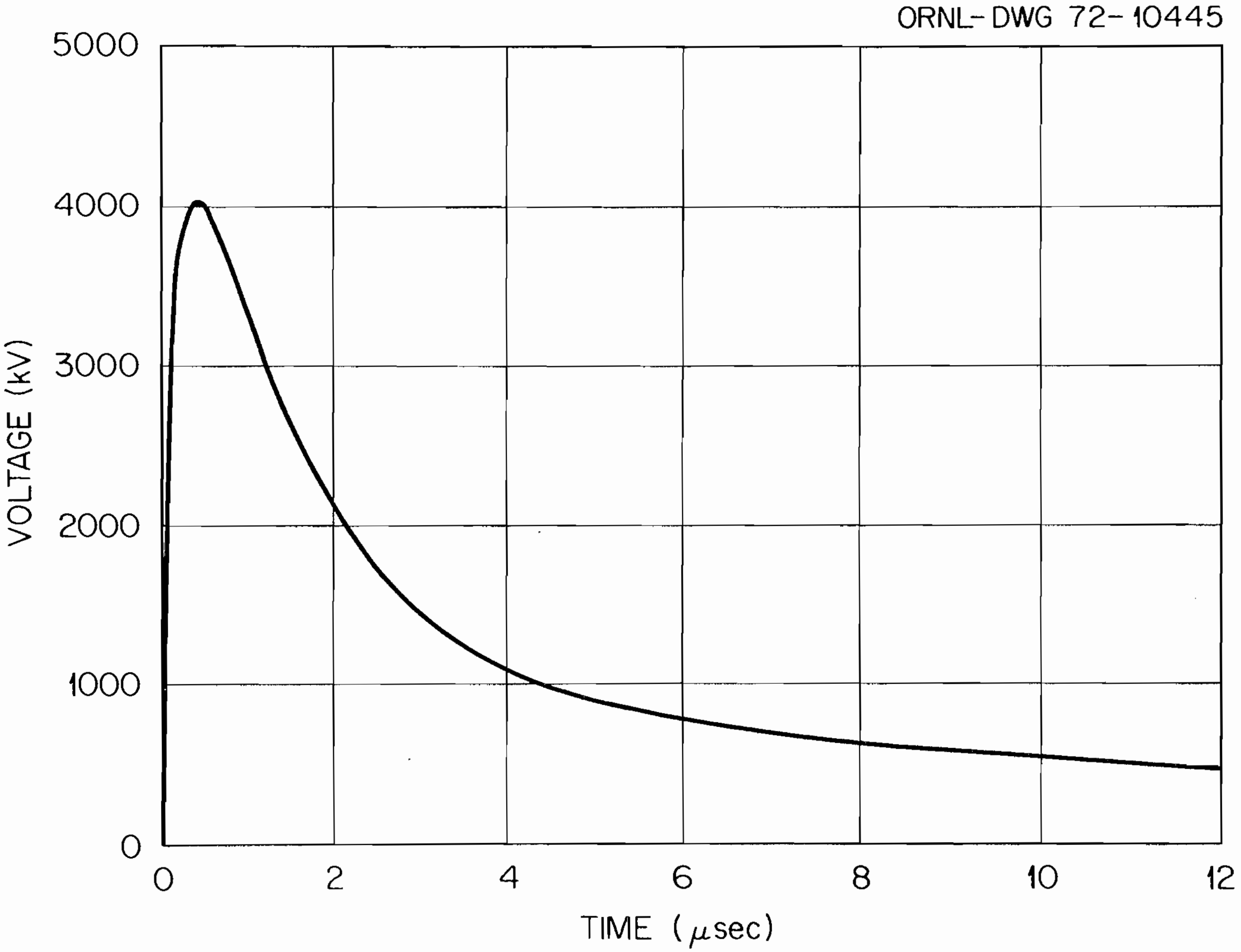

Fig. 3.8. The Voltage Corresponding to Fig. 3.7.

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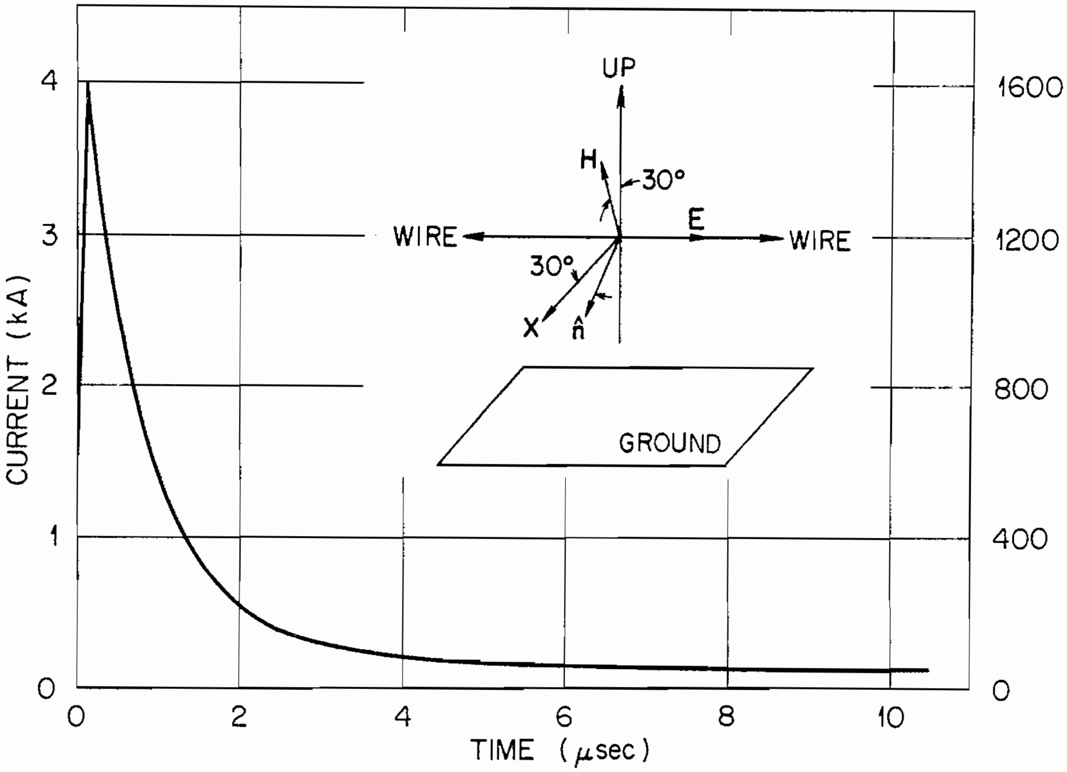

Fig. 3.9. Pulse Incident Broadside to the Wire, 60° with Respect to Vertical (Source 30° Above Horizon). Electric Field Horizontally Polarized. Infinitely-Long Perfect Conductor. Conductivity and Dielectric Constant of Ground Independent of Frequency.

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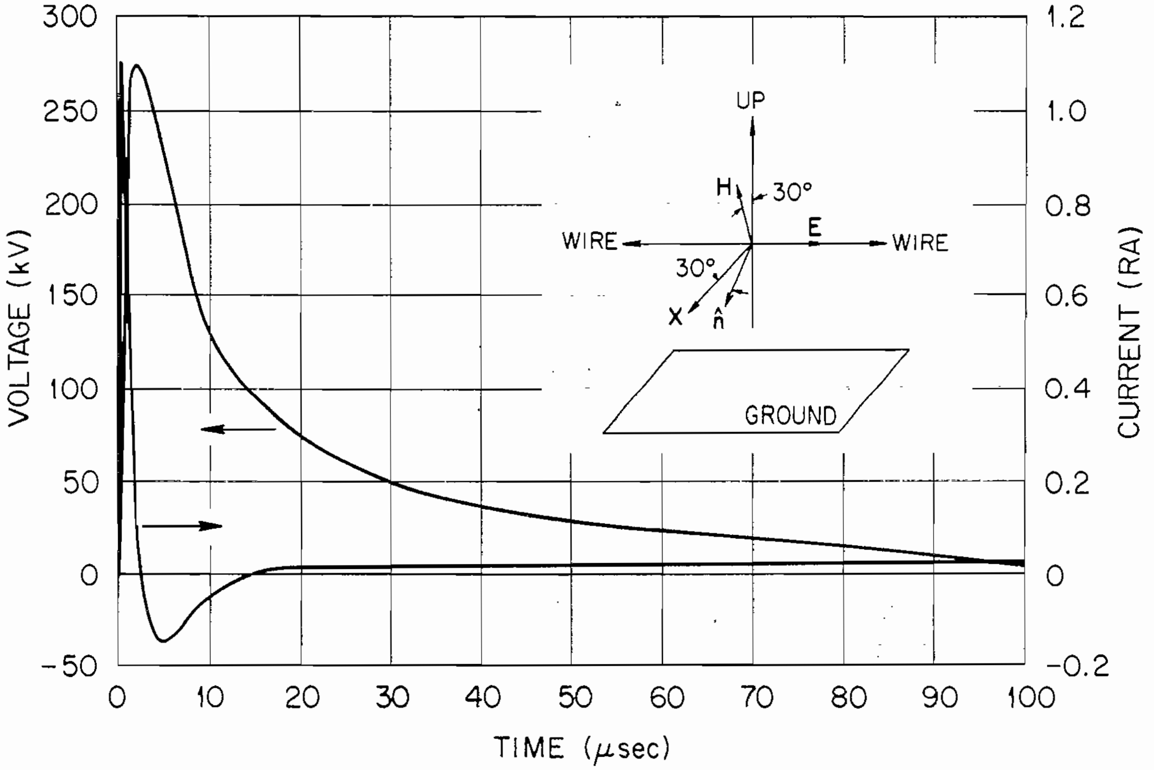

Fig. 3.10. Pulse Incident Broadside to the Wire, 60° with Respect to the Vertical (Source 30° Above Horizon). Electric Field Horizontally Polarized; Semi-Infinite Wire; Voltage Calculated at Transformer Termination. Conductivity and Dielectric Constant Functions of Frequency.

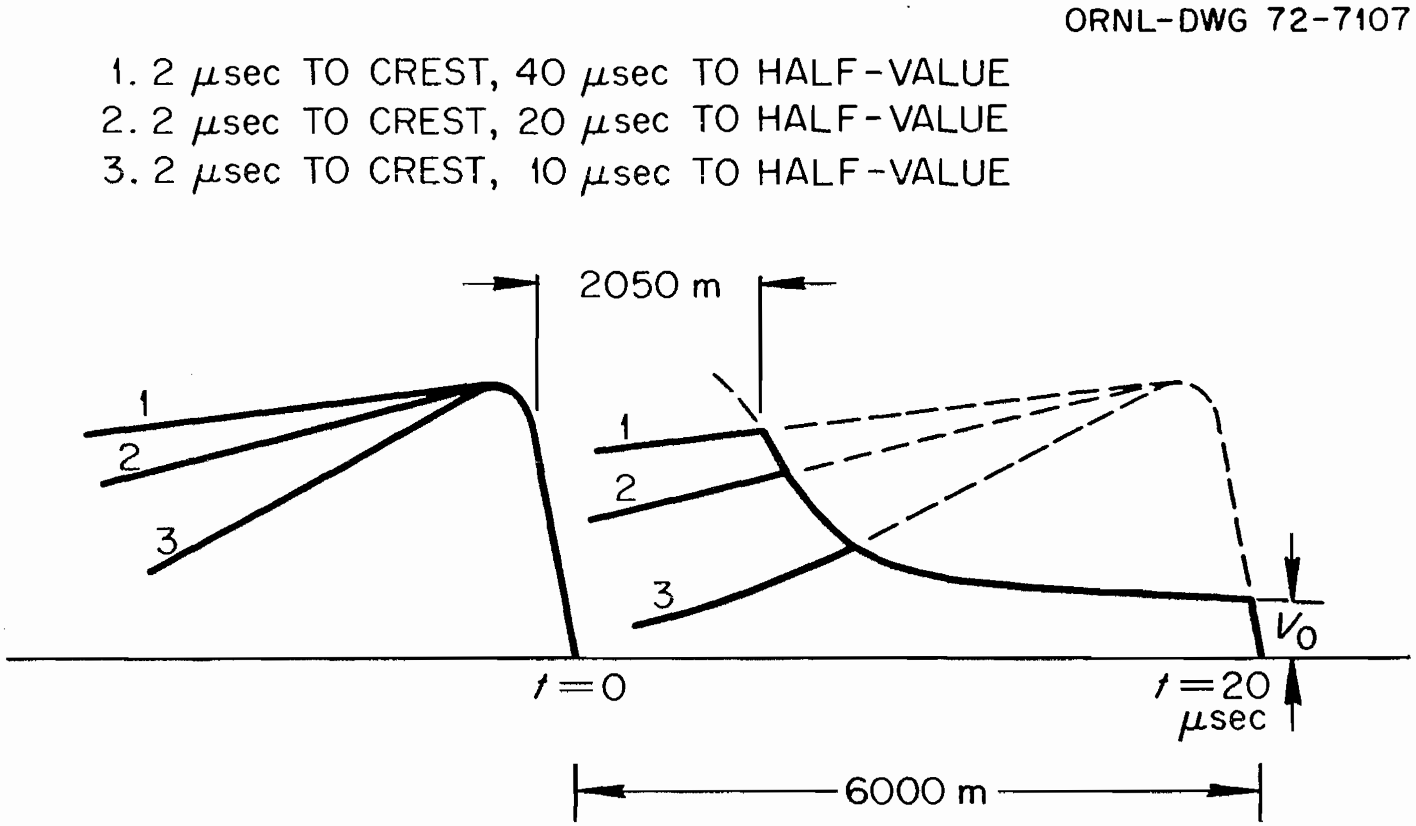

Fig. 3.11. Attenuation and Distortion due to Corona when Ratio of Initial Crest Voltage to Corona Voltage V_o Equals 5, for Three Surges with same Wave Front but Different Tails. Tails.

