NEUTRAL-TO-EARTH VOLTAGE ANALYSIS OF A SINGLE-PHASE PRIMARY ELECTRICAL DISTRIBUTION SYSTEM

By

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Dedicated To

Anibal and Avani, my parents, with gratitude

Jose, my husband, with love

Helga, Herta, and Helen, my daughters, with hope.

ABSTRACT

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Several circuit network model representing single-phase grounded distribution line has been developed and utilized to determine the neutral-to-earth voltage produced along the line and to analyze neutral-to-earth voltage profile along the line in function of neutral grounding resistance, neutral conductor resistance, substation grounding resistance, and ground faults.

The circuits represented a 7.2 kV multi-grounded single-phase, distribution line with 4.5 Km of length, with the load concentrated at the end of the line, and distributed along the line.

A significant reduction of the grounding resistance in a specific point results in a significant reduction of neutral-to-earth voltage in that point and to a lesser extent, in the immediate area. Changes made near the substation do not affect the general neutral-to-earth voltage conditions over the entire line.

Increasing the primary neutral conductor resistance in a segment located at the beginning of the line resulted in increased neutral-to-earth voltage at all points along the line. However, changes made at the end of the line did not have a significant effect along the line. The effects of

varying the resistance of the substation grounding mat is more apparent at the substation and adjacent locations. The effects of primary ground faults were found to be location-independent wherever the fault was located, and had the same effect on neutral-to-earth voltage along the line.

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LIST OF SYMBOLS

V	substation voltage, volt
R_C	primary ungrounded conductor resistance, ohm
R_L	primary load resistance, ohm
R_N	primary neutral conductor resistance, ohm
R_S	substation grounding mat resistance, ohm
R_G	primary neutral grounding resistance, ohm
R_T	customer transformer grounding resistance, ohm
V_S	secondary voltage, volt
R_{LA}	secondary load resistance, at building A, ohm
R_{LB}	secondary load resistance, at building B, ohm
R_{LC}	secondary load resistance, at building C, ohm
R_{GSA}	secondary neutral grounding resistance, at building A, ohm
R_{GSB}	secondary neutral grounding resistance, at building B, ohm
R_{GSC}	secondary neutral grounding resistance, at building C, ohm
R_{NF}	secondary neutral conductor resistance, ohm
R_{NS}	secondary neutral conductor resistance, from the transformer to the metering point, ohm
R_F	secondary neutral conductor resistance, from the metering point to the buildings, ohm
VTE	neutral-to-earth voltage at the customer transformer, volt

VME	neutral-to-earth voltage at the metering point, volt
VAE	neutral-to-earth voltage at building A, volt
VBE	neutral-to-earth voltage at building B, volt
VCE	neutral-to-earth voltage at building c, volt

CHAPTER I

INTRODUCTION

The necessity of using electrical energy safety has resulted in strict grounding requirements for electrical systems. By 1947, the National Electrical Code required that metallic structures in contact with the electrical system neutral conductor be connected together, and all connected to the earth for safety purposes.

United States utility companies have adopted a distribution system with the primary system neutral multi-grounded along the line, and connected to all grounded secondary low voltage neutrals that are, in turn, connected to the equipment grounding system at the transformer.

This safety procedure places the neutral conductor and the metal enclosures of the customers' wiring system and equipment at earth potential to avoid electrical shock and to stabilize system voltages during faults, lightning strikes and other disturbances. The introduction of this system has greatly improved personal safety when high voltages are used.

Unfortunately, concurrent with grounding for safety reasons, another problem develops. Small voltages from the neutral conductor to the earth may appear throughout the neutral grounding system. Depending on the situation, this small voltage may disturb both humans and animals.

This voltage has been of interest to agricultural researchers since electricity became a main source of energy supply in rural areas. Only recently, however, has it been investigated in a systematic way. Several designations have been given to these low voltages appearing on the neutral grounding system: neutral-to-ground potential, neutral-to-earth voltage, transient voltage, single voltage, extraneous voltage and stray voltage. The term neutral-to-earth voltage will be used throughout this document.

Electrical energy supply to most American farms is through a multi-grounded three-phase wye distribution system although the farm itself is likely to be supplied from a grounded single-phase portion of the wye system. This system offers construction economy in relation to the other distribution systems.

Among the economic advantages of the grounded wye system is the ability to supply economical single-phase or open wye radial feeders through the use of one or two energized conductors and a neutral conductor in low-density load areas.