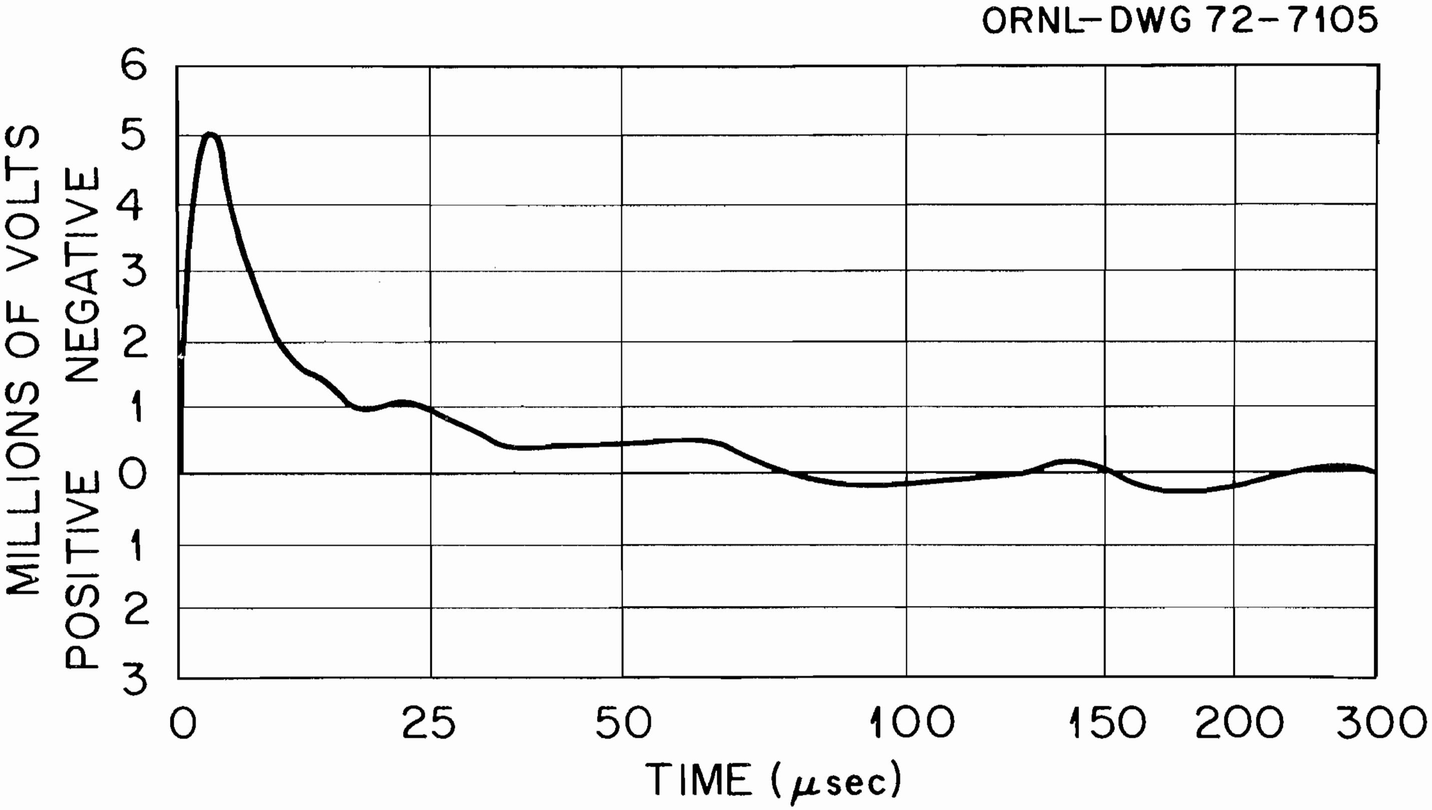

Fig. 3.12. Cathode-Ray Oscillogram of Highest Voltage Recorded on a Transmission Line; 110-kV Wood-Pole of Arkansas Power and Light Company; no Ground Wire.

station and because the voltage was much above the corona threshold voltage, it follows that the rate of rise at the point struck may have been on the order of 10,000 kV per microsecond. This is about the average rate of rise of the large EMP-induced voltage pulse shown in Figure 3.8.

It should be pointed out that this lightning surge was produced on a 110 kV wood pole line without ground wire. Guy wires were entirely absent within 4.5 miles of the oscilloscope station, so that this line had an effective insulation level much above that of urban distribution lines. Hence, the probability of such a stroke on a ground-wire protected urban line may be quite small, and even if struck, the urban line would propagate the pulse with greater attenuation.

On the other hand, it should be noted in the comparison of the EMP pulse and the lightning pulse that the former is the result of a calculation neglecting flashover and corona, whereas the latter actually occurred in a situation in which both flashover and corona were significant.

Some idea of the lightning surge voltages which ordinarily appear on primary distribution lines can be obtained from Figure 3.13.[9] The curves show that voltages greater than 200 kV seldom appear on urban circuits, which are much better shielded than rural circuits. Again, it should be noted that these curves are based on observations in which the strokes occurred at various distances down the line and that the pulses were attenuated before being observed.

The calculated voltage of Figure 3.10 may be regarded as a fairly typical pulse to be expected from high altitude EMP. A comparison of this with the above lightning voltages on urban primary distribution lines shows that the EMP voltage is of the order of the maximum lightning surge voltage.

It is also interesting and enlightening to compare EMP-induced currents with lightning stroke currents. Figure 3.14 shows the probability distribution of the crest magnitudes of direct stroke currents as well as of arrester currents.[9]

Since the lightning stroke current divides itself according to the number of paths by which it may reach ground, the stroke current

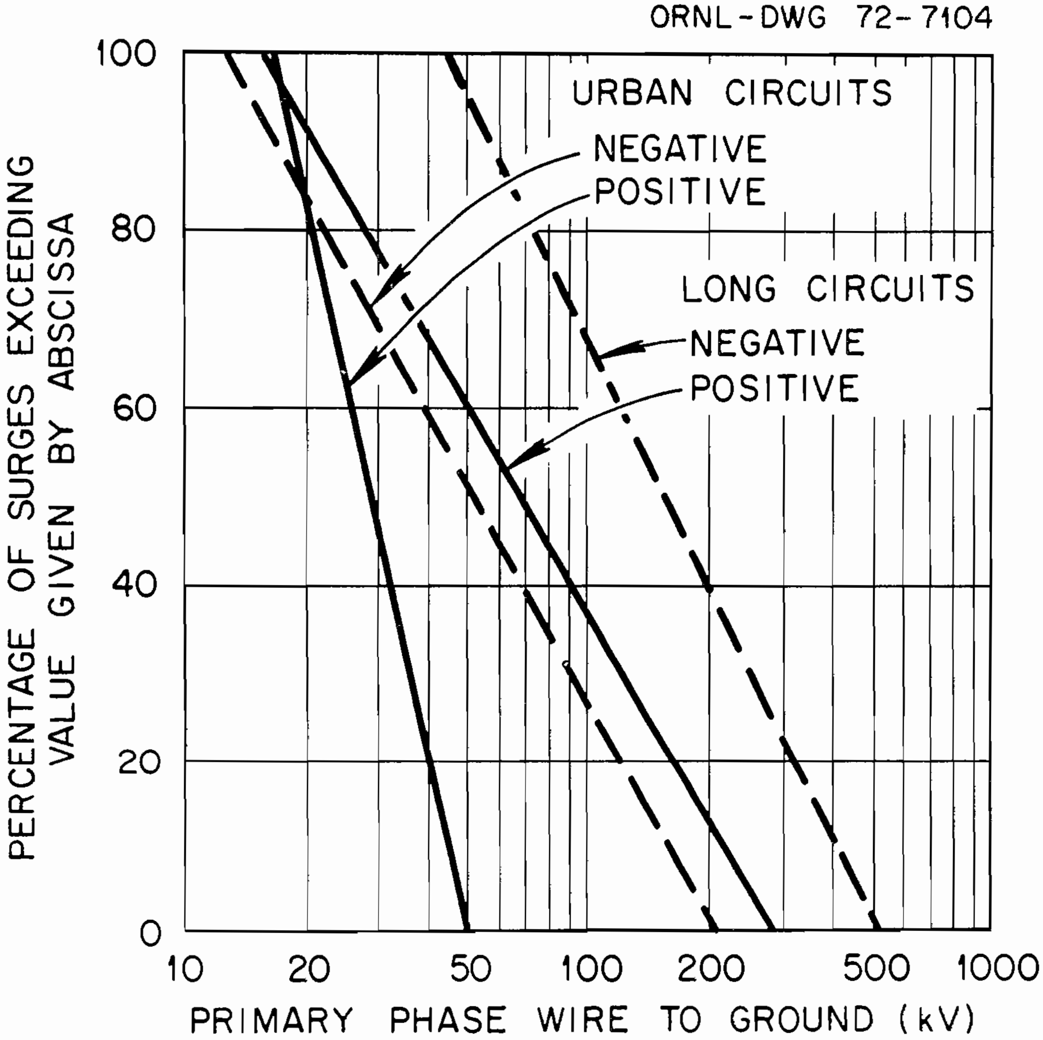

Fig. 3.13. Lightning Surge Voltages Recorded by Halperin and McEachron on 4-kV Overhead Circuits of the Commonwealth Edison Company.

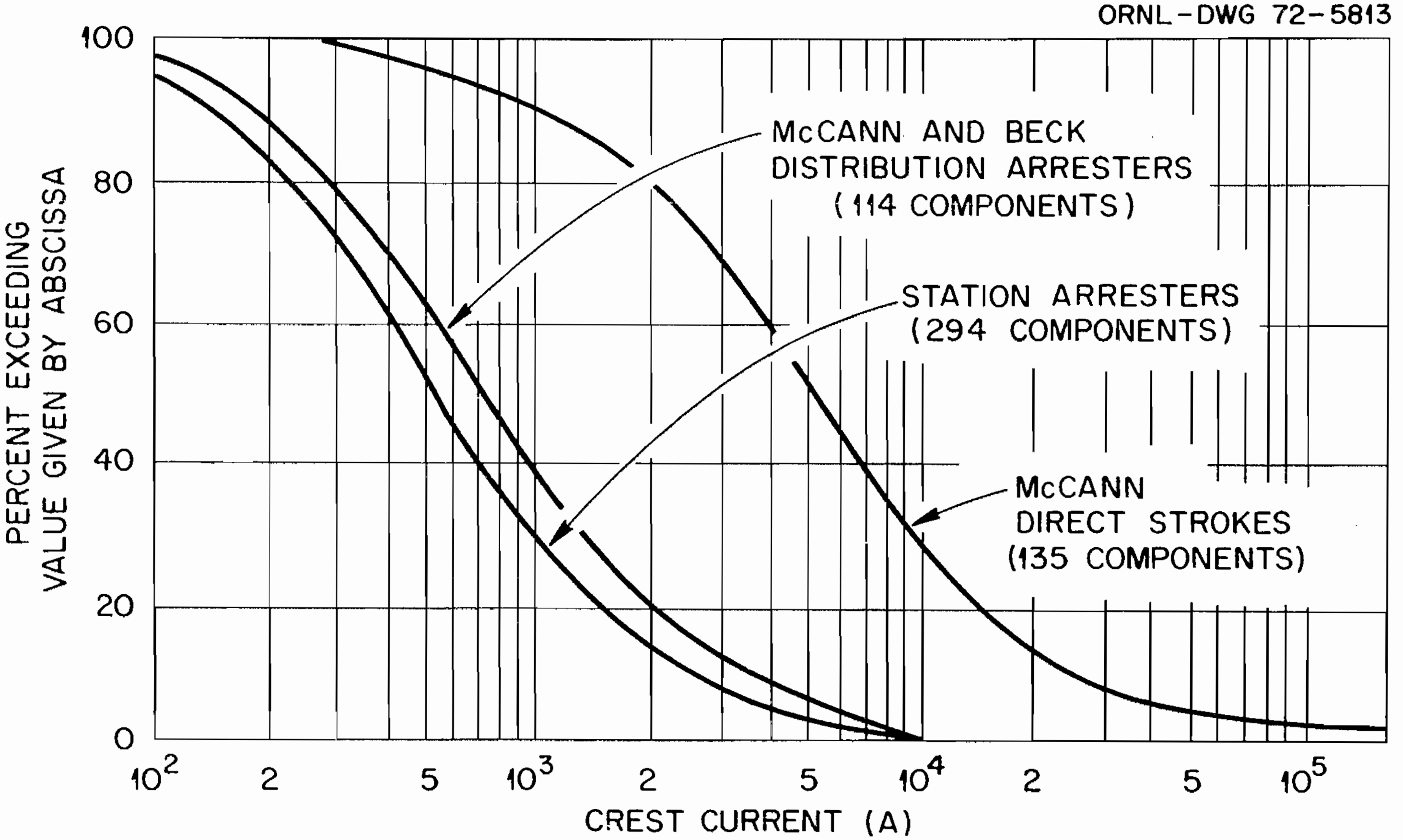

Fig. 3.14. Percentage Distribution Curves of Crest Magnitude of Individual Components of Surge Currents.

is greater than the current that appears in the transmission line. For the purpose of comparing EMP currents with lightning current, the arrester current curves may be the most realistic. Experimental results of arrester discharge crest currents are summarized in Figure 3.15. It is then clear that the calculated EMP-induced crest currents are of the same order as most lightning-induced crest currents. Only about five percent of the latter having greater crest values.

The time dependence of the EMP-induced pulses are characterized by rise times of 1/4 to 1 microsecond and a time to half maximum of from 2 to 10 microseconds at most. A comparison with lightning may be made by observing Figures 3.16 and 3.17. In Figure 3.16 we see that the time to half maximum is greater than that of the EMP, indicating that lightning pulses carry more total energy. The rise times are also generally large compared to the EMP rise times, although Figure 3.17 does show that rise times of the order of the EMP rise times are possible. It should be noted these lightning data are based on strokes to the Empire State Building and not on strokes to transmission lines. For strokes to transmission lines the times to half maximum have a similar distribution. But McCann's study of direct stroke lightning currents to tower-like structures showed longer rise times, one-half to ten microseconds. His lightning data indicated that the rise time increased with the crest current. This correlation is also indicated by the calculated EMP currents. McCann also found average rates of current rise in the lightning pulse fronts up to 45 kiloamperes per microsecond.

These comparisons of the calculated EMP-induced surges with actual lightning surges in transmission lines indicate that crest voltages and crest currents induced by the EMP can be of the order of the average crest voltages and average crest currents from direct lightning strokes. However, the maximum direct lightning stroke currents are much larger than those induced by an EMP. On the other hand, the rates of rise of the EMP currents and voltages are as large as the maximum rates of rise from direct lightning strokes.

Many transmission and distribution lines are protected from lightning by overhead ground wires. These ground wires are effective shields

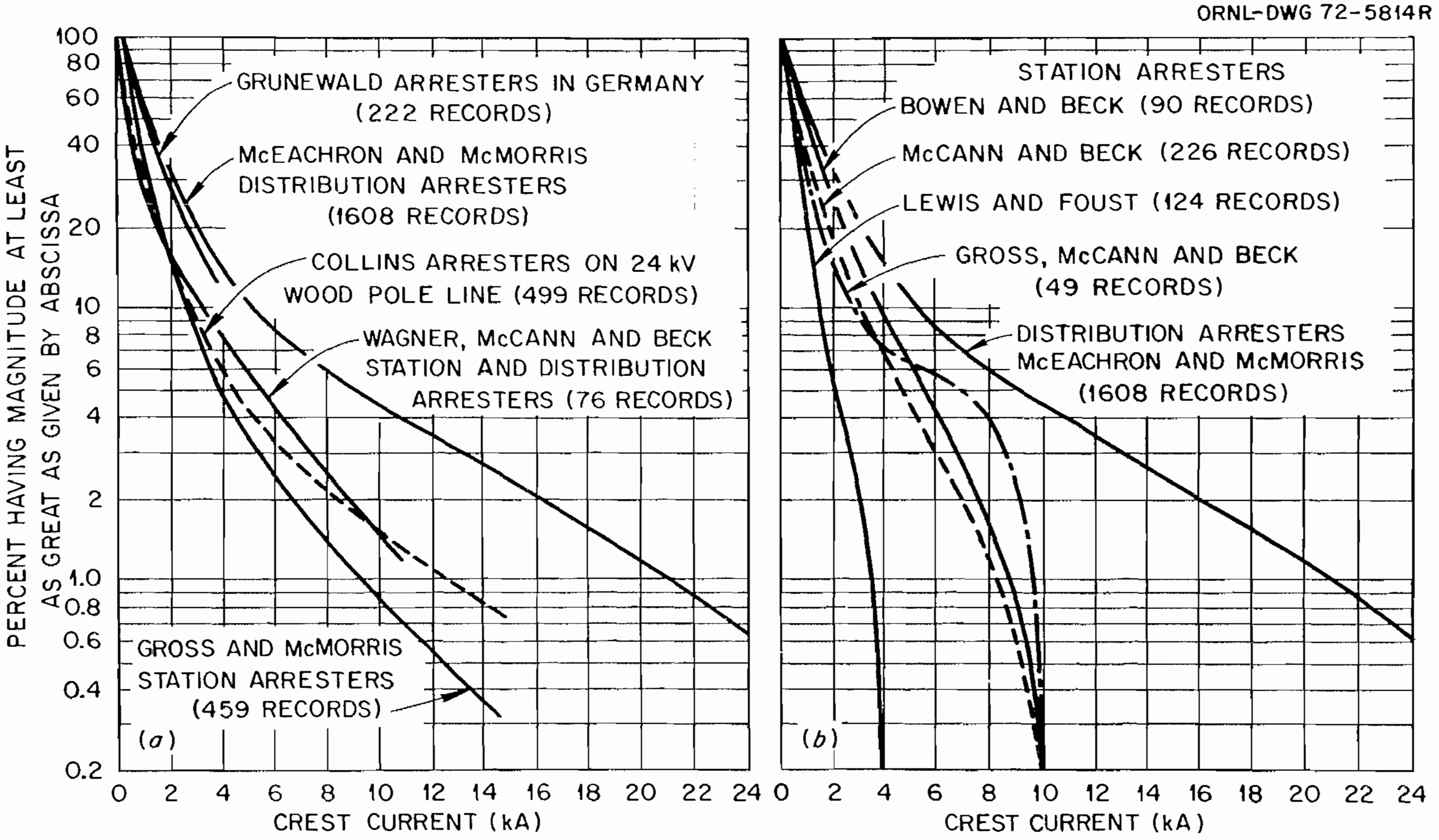

Fig. 3.15. Percentage Distribution Curves of Discharge Currents in Lightning Arresters.

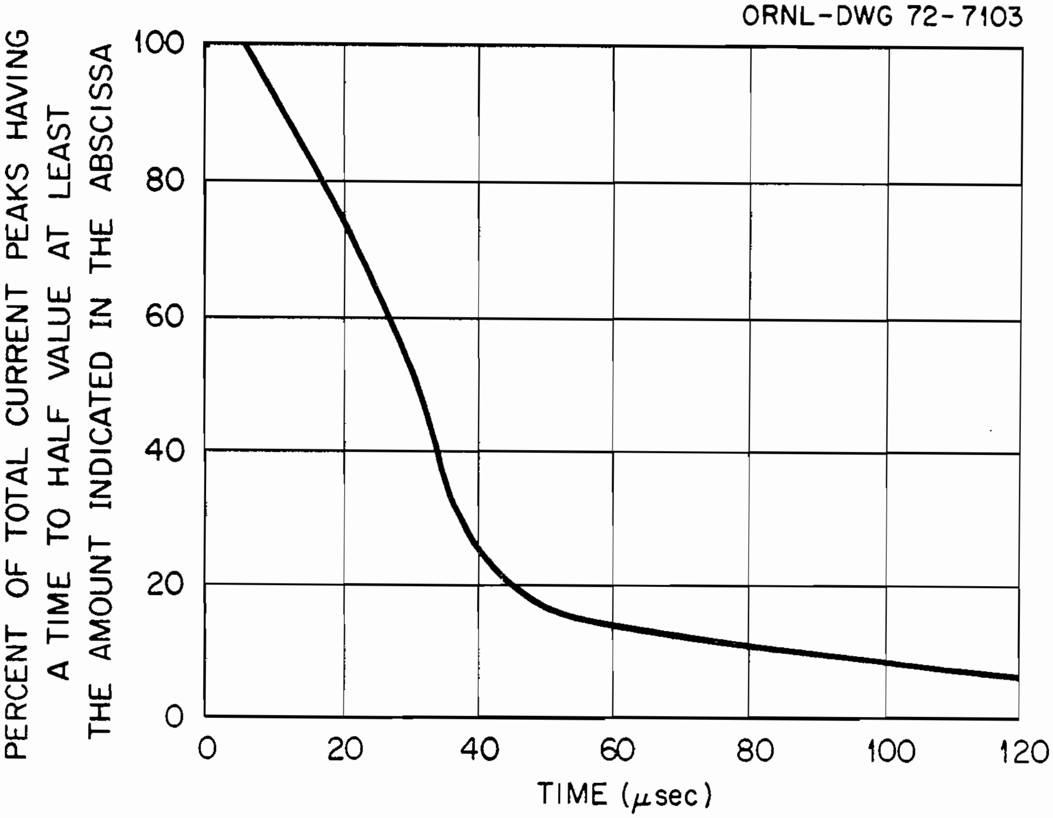

Fig. 3.16. Duration of Current Peaks Measured to Half-Value, as a Function of Frequency of Occurrence, Based on 11 Strokes Measured with Cathode-Ray Oscillograph.

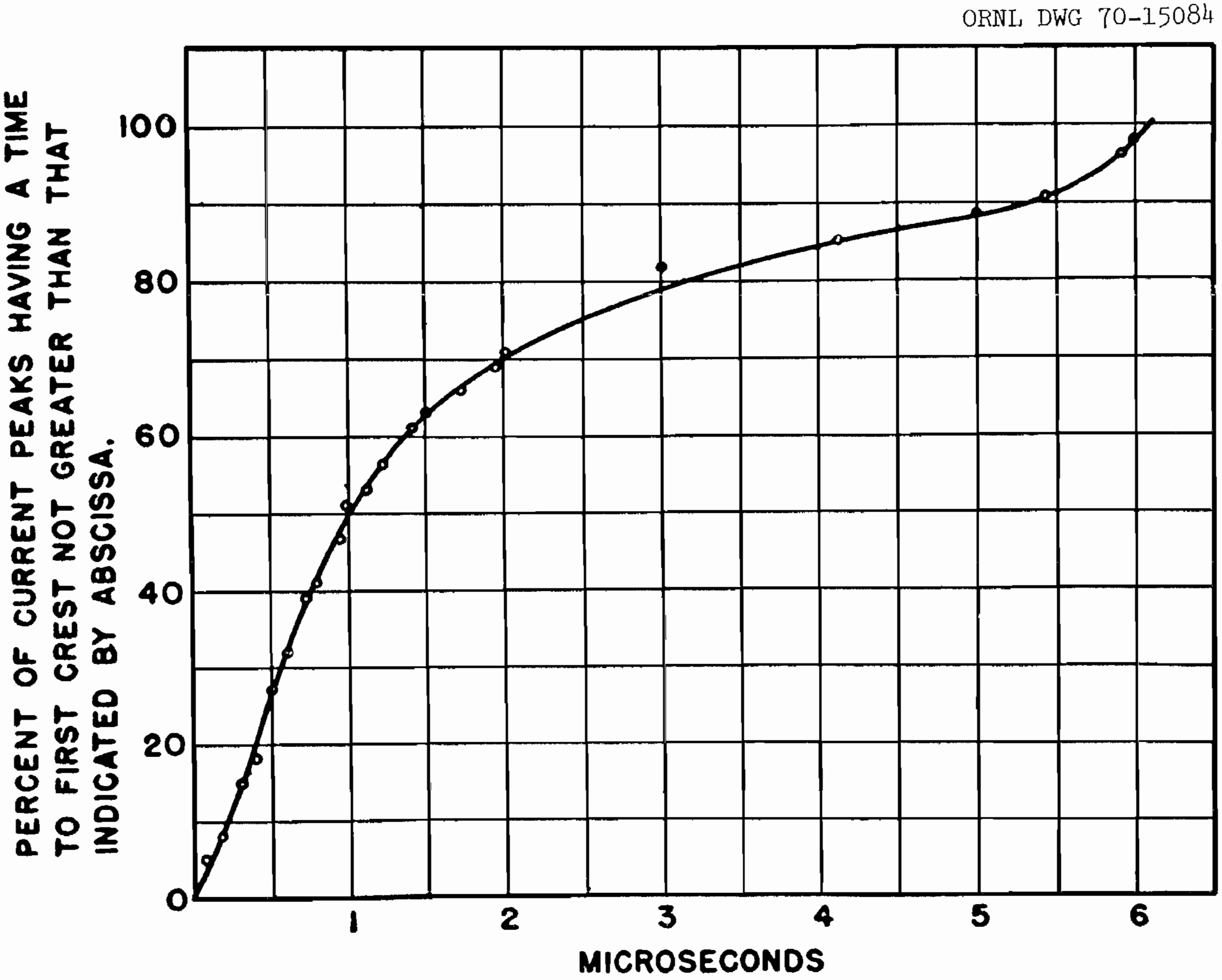

Fig. 3.17. Time to Crest of Direct Lightning Strokes. Taken from Reference 9.

against direct lightning strokes but offer little shielding against EMP. When the comparison of an EMP and lightning takes this factor into account, it is seen that crest voltages from an EMP can be well above average crest lightning voltages on shielded overhead circuits, as was shown in Figure 3.15.

CHAPTER IV

SYSTEM COMPONENTS

4.1 INTRODUCTION

Apparatus which must be protected against voltage transients at a typical outdoor electric power substation, such as the Dixie substation of the Knoxville Utilities Board, generally includes the following: power transformers, instrument transformers, circuit breakers, disconnect switches, and buses. Some stations also include reactors and regulating equipment.

The Dixie substation transforms power from the 66 kV subtransmission system to the 13.8 kV primary distribution system. All of the apparatus on the 66 kV side of the substation is insulated with respect to ground at a Basic Insulation Level (BIL) of 350 kV and all on the 13.8 kV side at a BIL of 110 kV. (A piece of apparatus is said to have a BIL of E kV, if its insulation will withstand without dielectric breakdown, the application of the standard voltage pulse shown in Figure 4.1. This pulse has been determined through international collaboration as the best representation of the true voltage induced in a power line by lightning. The pulse is characterized by a rise time $0_1X_1 = 1.2\ \mu$sec and a time to fall to half maximum $0_1X_4 = 50\ \mu$sec. As a short hand notation, the standard pulse is referred to as an 1.2 x 50 pulse.)

In analyzing the effect of EMP on the Dixie substation, the following voltage pulses were assumed induced by an EMP onto the subtransmission (66 kV) and primary distribution (13.8 kV) lines associated with the substation:

> Pulse A (see Fig. 3.3) - Pulse incident along the wire, 80° with respect to the vertical (nuclear explosion located 10° above the horizon). Electric field vertically polarized. The wire is an infinitely-long perfect conductor. Maxwell's equations are solved. The conductivity and dielectric constant of the ground are independent of frequency.
>
> Pulse B (see Fig. 3.9) - Pulse incident broadside to the wire, 60° with respect to the vertical (nuclear explosion located 30° above the horizon). Electric field is horizontally polarized. The wire is an infinitely long perfect conductor.

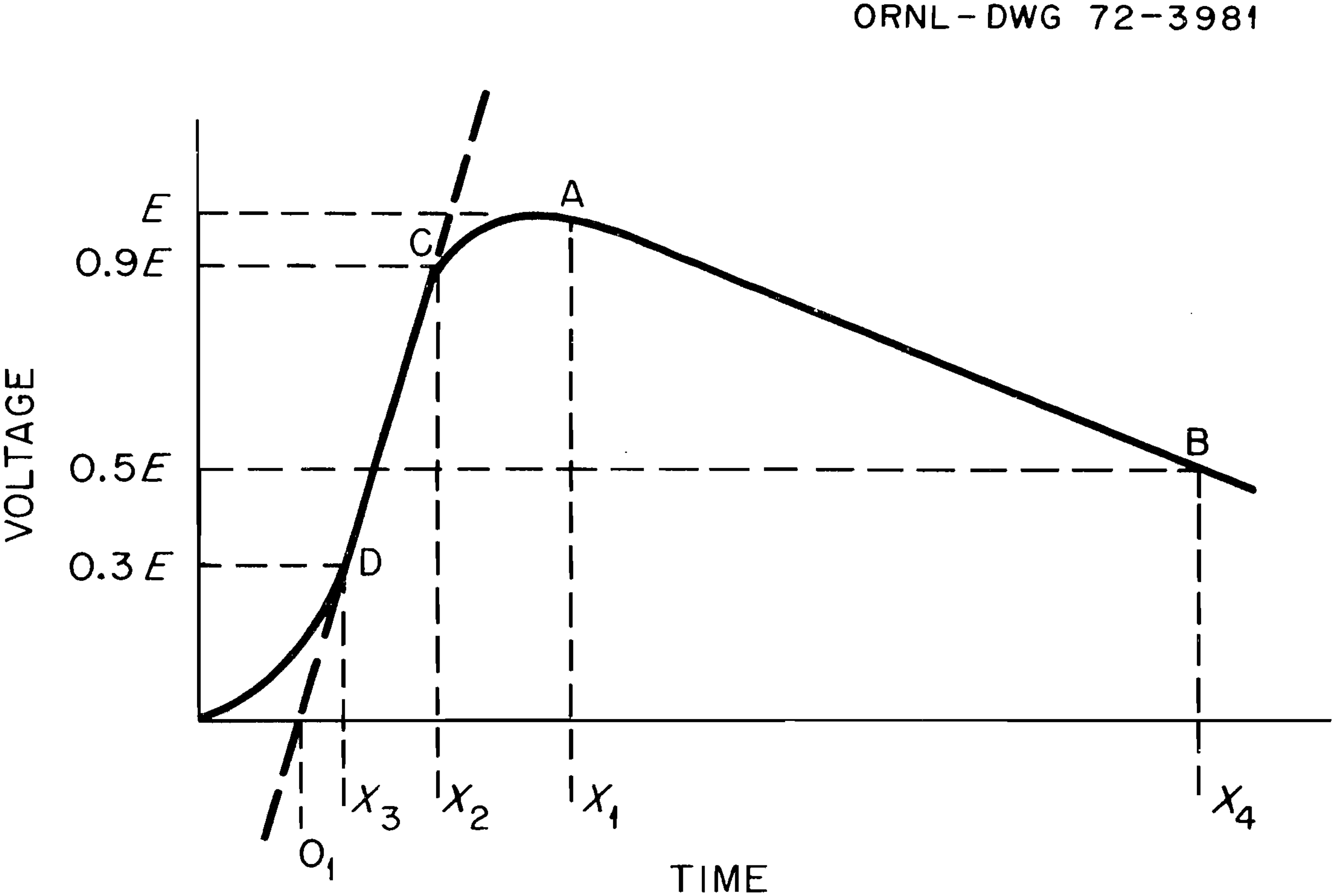

Fig. 4.1. O_1X_1 by O_1X_4 Test Wave.