To improve operational safety in a multi-grounded distribution system, the primary neutral conductor is bonded to grounding electrodes along the line. The secondary farmstead wiring system is also grounded and the primary and secondary systems are bonded together at the distribution transformer. All of these procedures are regulated by the National Electrical Safety Code and the National Electrical Code. Under normal operating conditions, currents flow in the primary and secondary neutral conductor, and also through the grounding system. The current which acts through the impedances of the neutral conductor and the grounding system may produce voltages between the neutral conductor and earth to a level that may be felt by human and/or animals. The magnitude of these voltages are affected by resistance of both the grounding system and the neutral conductors as well as the neutral load. Lack of understanding exists in regard to the flow of electrical current through complex grounded distribution networks, and the effects of the farm grounding system on neutral-to-earth voltages. It is known that an improved grounding system at a farm can change the value of neutral-to-earth voltage, although the amount of voltage change is difficult to predict (Surbrook & Reese, 1982.)

Possible symptoms of neutral-to-earth voltage problems in dairy operations are described as mastitis, nervousness, reluctance to enter the parlor, poor letdown, slow milking, reluctance to drink water, reduced feed intake in the milking parlor, and lowered milk production. For the dairy farmer, poor animal health, loss of milk quality, loss of market, replacement animals, and lower-than-expected milk production are serious economic problems.

Moreover, this problem is not restricted to dairy farms alone. Occurrences have been cited in other animal operations, and in instances where people may come in electrical contact between the earth and metal objects grounded to the neutral. Given the number of occurrences, this problem can no longer be discounted. Hence, the use of circuit models can be instrumental in improving the understanding of various sources of stray voltage and be applied to new methods of alleviating the problem.

The focus of this thesis is on these special kinds of small voltages. A model was developed to analyze neutral-to-earth voltages of a single phase distribution system originating from a grounded wye substation.

CHAPTER II

LITERATURE REVIEW

The literature on neutral-to-earth voltage is both scarce and recent. Early studies of power line neutral voltage problems concerning hazards to humans or animals have been conducted by MacPherson (1950), Buchanan (1950), and Waghorne (1950). Around the same time, studies were being conducted in New Zealand by Phillips, Salisbury and Curry et al. Their work focused on the effects of neutral-to-earth voltage on milk production. According to Craine (1980), neutral-to-earth voltage problems have been reported internationally (i.e., Sweden, Germany, Austria, Canada) since the 1970's. In the United States, problems were reported to milking machine manufacturers, public utility commissions, power utilities, United States Department of Agriculture, and university researchers.

This literature review is focused on two topics: (1) sources of neutral-to-earth voltage, and (2) models of neutral-to-earth voltages in distribution lines. These topics are essential in the comprehension of the issue approached in this thesis. The first topic deals with the causes of neutral-to-earth voltage and the second with the effects of this phenomenon on distribution lines.

2.1 - Sources of Neutral-to-Earth Voltage

The neutral-to-earth voltage is an inherent characteristic of the grounded primary distribution system, which is used throughout the United States and in several other countries. Usually, the neutral-to-earth voltage produced by the system configuration is small. However, some conditions may increase the level of the neutral-to-earth voltage to the point of causing discomfort or even damage to animals. (MacPherson, 1950; and McCormack, 1969). The literature refers to these conditions as being the sources of neutral-to-earth voltage. There are several of these sources and they and usually appear simultaneously, making their location a difficult problem (Appleman & Cloud, 1981, Surbrook & Reese, 1981). The neutral-to-earth voltage sources may be classified according to either the place of origin (on-the-farm and/or off the farm) or the nature of the current (DC or AC).

2.1.1 - Sources of DC Neutral-to-Earth

DC sources of neutral-to-earth voltage do not occur often, but their presence has been reported by the literature (Lillmars & Surbrook, 1980; Seeling, 1980; Bodman et al, 1981; Stetson et al, 1979). Four different sources are identified:

1. Galvanic action. DC voltage may appear in metal pieces buried in earth or concrete due to the galvanic action, which occurs between the acids in the soil or concrete and the metal (Williams, 1976; Bodman et al, 1981).
2. An inadequately grounded pulsator circuit of the milking machine (Stetson et al, 1979).
3. Corrosion protection rectifiers on an undergrounded utility piping system (Seeling, 1980).
4. Problems from nearby telephone system (Seeling, 1980; Lillmars & Surbrook, 1980).

The first two sources originated on the farm whereas the last two are sources originated off the farm.

2.1.2 - Sources of AC Neutral-to-Earth

In most of the research conducted neutral-to-earth voltage sources have been done on the AC sources for they are the most frequently found. The voltage originated by

AC source is often transient. The transient effect may vary in predictable manner or it may vary completely without pattern. The source may also be originated on the farm or off the farm (Surbrook & Reese, 1981).