Maxwell's equations are solved. The conductivity and dielectric constant of the ground are independent of frequency.

Pulse C (see Fig. 3.10) - Pulse is incident broadside to the wire, 60° with respect to the vertical (nuclear explosion located 30° above the horizon). Electric field is horizontally polarized. The wire is assumed to be semi-infinite in length, and the voltage shown in the Figure appears at the input to a power transformer. Transmission line equations are solved with the conductivity and dielectric constant of the ground allowed to be functions of frequency.

The three pulses (A, B, and C) are a representative sample of the results obtained in this study for a variety of conditions of incidence of the EMP on the wire, for frequency independent and frequency dependent models for the electrical properties of the ground, and for the use of Maxwell's equations or transmission line equations to describe the dynamic response of the wire. Voltage pulse A could never occur from a high altitude nuclear explosion over a region away from the earth's equator where the earth's magnetic field causes the electric vector of the EMP to be polarized horizontally with respect to the surface of the earth. However, of the three pulses considered, pulse A produces the most severe stresses to the insulation of a 66 kV/13.8 kV substation and is of interest for that reason.

4.2 PROTECTION BY LIGHTNING ARRESTERS

The full magnitudes of the pulses discussed in the previous section will not be impressed upon the insulation of the substation. The lightning arresters protecting the substation will afford some protection. The 66 kV side of the Dixie substation is protected with 60 kV rated arresters and the 13.8 kV side by 10 kV rated arresters. An exact analysis of the protection afforded against pulses B and A is not possible unless the presently available performance data for lightning arresters are extended by experiment to cover voltage pulses with rates of rise in excess of 1 MV/μsec. However, an estimate of the protection can be made by extrapolation of the known data to these rates of rise as shown below.

Shown in Figure 4.2 is a plot of the standard station type or distribution type lightning arrester breakdown voltage in kilovolts per kilovolt of arrester rms voltage rating. The arrester breakdown voltage may be defined as the voltage held across the arrester terminals at the instant before the arrester spark gaps fire. The abscissa in this plot is the time between application of a voltage pulse to the arrester terminals and the onset of arrester breakdown. It is clear from the shape of the curve, that larger pulses produce breakdown in shorter times. Figure 4.3 shows the discharge voltage in the same units for the same standard lightning arrester. The discharge voltage is that voltage which appears across the lightning arrester terminals after the initial breakdown of the spark gaps and at a time when the current limiting elements of the arrester are beginning to draw current. From Figure 4.3 it is apparent that the discharge voltage depends upon both the current and its time rate of change.

Table 1 gives a comparison of crest values and slopes of the current and voltage associated with each of the three pulses, A, B, and C. Using the curves in Figures 4.2 and 4.3, extrapolating where necessary, and the data in Table 1, estimates have been made of the breakdown and discharge voltages expected from 60 kV rated and 10 kV rated lightning arresters such as appear in the Dixie substation. These results are summarized in Table 2.

Table 1. Pulse Parameters

	Pulse		
	A	B	C
Max. Voltage (kV)	24,000	1,609	275
Max. Current (kA)	60.50	4.02	1.15
Average Front Slope Voltage (kV/μs)	24,000	12,200	184
Average Front Slope Current (kA/μs)	60.0	30.5	18.4

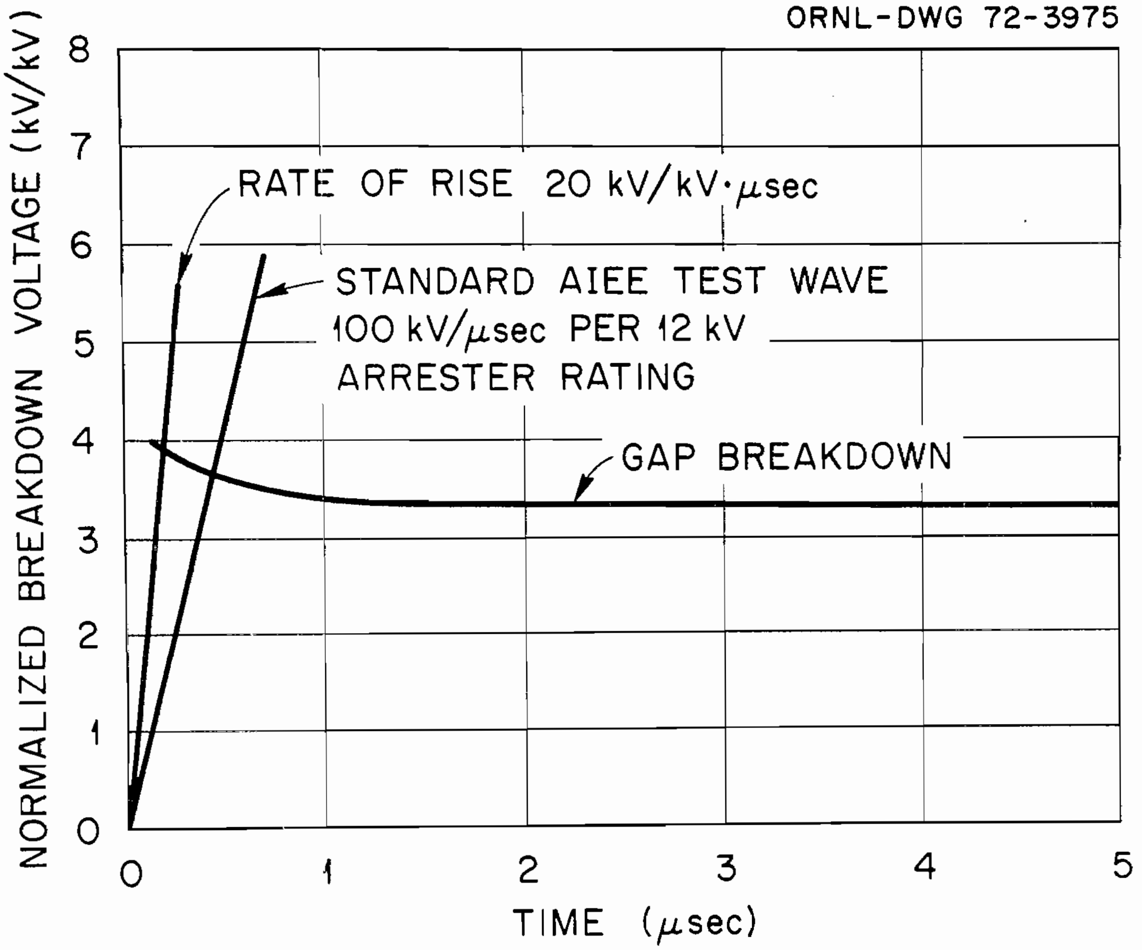

Fig. 4.2. Average Impulse Gap Breakdown of Station and Line Type Arresters.

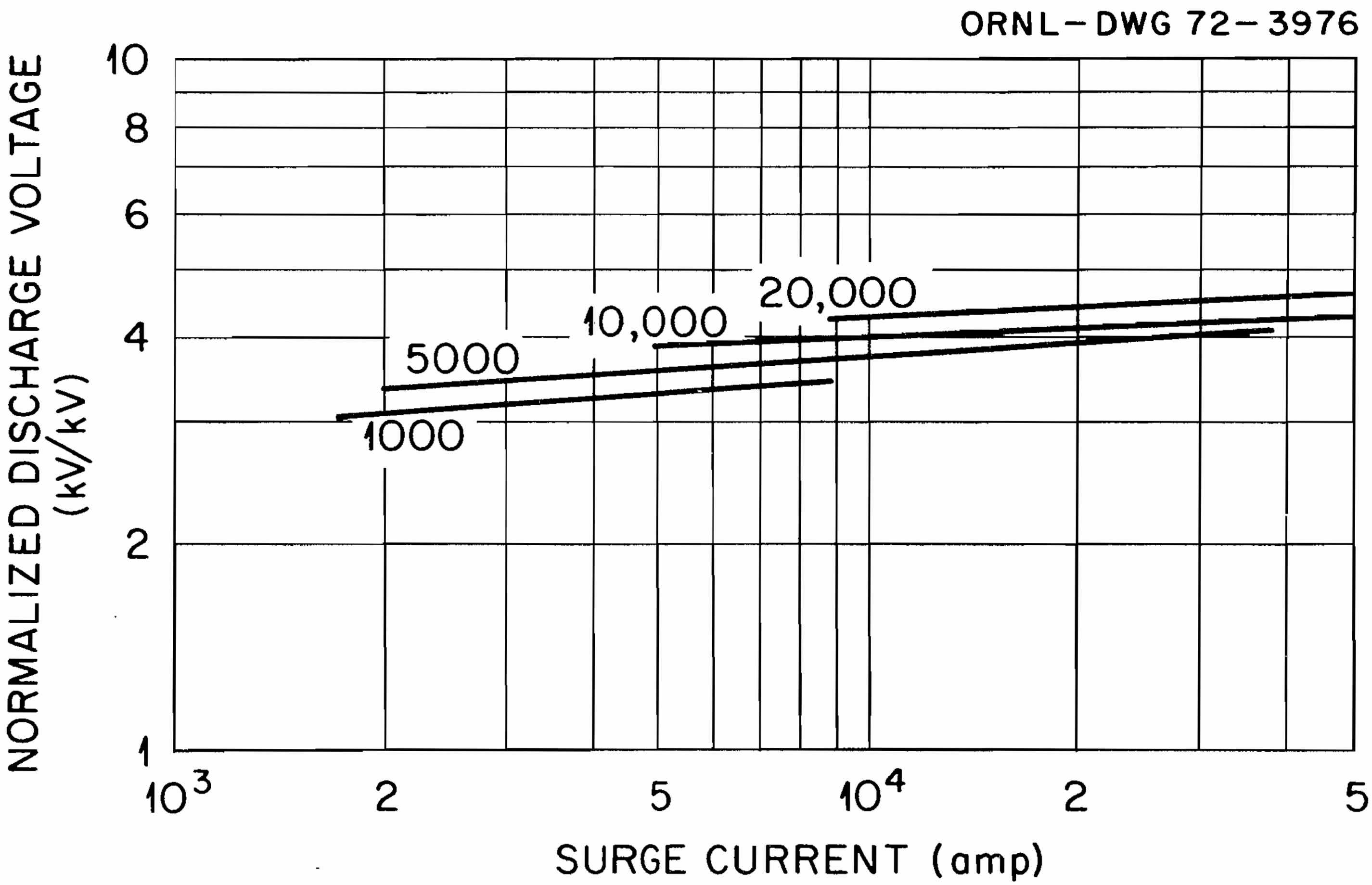

Fig. 4.3. Average Discharge Voltage Characteristics of Typical Station Type Arrester. Numbers on Curves Represent Rate of Rise of Current in Amperes per Microsecond.

Table 2. Lightning Arrester Behavior

	Pulse A	Pulse B	Pulse C
	60 kV Lightning Arrester		
Breakdown Voltage (kV)	534	438	204
Discharge Voltage (kV)	330	246	222
Time to Reach Breakdown Voltage (ns)	10	30	1,000
Energy Dissipated (kWsec)	22.8	0.35	1.20
	10 kV Lightning Arrester		
Breakdown Voltage (kV)	190	140	40
Discharge Voltage (kV)	55	41	37
Time to Reach Breakdown Voltage (ns)	4.7	10.5	200
Energy Dissipated (kWsec)	3.81	.054	.202

With pulse C, the discharge voltage for the 60 kV arrester exceeds the breakdown voltage and for the 10 kV arrester the corresponding discharge voltage nearly equals the breakdown voltage. By contrast, the rates of rise of the voltage in pulses A and B are so high that the breakdown voltages for both arresters greatly exceed the discharge voltage. The qualitative behavior of the voltage in such a case is illustrated in Figure 4.4. In Appendix C, such an example of the calculation of breakdown and discharge voltages is given.

Table 2 also gives an upper limit on the energy expected to be discharged by both arresters. The type of lightning arrester found in the Dixie substation is capable of discharging 4 kWsec per kV per rating. Thus, the energy in all three pulses can easily be handled by the arrester.

In standard lightning protection practice, the lightning arrester is placed between the incoming line and the substation to the protected. This practice also helps to protect against the effects of EMP; but, as in lightning protection, the length of the arrester electrical lead cannot be chosen arbitrarily. Because of the traveling wave nature of

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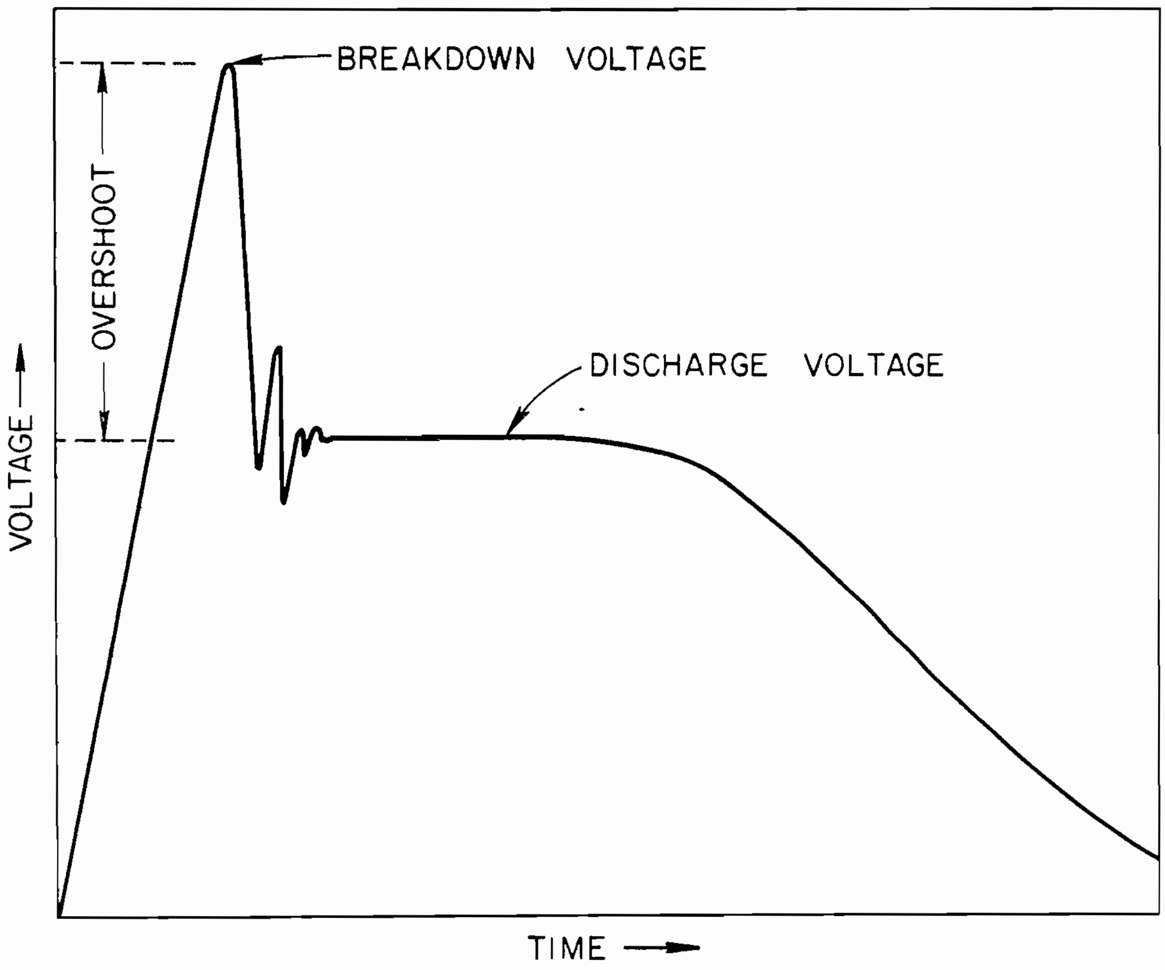

Fig. 4.4. Voltage Across Lightning Arrester Illustrating Overshoot.

the EMP pulse on the power line, time is required for the pulse to travel down the arrester electrical lead, for the arrester to reach its breakdown voltage, and for this new voltage to travel back to the power line. If the arrester lead is too long, the protected apparatus has already been stressed to the full EMP voltage before the action of the arrester has affected the power line.

Analysis of traveling waves on the lightning arrester lead results in the following equation

$$\frac{m}{x} = 0.0284 \left[\sqrt{1 + 0.0416r} - 1\right] \tag{4.1}$$

where r is the rate of rise of the EMP in kV/μsec divided by the lightning arrester rating in kV and x is the length of the arrester lead in feet. The quantity m is the margin of protection for the substation and is defined by the equation

$$m = \frac{E_w}{E_b} - 1 ,$$

where E_w is the withstand voltage in kV of the substation insulation and E_b is the breakdown voltage in kV of the arrester.

Equation 4.1, which is plotted in Figure 4.5, gives the relationship between (m/x) and r in the case that E_p, the peak voltage of the EMP, exceeds E_w. If this is not the situation, the following cases in which R represents arrester rating in kV may be distinguished.

(1) $E_p < 3.4R$. The asymptotic value of the lightning arrester breakdown voltage curve is 3.4R. If E_p is less than this, the lightning arrester fails to fire and the protected point senses the full pulse.

(2) $3.4R < E_p < E_b$. In this case the lightning arrester fires after the peak voltage has passed. The protected point senses a pulse which has been chopped on the tail and has peak voltage E_p.

(3) $E_b < E_p < E_w$. The lightning arrester fires. Depending upon length of the arrester lead, the protected point may sense any voltage between E_b and E_p.

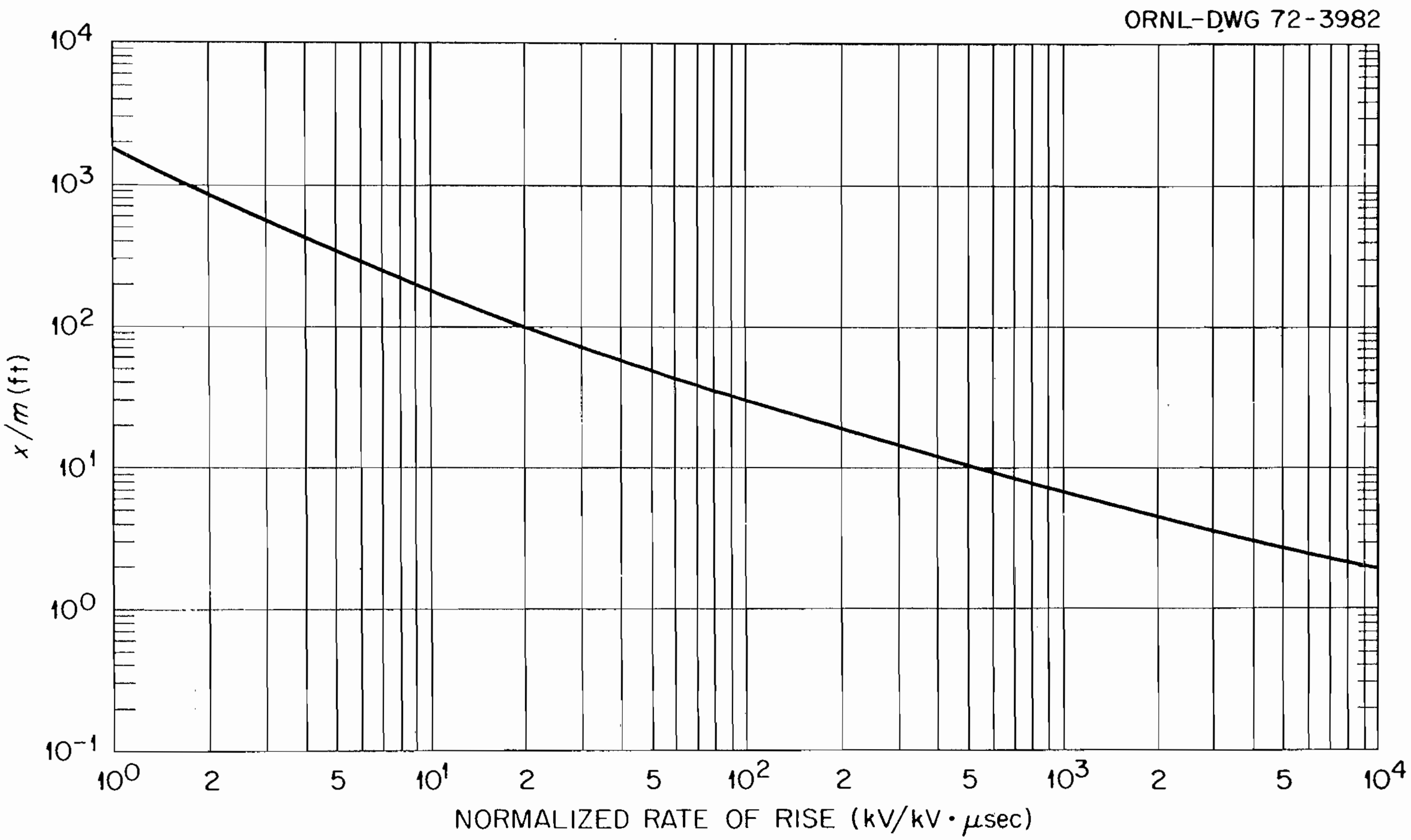

Fig. 4.5. Lightning Arrester Lead Length Curve.

Appendix C shows how one may use Figure 4.5 to calculate the maximum admissible lead length of an arrester of any rating.

4.3 STATION INSULATION

The insulation of the circuit breakers, disconnect switches, and buses on the high voltage side of the substation have a BIL of 350 kV. It is clear from the results presented in Table 2 that this apparatus is protected against the effects of pulse C, since the breakdown voltage and the discharge voltage of the arrester in this case is less than 350 kV. For pulses A and B, however, the breakdown voltages of the arrester overshoots and exceeds 350 kV. Whether pulses A and B will cause the insulation to breakdown, however, is problematical because the widths of the overshoot voltages are much less than the duration 1.2 x 50 μsec wave used to define the BIL. It is known that insulation will withstand high instantaneous voltages for short times (for example, the "steep front wave" discussed below), so that it is possible that the overshoot voltages of pulses A and B will fail to break down the insulation.

4.4 TRANSFORMERS

The distance traveled by an EMP-induced voltage into a transformer winding during the time the voltage is appreciably changing (rise time) is short compared with the length of the winding. For this reason a distributed parameter circuit model similar to that used to represent transmission lines is needed if the voltage distribution in the winding is to be calculated. The results of calculation with such a model predict that when an EMP voltage reaches a terminal of one winding of a two winding transformer, the voltage is initially distributed nonuniformly in both windings due to the effect of the turn-to-turn capacitance, the capacitance to ground of each winding, and the mutual capacitance between the windings. Following this initial capacitatively-coupled transient, both windings go into oscillation due to the interaction of their inductances and capacitances.

The voltage stresses inside transformers and bushings depend upon the shape of the wave impressed on the winding. In addition to the "full" wave used to define the BIL, transformers and bushings for use in 66 kV systems are also given a breakdown test with the "chopped" wave shown in Figure 4.6. Because of the abrupt changes of voltage in the "chopped" wave, larger dielectric stresses are developed across the insulation of the transformer than are found when the "full" wave is applied. Recently, manufacturers have also tested transformers of this class with a "steep front" wave shown for a 66 kV system in Figure 4.6. The "steep front" wave causes even more severe dielectric stresses than the "chopped" wave; and, because it rises with a slope of 1 MV/μsec, it more closely approximates the effect on a transformer of pulses A and B.

Figures 4.7, 4.8, and 4.9 show plots of various voltages calculated using this model which can be expected in windings of a single phase transformer when stressed at the high voltage terminal with a pulse with the discharge voltage of pulse A. The neutral of the primary winding and both of the terminals of the secondary winding of the transformer are assumed to be grounded. The pulse applied to the primary high voltage terminal was assumed to rise to a peak of 330 kV in 0.01 μsec. This pulse only approximates the effect of the lightning arrester on pulse A, since the large overshoot of the breakdown voltage over the discharge voltage has been ignored. This was necessary because the details of the transition of the voltage from breakdown to discharge were not known. It was further useful to ignore this difference to achieve a simple mathematical form to represent the pulse in order to apply the distributed parameter circuit model.

Figure 4.7 shows the spatial distribution of the voltage inside the primary and secondary winding for various early times during which only the winding capacitances are playing a role. The spatial coordinate is the distance along the axis of the winding, which is assumed to be cylindrical in shape. The zero of the spatial coordinate is assumed to be at the high voltage terminal of the winding with 100% of the winding having been traversed upon reaching the neutral. It is clear from the figure that for times of the order of the rise time of the pulse the voltage applied to the high voltage terminal does not distribute itself uniformly over the entire winding but tends to pile up across the first 40% of the

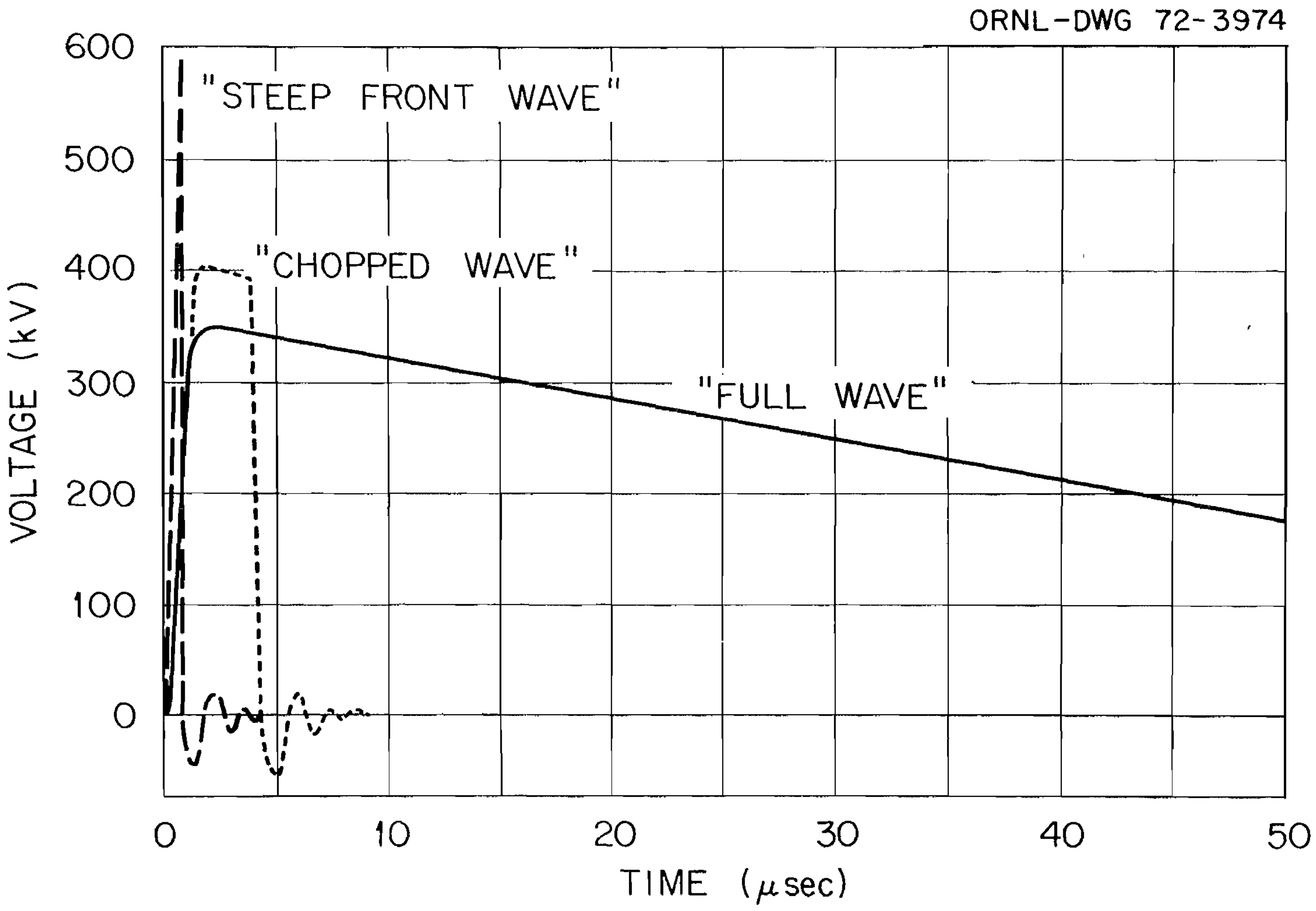

Fig. 4.6. Transformer Test Impulse Voltages.

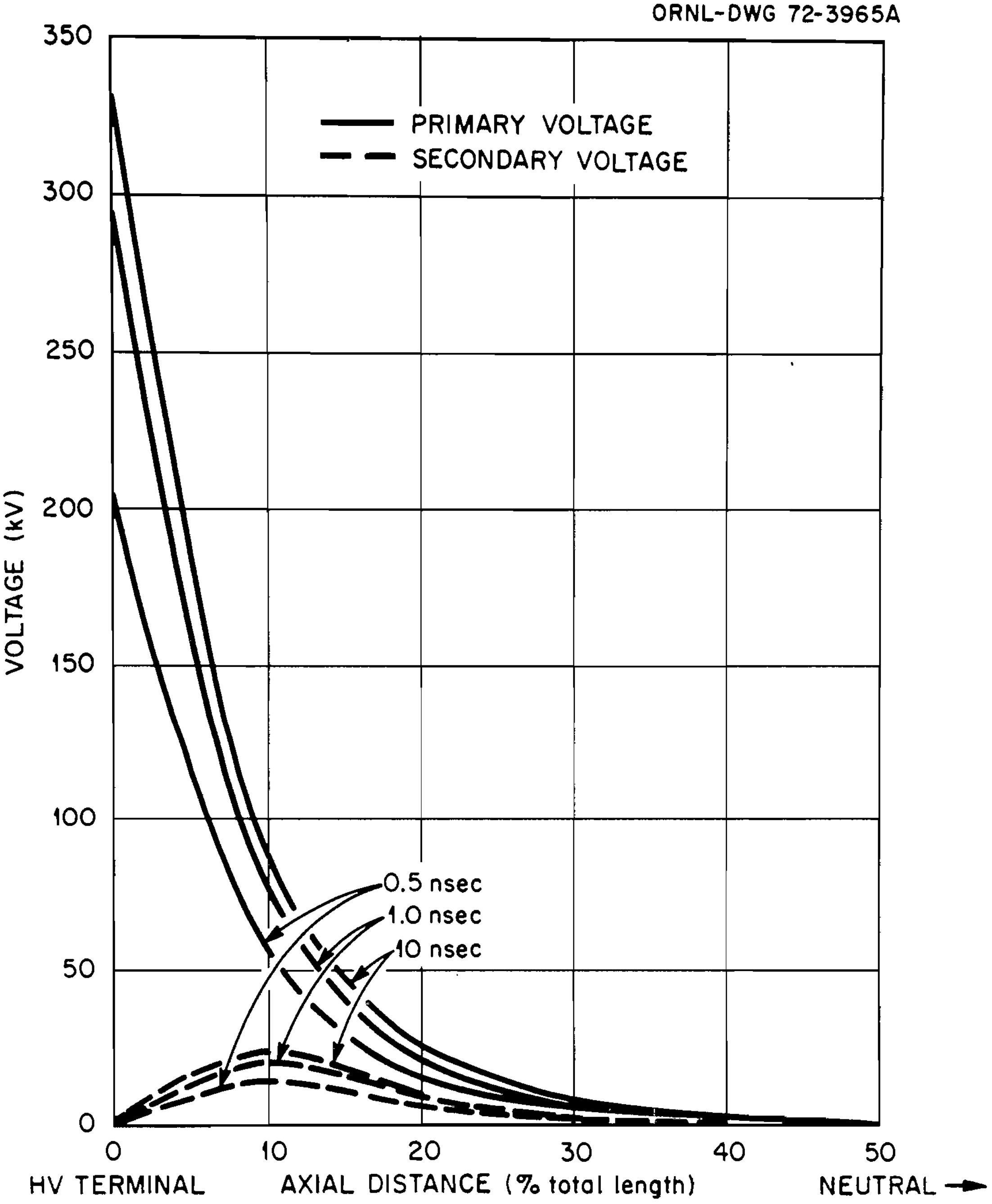

Fig. 4.7. Distributed Parameter Transformer Winding Model.

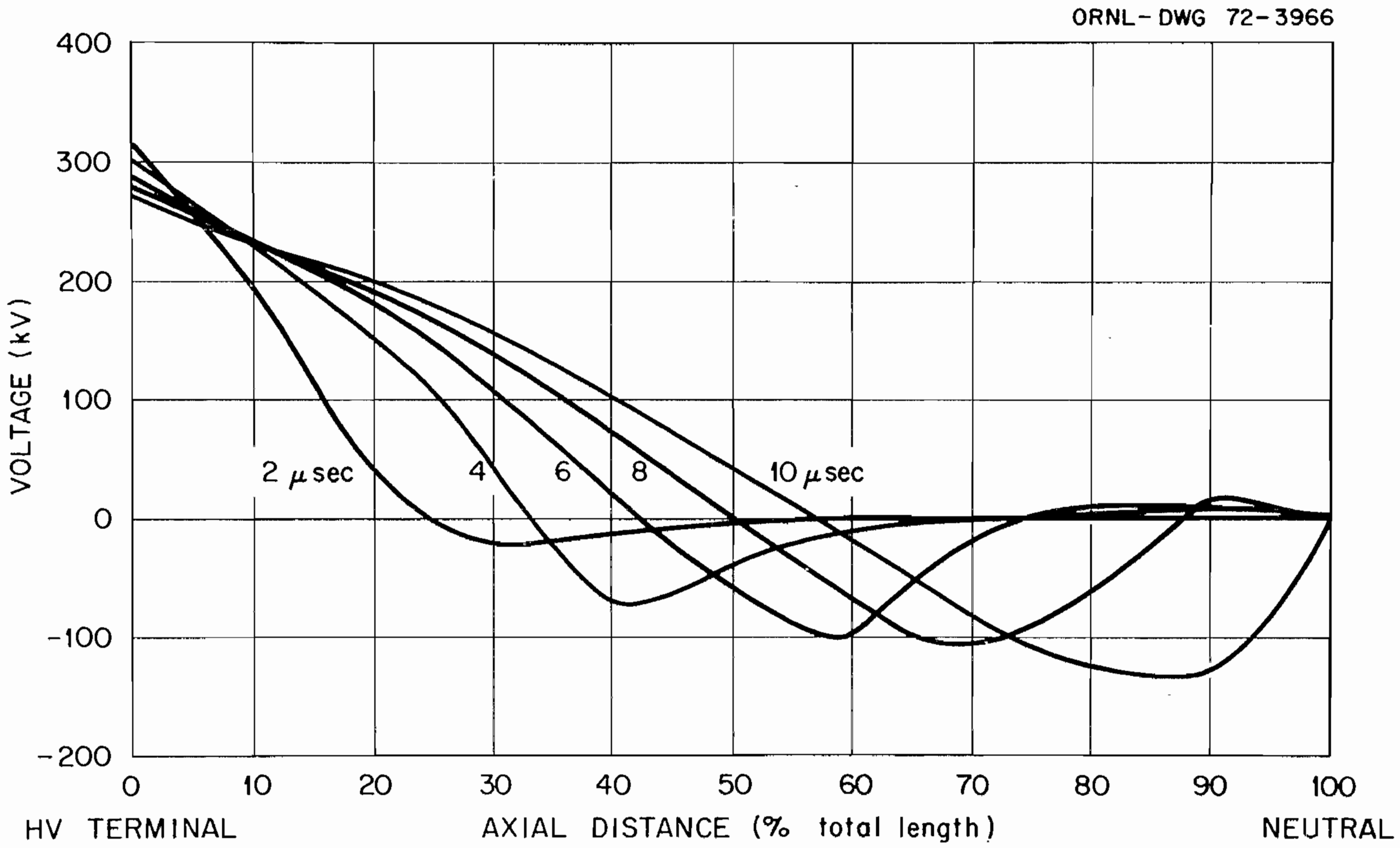

Fig. 4.8. Distributed Parameter Transformer Winding Model--Oscillations of the Primary.

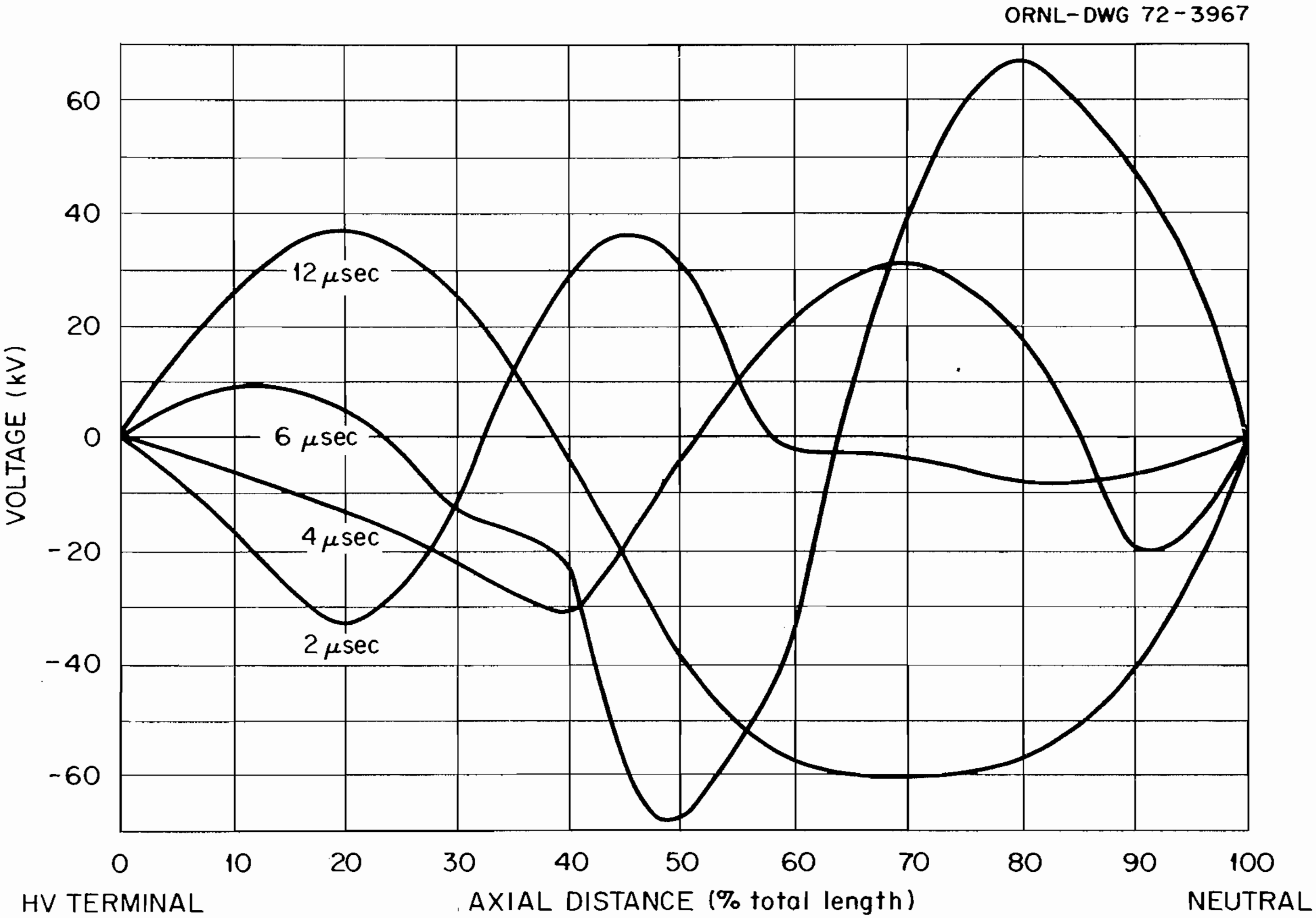

Fig. 4.9. Distributed Parameter Transformer Winding Model--Oscillations of the Secondary.

turns nearest the high voltage terminal. Hence, the peak voltage of 330 kV is impressed upon the insulation of these first turns alone and, depending upon the insulation strength, could cause breakdown. From the figure it is also apparent that the voltages in the secondary winding due to the various winding capacitances are much less than those in the primary.

After the initial transients shown in Figure 4.7, which propagate through the windings via their turn-to-turn capacitance, their capacitance to ground, and their mutual capacitance, oscillations are set up due to the combined effect of the winding inductances and capacitances. This behavior is shown in Figures 4.8 and 4.9. The oscillations become apparent only for times of the order of or greater than the first natural period of the windings which lies in the range of a few microseconds. By these times, the pulse voltage at the high voltage terminal of the primary is also beginning to decay.

The results shown in Figures 4.7 through 4.9 are indicative only of the qualitative behavior of a 66 kV/13.8 station transformer stressed by EMP. This is true for the reasons stated above concerning the need to ignore the overshoot of the discharge voltage of the lightning arrester and also because the circuit constants for this transformer were unknown and could be estimated only crudely.

From the qualitative behavior of this particular transformer model, however, some conclusions can be drawn. The presence of voltage oscillations indicates that the transformer is only imperfectly protected against transients. Better suppression of voltage oscillations than this is often included in transformers of this class and should be encouraged to enhance the protection of the transformer against EMP. Any of the standard techniques for reducing the oscillations such as electrostatic shielding, interleaving of turns, layer windings, and graded capacitance are desirable . Furthermore, by comparing pulse C with the three standard transformer test waves (Figure 4.6), it may be concluded that the similarity is sufficient that if the transformer insulation will withstand the test waves, it will withstand pulse C also. Pulses A and B, however, because of their large rates of rise, form another class and remain problematical.

CHAPTER V

THE EFFECTS OF THE EMP ON DISTRIBUTION SYSTEMS

5.1 INTRODUCTION

It must be emphasized that the effects of an EMP considered in this study are restricted to those which arise from surges in the power circuits of the distribution system. The effects of surges induced in supervisory and control circuitry are being studied presently and will be described in a later report.

Even with this limitation it is impossible at the present stage to calculate the EMP-induced voltage at every point of an electric power distribution system. This is because of the complex geometrical arrangements possible and the complex and nonlinear behavior of components such as lightning arresters and transformers. Even if one knew the voltages he would be faced with the task of using them to predict the breakdown and flashover of insulation, puncturing of dielectric, etc., at all points of the system. Each of these flashovers would modify the voltage and current at other points in a nonlinear fashion and as a complicated function of time.

What is known at the present are some representative and typical pulses induced by an EMP, such as those shown in Chapter III. These show that such EMP-induced current pulses can be larger than the average lightning induced currents in components but less than the average total current in a lightning stroke and certainly much less than the greatest lightning stroke currents. Hence, speaking broadly, we can say that the effects to be expected from EMP correspond to effects from something like the weakest quarter of direct lightning strokes or from the weaker two-thirds of lightning strokes hitting down the line a bit.

Of course, we must be cognizant of the differences between lightning-induced and EMP-induced pulses in applying this rough rule of thumb. As pointed out in Chapter III the principal differences are: (1) lightning is a point charge-injection process with pulses moving away from the point of injection whereas EMP induces current continually along a line with charge and voltage building up at terminals and sharp turns, (2) EMP is basically a faster process than lightning with much shorter rise times (this may be partially compensated by natural tendencies, such as corona, to spread out the wave front and by a corresponding smaller total energy in the pulse), and (3) EMP-induced pulses will appear simultaneously throughout an entire power grid whereas lightning is a local intermittent phenomenon.

The effects which are important to consider are similar to the effects from lightning. These include corona, flashover of insulators, follow current discharge, and discharge through arresters. Attendant with these are the possibilities of permanent damage to equipment and components, in particular, the puncturing of solid insulation.

The burnout of fuses and recloser operation, especially lockout of reclosers, are important effects which can result from a flashover with follow current caused by the EMP. In addition, because of its wide coverage the EMP can influence the stability, security and control of the entire electrical system.

5.2 THE EMP SURGES TO THE CONSUMER

The effects of EMP-induced currents and voltages can be classified according to the part of the system on which they appear. In addition to the long transmission lines supplying the major substations, there are three major divisions of the distribution power circuits classified according to voltage: the subtransmission lines, the primary distribution lines, and the secondary distribution lines. The first two types of lines ordinarily have lengths of the order of miles. The secondary distribution lines are typically quite short and may, in fact, consist merely in the drop to the consumer. The voltages and currents induced directly on such lines may be quite negligible.

A criterion for deciding whether a line is short may be found by comparing the times to the current peak in a line of infinite length to the time it takes a pulse reflected at the end to traverse the wire length. Thus, when the current in a long line would be reaching a maximum value, the current in a short wire would already include reflected components. A time to peak current of from 0.3 to 1 microseconds corresponds to a length criterion of from 100 to 300 meters. The secondary distribution lines of KUB are ordinarily less than 300 feet and always less than 500 feet. Thus, the KUB secondary lines are short.

The EMP surges appearing in a distribution circuit may be induced directly in that circuit or it may be transmitted through transformers from another circuit. As shown in Chapter III the magnitude of voltage surges passing through transformers are reduced to one-third or less. For long circuits, i.e., transmission, sub-transmission, and primary distribution circuits, the surge induced directly from EMP is the surge of importance. For the circuits of short length, i.e., the secondary distribution circuits and the consumer service drops, the surge coming through the distribution transformer is the critical surge.

EMP-induced pulses on the primary distribution circuits will be the same as those on the subtransmission circuit, but there is a difference in the basic insulation levels. In the KUB system the basic insulation level of the primary distribution circuit is 110 kV and 350 kV on the subtransmission circuits.

However, the insulation strength on wood poles, which are typical of primary systems, is ordinarily much greater than the nominal basic insulation level. This means that the induced voltages and currents are most likely to flashover at dead ends and at corners where guy wires and insulator strings are used, at distribution transformers and through their associated lightning arresters, and at the substation entrance or bus.

The currents and voltages on the subtransmission and primary distribution lines are then as described in Chapter III. A fairly typical voltage pulse on these lines being that described by Figure 3.10. Note that the 270 kV crest voltage of this pulse is slightly below the 350 kV basic insulation level (BIL) of the subtransmission system but well above the 110 kV BIL of the primary distribution circuit. However, the actual insulation strength of lines on wood poles is ordinarily well above the nominal value except at terminations, dead ends, etc. Hence, it is not unreasonable to expect the full 270 kV crest value to appear on much of the primary circuit.

The voltage passing on to the secondary distribution circuit will be about one quarter of that on the primary side. Hence, if the ordinate of Figure 3.10 is divided by four, the voltage curve then represents a typical pulse appearing on the secondary side of the distribution transformer if not protected by a lightning arrester.

If the primary side of the distribution transformer is protected by a lightning arrester then the voltage passed on to the secondary as well as that on the primary will be reduced. If a transformer rated at 13.8 kV/208/120 volts and protected by 10 kV primary arresters, as in the KUB system, receives a pulse from EMP, the arrester will spark over at more than 40 kV. About one quarter of this will be impressed on to the secondary with a crest voltage of more than 10 kV. In addition to this surge, a directly induced EMP voltage of the order of some tens of kilovolts may be induced on to the secondary depending on the geometrical orientation and length of the line.

Hence, EMP voltages on secondary distribution circuits will be of the order of 10 kV to 70 kV or more depending on the particular arrangement. These voltages are higher than the impulse withstand strength of most customer equipment connected to 208/120 volt circuits. Unless such equipment is protected by arresters and protective capacitors they will undergo failure. This failure will likely occur in solid insulation. Typical examples are motor-winding failures and power transformer winding failures.

5.3 SYSTEM MALFUNCTIONS

Possible damage of the components include puncturing and blistering of insulators where flashover occurs. Puncturing of the insulators does not occur as frequently as in the past because of improvements in material. However, the faster rise times of EMP in comparison with lightning increase the likelihood of punctured insulation.

The puncturing of insulation is especially serious at a dead end or sharp corner, where EMP induced voltages will appear earliest and with greatest magnitude. Insulation breakage with the resulting loss of an insulator string at such a point would cause loss of tension in the line for some distance. For lightning protection such an occurrence is guarded against by increasing the insulation at such dead ends and corners, so that flashover is more likely to occur down the line. On the subtransmission system KUB uses seven insulators at dead ends compared to five insulators at points with gravity load only.

In order to check the adequacy of the two extra insulator units for EMP protection, consider a voltage building up at such a dead end to a peak of 1100 kV in one microsecond, which is a typical rate for EMP-induced voltages. This will produce flashover across the seven insulators at the end of the microsecond. Down the line one hundred meters (which corresponds to a short span distance) the voltage at the end of one microsecond will be only 730 kV (because the velocity of the voltage pulse sent out from the end is limited to the speed of light). But this is not yet equal to the 800 kV required for flashover across five insulator units.

Thus, the two extra insulators in the dead end and corner insulator strings do not give the requisite added protection for pulses with the rise rates and time characteristic of EMP. In contrast to lightning, EMP-induced flashover is more likely to occur at these dead-end points than at points along the line.

These flashovers can appear on the primary distribution lines as well as on the subtransmission lines. It is not clear what fraction of these flashovers will result in sustained power follow since the probability of this depends on the duration as well as magnitude of the pulse flashover current. Lightning flashovers, with a current duration ordinarily many times greater than that of an EMP, cause sustained power follow with about 85 percent probability for high voltage steel tower lines of line length less than 100 miles.[9] EMP-induced flashovers have a much shorter current duration and will result in sustained power follow less frequently, but just how much is not known. A probability of several to some tens of percent, which appears reasonable, would mean that a number of flashovers with sustained power follow are likely to occur on the subtransmission lines of a system such as KUB. Assuming normal recloser operation, these would be cleared unless four pulses occurred within about three minutes for the KUB system.

The lines in the substation are fairly short in length and most of the EMP voltage will be due to the voltage coming in from the subtransmission and distribution lines. These pulses will be shaped by corona, flashovers, reflections, and inductive and capacitive elements in the system, so that by the time the pulse gets to the transformer terminals, the pulse shape may be more nearly like that characteristic of lightning. As shown in Chapter IV, the lightning arrester should give protection if the lead length is sufficiently short. It is common practice to mount the lightning arrester directly on the transformer cases. At Dixie substation, the lead lengths are about two meters long.

Lightning arresters will function without sustaining damage. However, power follow after a flashover will cause fuses to blow, or reclosers to open, or both depending on the coordination scheme of the power system and the timing of successive nuclear detonations.

On the subtransmission lines of the KUB system the arrester breakdown voltages of pulses A and B are greater than the BIL of 350 kV. This is due to the so-called turn-up of the arrester characteristics. The insulation shows even greater turn-up for that time range in which measurements have been made. There is some opinion that those components, station transformers in particular, which are adequately protected by arresters against lightning will also be protected against EMP. According to this, substation transformers would not likely be damaged by EMP on the subtransmission side. This statement should be tested by experimentation using current-injection techniques, which should not be expensive if the statement is true. It should be pointed out that substations are shielded against direct lightning strokes by overhead ground wires. Although these are very effective for protection against lightning, these ground wires offer little protection against EMP induced surges.

Discounting the effect of the failure of unprotected consumer apparatus, a distribution system with well coordinated reclosers and fuses should survive a single nuclear detonation with ease. But a series of such detonations in a span of a few minutes will cause reclosers to lock open and fuses to blow, resulting in a power outage over at least a part of the system.

Such power outage in virtually all distribution systems combined with damage to unprotected consumer equipment will lead to large load losses at the generating stations. This may necessitate shutting down some of the generating capacity. It is not clear to what extent synchronism may be maintained in such a situation. The full extent of these implications in addition to the effects of flashovers occurring simultaneously at a number of points on the high voltage transmission lines have yet to be studied.

CHAPTER VI

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 SUMMARY

The results of this study indicate that the EMP from a high altitude nuclear explosion will induce a current and voltage surge throughout the electric power system. The voltages and currents will be induced on the transmission and distribution lines and will be characterized by very fast rates of rise, high peak values, and short time durations. The peak values of the current pulses depend on the orientation and geometry of the lines and can be as great as ten kiloamperes. Although this is less than the total current of the average lightning stroke, it is greater than the average lightning current appearing in lightning arresters. Voltages to the consumer outlets can be of the order of 10 kilovolts to 70 kilovolts.

These EMP-induced pulses differ from lightning in two essential ways. First, the rise times of the pulses may be up to ten or more times faster than the rise times associated with lightning. Second, as mentioned above, these pulses can appear simultaneously throughout the entire power system. In particular, and in connection with this study, the pulses will appear throughout each distribution system.

This universal aspect of high-altitude-EMP-induced pulses means that the system will be thoroughly tested for its weakest components. This is in contrast to lightning-induced pulses which analagously only "spot-check" the system for weaknesses. Furthermore, in an attack, there may be many high altitude explosions. This means that the power system will be subject to repeated universal tests by EMP-induced surges.

It is virtually certain that weak points will be found. Those points in the system which are not adequately protected against lightning-induced pulses are especially vulnerable. But adequate lightning protection does not guarantee adequate protection against EMP. In particular, overhead ground wires offer little protection against EMP.

In addition to the direct coupling of EMP into transmission and distribution lines up to one third of the voltage on the primary may be passed on to the secondary by capacitive coupling. This means that transformers will not offer substantial protection against such pulses coming in to the equipment of the consumer. Such voltage pulses may reach peak values of 10 kV to 70 kV and will damage consumer equipment unless protective measures are taken. Such protective measures include the use of lightning arresters and protective capacitors.

6.2 CONCLUSIONS

An EMP is not likely to cause extensive damage to power system components. There is still some question concerning the vulnerability of transformers which are not completely protected against lightning by arresters. An experimental program to study this problem should be promoted and carried out.

If the transformer is adequately protected against lightning on each side by an arrester then such protection may well be sufficient protection against EMP-induced pulses. This is ordinarily the case for large station transformers for which the investment justifies complete protection by station type arresters.

Distribution transformers are another matter. These may be of the completely self-protected type, each of which has passed a surge test equivalent to a direct stroke of lightning. It has been the custom on the west coast to use distribution transformers without any protection from lightning arresters, but a trend in which arresters are being used to protect distribution transformers seems to be getting established. As we have seen, this will also reduce the size of the pulse to the consumer from perhaps 70 kV to around 10 kV.

Consumer equipment is vulnerable to the effects of even a single pulse. This damage may be prevented by (1) disconnecting the equipment from the power line before a nuclear attack and (2) protecting the equipment, if it must remain connected to the line, by filters, capacitors, or arresters.

If the consumer equipment is adequately protected, a distribution system should be able to recover easily from the effects of a single EMP pulse, or from a series of such pulses spaced more than a minute apart. If four or more pulses occur in a period of the order of three minutes (for the KUB system) then reclosing breakers are likely to lock open on a large scale.

6.3 INFORMING THE POWER COMMUNITY

It is most urgent that the power industry be made aware of the EMP threat. This awareness must be at both the engineering and managerial levels.

There are a number of channels through which this may be implemented. Defense Civil Preparedness Agency (DCPA), with the cooperation of other governmental agencies, should contact each segment of the industry directly or through appropriate channels. These segments include the public and private utilities, the manufacturers, and related governmental, technical, and industrial organizations. Among these which should be aware of the threat and work together as much as possible are the following: The Federal Power Commission, the Office of Emergency Preparedness, the Defense Electric Power Administration, the National Bureau of Standards, the Atomic Energy Commission, the Defense Civil Preparedness Agency and its regional offices and emergency operations centers, the National Electrical Manufacturers Association, the Electronic Industries Association, the Edison Electric Institute, the National Electrical Reliability Council, the Electrical Research Council, the Institute of Electrical and Electronics Engineers.

This spread of information concerning an EMP is most urgent. It will help the utility engineer to know what to expect under the conditions of an attack, so that he can understand the problems, prepare for them and cope with them when and if they do occur. Such knowledge will be invaluable not only in preventing and reducing power shutdown, loss of loads, instabilities, and speeding repairs, but also in shaping the trend of future developments which can coordinate protection against the EMP, lightning, and switching surges. This knowledge of the EMP can influence the designers and manufacturers of power equipment as well as the utility engineers themselves to proceed along a direction in which EMP protection and lightning protection are coordinated, resulting in increased protection at a minimum cost.

Efforts should be made now to introduce the concept of EMP to electrical engineering students so that they are aware of its threat and the corresponding need for considering it in planning and design.

6.4 COORDINATED PROTECTION

The need for lightning protection has long been recognized in the electric power industry. Standards for equipment and protective devices have been established along with the development of testing procedures.

A trend must now be started in which the industry recognizes the need for EMP protection and existing standards and tests are appropriately modified to include comprehensive and coordinated protection against both EMP and lightning.

More concern must be given to the problem of the protection of consumer equipment. This again may be coordinated with lightning protection. While the number of people killed indoors by lightning is relatively small, deaths still occur. Between 1959 and 1965 four persons were killed by lightning while using their telephones,[13] while many others were killed near appliances plugged into the house wiring system or fixtures connected to house plumbing.[14] Damage by lightning to home appliances and equipment is even more frequent. It is apparent that there is a need and use for increased consumer lightning protection. Such added lightning protection can be coordinated with EMP protection with little or no added cost.

Protection against lightning is gauged according to the lightning threat. A measure of lightning threat which has been used for many years is the isokeraunic level. This is the number of thunderstorm days (days on which thunder is heard) per year. Figure 6.1 shows the isokeraunic levels over most of the United States. It is seen that central Florida has a maximum level; hence, lightning protection devices are used plentifully, even on secondary lines. On the other hand, the west coast has a level which is practically zero right on the beach. The use of lightning arresters on distribution lines has accordingly been negligible.

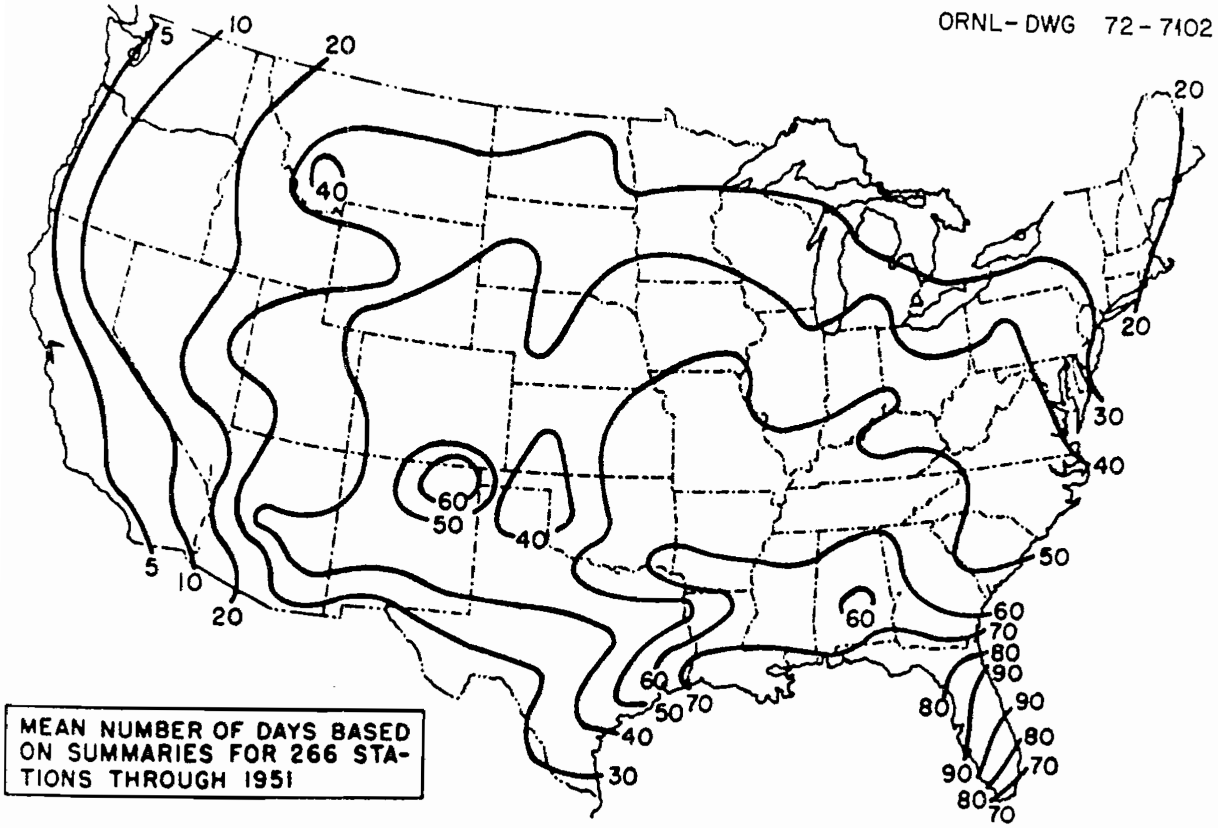

Fig. 6.1. The Number of Days per Year on Which Thunder is Heard at Various Locations in the U.S.A. Adapted from "Mean Number of Thunderstorm Days in the United States," Technical Paper No. 19, Climatological Services Division, Weather Bureau, September 1952.

In spite of this low thunderstorm level, extensive lightning occurs in something like nine year cycles. In the period 1967-1968, Southern California Edison Company lost 2200 distribution transformers from such lightning activity. Since that time, they have established a policy of protecting distribution transformers, 25 kVa and above, with arresters. Such a policy is not universal on the west coast, however. Substation transformers are still not protected by arresters.

The west coast is therefore especially vulnerable to EMP pulses in the distribution systems since they have a minimum of lightning protection. But even on the west coast more protection against lightning is desirable as well as the added protection against EMP which would be obtained by a coordinated program.

6.5 OTHER RECOMMENDATIONS

Extensive hardening of the electric power system is not recommended on a crash basis. A coordinated program of research, the development of standards, with increased protection against both lightning and EMP should be followed. This increased protection is obtainable through the use of modern, sophisticated arresters which fire rapidly (in the submicrosecond time range).

A principal problem besides that of protecting consumer equipment (which is possible using presently available devices) is that of the locking out of reclosing breakers. The only solution to this seems to be that of overriding the lockout by remote control. This is not yet available in many substations, but it is the trend to go to more and more remote control. This solution in turn requires a control and supervisory system which is hardened against EMP. It is suspected that present control and supervisory systems may be vulnerable to EMP and this problem is being investigated. More study of the lockout problem is needed. Perhaps other solutions will be forthcoming.

A big unknown which requires extensive study is the dynamic effect of an EMP on the entire power system. The need for attention to system security was emphasized by the so-called Northeast power failure in November 1965. That failure showed that concern with stability and system security is not merely academic and that a relatively small single local failure can have widespread effects of major proportions.

In contrast to the Northeast power failure, EMP-induced effects on consumers and distribution systems would essentially blanket the country. There is no question that such a widespread phenomena would imply important consequences regarding the stability of the system and maintenance of synchronism, and hence system security. This important and difficult problem remains even if all the problems of consumer protection and lockout are solved. This is because of the shock to the system which would result from the momentary simultaneous operation of many circuit breakers in the system.

The study of this problem of stability resulting from distribution system effects as well as from possible EMP induced flashover conceivably causing three-phase faults is imperative. It might be pointed out that even the Hoover Dam lines of the city of Los Angeles were not designed for transient stability during three-phase faults. This fact should indicate the seriousness of the problem and the importance of such studies.

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APPENDIX A

EXPERIMENTS ON SURGE COUPLING THROUGH A DISTRIBUTION TRANSFORMER

A 2400/4160-120/240 V, 3 kVA single phase transformer manufactured by Precision Transformer Company was connected as shown in Figure A.1. With this arrangement of grounded terminals which is standard for distribution transformers, the following experiments were performed.

The transformer was excited by connecting a 120 V, 60 Hz source in series with a power line filter between terminal B and the secondary neutral SN. Also between B and SN and in parallel with the source was connected a small transistorized AM radio. A 3 kV distribution type arrester was connected between A and PN. Terminal C was left floating. While the radio was in operation, a voltage pulse with a peak of 60 kV and a rise time of 10 ns was applied between A and PN. The powerline filter prevented the pulse from damaging the 120 V, 60 Hz source. Ten successive such pulses separated by no more than 2 minutes failed to cause any damage to the radio, although the pulse could be heard as static in the radio reception.

Next, the lightning arrester was removed from the primary and the pulse applied again. On the fifth pulse applied with this arrangement, the radio failed due to damage to its input transformer.

As a supplementary experiment, pulses with the same rise time but of increasing voltage were applied directly to the power input of an identical radio. The input transformer on this radio failed when the peak voltage of the pulse was 10 kV. This 10 kV was a measure of the direct vulnerability of the radio. Thus, when the 60 kV pulse was applied to the 3 kVA transformer primary, about 1/6 of this peak voltage was impressed across the radio.

In a second experiment terminals B and C were left open circuited and a square pulse of 50 V amplitude and various widths ranging from 50 ns to 8 microseconds was applied between A and PN. Measurements showed that the voltage between B and SN and C and SN was only 1/6 of the 50 V applied at A. This result correlates well with the high

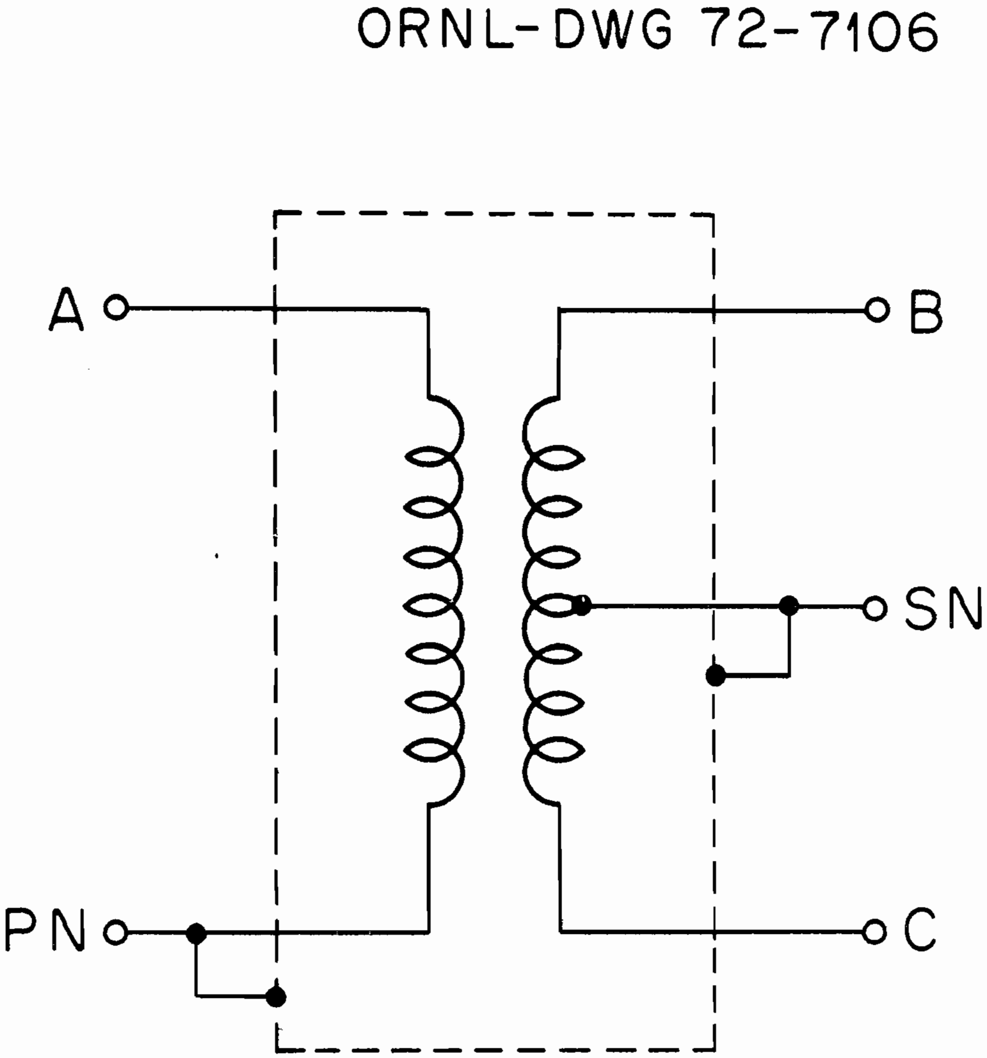

Fig. A.1. Distribution Transformer.

voltage pulse results described above with this same transformer and the AM radio.

In another experiment, terminals A and C were left floating, and the 120 V 60 Hz source in series with the power line filter was connected between terminals B and SN. The pulse with 60 kV peak and 10 ns rise time was applied between terminals B and SN. Although no statistical study was attempted, in a majority of cases the effect of the pulse was to produce a spark between either B and SN or C and SN. With the top of the transformer tank removed, one could observe that the sparks occurred between the bushings, most often inside the tank but also occasionally outside the tank.

APPENDIX B

USE OF LIGHTNING ARRESTER DATA

As an example of the use of the published lightning arrester data, we will use the curves in Figures 4.2 and 4.3 to determine the response of a 60 kV lightning arrester to pulse B of this chapter. In Table 1 we find that the maximum value of the current in the pulse is 4.02 kA, which rises with an average slope of 30.5 kA/μsec. The voltages associated with the pulse rises with an average slope of 12,200 kV/μsec.

Dividing the voltage rate of rise by the lightning arrester rating, we calculate a "normalized" rate of rise of 203 kV/kV μsec. We plot a line through the origin with this slope on the graph in Figure 3. This line intersects the graph at 7.3 kV/kV. If we multiply 7.3 kV/kV by 60 kV, the lightning arrester rating, we find that the breakdown voltage of the arrester is 438 kV.

To determine the discharge voltage of the arrester, we turn to Figure 4.3. From the figure, we see that the maximum rate of rise of the current for which there is a curve plotted is 20 kA/μsec. This is less than the average rate of rise of the current for pulse (B) which is 30.5 kA/μsec. Since the spacing between the curves in Figure 4.3 is not great, it is apparent that the discharge voltage is not a strong function of the rate of rise of the current in the pulse. If the current rate of rise of the pulse under question were a great deal larger than 20 kA/μsec, it would be necessary to draw in a new curve on the figure using the spacing between the existing curve as a guide to represent this greater rate of rise. In the case of pulse B, we can still use the curve for 20 kA/μs without appreciable error. Extrapolating this curve linearly to the left, we find that when discharging a current of 4.02 kA, the "normalized" lightning arrester discharge voltage is 4.1 kV/kV. Multiplying this result by 60 kV, the arrester rating, we find that the arrester discharge voltage is 246 kV.

APPENDIX C

EXAMPLES OF USE OF LIGHTNING ARRESTER LEAD LENGTH CURVE

The lightning arrester lead length curve can be used to analyze the protective capability of existing arresters or to design new substations in which the allowable arrester lead length must be established.

Example: An analysis problem. The 66 kV side of a distribution station has a BIL of 350 kV and has installed lightning arresters rated at 60 kV. The longest lead of any of these arresters is 15 ft. A margin of protection of 25% is considered desirable. What is the maximum rate of rise for an EMP with peak voltage in excess of the BIL that the 66 kV side of the substation will withstand?

We calculate x/m = 15 ft./0.25 = 60 ft. From the graph (Figure 4.5) we find r = 38 kV/kV µs. Multiplying this value of r by 60 kV, the arrester rating, we find that the substation is protected for an EMP with rate of rise 2280 kV/µs or less.

Example 2: A design problem. A substation is under construction. One side of the substation has 23 kV lines with a BIL of 150 kV. The arresters to be installed on this side of the substation are rated for 21 kV. A margin of protection of 50% is designed for the station. The EMP threat to this side of the substation is estimated to be from pulses with 500 kV peak voltage and rate of rise of 1000 kV/µs. What is the maximum allowable lead length for the arresters?

The normalized rate of rise of the EMP is $r = 1000 \text{ kV } \mu\text{s}^{-1}/21 \text{ kV} =$ 47.6 kV/kV µs. From the graph we find x/m = 50 ft. From this we calculate that x can be no greater than 50 ft. x .5 = 25 ft.