2.1.2.1 - On Farm Sources of Neutral-to-Earth Voltage

1. Voltage Drop on Secondary Neutral. This is the most frequent source of on-the-farm neutral-to-earth voltage (Surbrook & Reese, 1983). The problem occurs when there is too much neutral current flowing through a high resistance neutral conductor. The neutral current is caused by unbalanced loads and the voltage drop is caused by excessive neutral resistance. According to Gustafson & Cloud (1981) since the secondary neutral current may be either in-phase or 180^{o} out-of-phase with primary neutral, the phase relationship between this voltage source and that due to the primary neutral source must be taken into consideration. A voltage drop created by imbalance current in-phase with the primary will increase the secondary neutral-to-earth voltage. The opposite occurs if the imbalance secondary current is 180^{o} out-of-phase with the primary neutral current. High resistance in the secondary neutral can be caused by loose or oxidized connections, inadequately sized feeder for the load and length of run (Stetson et al, 1979; Soderholm, 1979;

Lillmars & Surbrook, 1980; Seeling, 1980; Surbrook & Reese, 1981).

2. Ground Faults. Leakage currents to earth from an ungrounded conductor must return to the center tap of the distribution transformer. Ground fault currents can arise from numerous types of problems in wiring and equipment. Insulation breakdown in equipment or a loose connection can short wiring to metal frames (Surbrook & Reese, 1981). If a ground fault develops, the seriousness of the situation depends on the electrical resistance of the return path from the fault to the grounded neutral system. If a grounding conductor is provided, sufficient current will usually flow when the fault occurs to operate the protective equipment. If adequate grounding is not provided, current must take a high resistance path through the earth, and thus, dangerous step and touch potentials can be present in the area of the fault (Surbrook & Reese, 1981; Gustafson & Cloud, 1981). Usually a ground fault results in a local problem only, that is, there will be an elevation of potential of equipment in close proximity to the ground fault and nowhere else. MacPherson (1950) concluded after investigations in Canada that the most common source of neutral-to-earth voltage was ground faults. This source of neutral-to-earth voltage was mentioned by Lillmars & Surbrook (1980). It has also been common in Michigan.

3. Voltage Gradient. A special case of a ground fault is the presence of voltage gradients through the earth or across a floor when an underground conductor faults to earth. Insulation breakdowns on an underground conductor are frequent when they are buried above the proper depth of 24 inches. Usually current flow through the earth is not enough to operate protection devices that make this kind of fault dangerous. Animals have been killed due to a high voltage gradient between the front and rear hooves when faults in underground conductors occur (Surbrook & Reese, 1981).

4. Induced Potentials. It is possible for induced voltages to exist on isolated conductive equipment located in an electric field. A common source of the electric field in stanchion barns is high voltage cow trainers running parallel to electrically isolated pipes (water lines, milk pipelines and vacuum lines). Any other isolated conductive equipment in close proximity to the electric field source may also show a potential difference. If a capacitive charge builds up in any isolated metal equipment it may be discharged to the ground in the case of animals touching the equipment (Bodman et al, 1981).

5. Electric Fences. Another source of neutral-to-earth voltage may be wires of electric fences running through buildings. An electric fence has as output a high voltage pulse whereas the maximum insulation rating

of building electrical wire is 600 volts. A breakdown of the wire insulation may occur causing a fault to ground.

6. Grounding and Grounded (Neutral) Conductor Interconnections. Before presenting this source, the following two definitions are necessary: a) "Grounding Conductor: the conductor which connects metal parts of equipment to ground. This conductor is part of the equipment grounding system. Under normal conditions, this conductor carries no current." (Gustafson, 1983), and b) "Grounded Conductor: Neutral. Provides a return path for current supplied to 120 volt loads. This conductor, like the grounding conductor, runs from a piece of equipment to the service entrance ground; but unlike the grounding conductor it normally carries load current when the equipment is operating and is insulated from the frame of the equipment" (Gustafson, 1983). The grounded conductor is permitted to be connected to earth only at the service entrance and this connection is called the grounding electrode.

The National Electrical Code requires that the conductors defined above are only permitted to be directly connected at the service entrance panel to a building and these conductors must be kept separated for all feeders and branch circuits panel and equipment supplied by the service entrance panel to a building and these conductors must be kept separated for all feeders and branch circuits panel and equipment supplied by the service entrance (Surbrook &

Reese, 1981). Neutral-to-earth voltage has been found when these Code rules are violated, that is (1) the grounded conductor (neutral) is used as the grounding conductor, (2) the grounding conductor is used as a grounded conductor (neutral) and (3) the grounded and grounding conductors are interconnected beyond the service entrance.

2.1.2.2 - Off-Farm Sources of Neutral-to-Earth Voltage

1. Voltage Drop on Primary Neutral. The most common causes of voltage drops on the primary neutral are due to resistance at a splice, or an undersized conductor for the current load, and distance to the load. The voltage drop on the primary neutral appears on the secondary neutral system because of the bond between the primary and secondary at the distribution transformer (Surbrook & Reese, 1983).

2. Ground Faults at Neighbor's Property. The bond connections between the primary and secondary neutrals at each transformer permit that a fault in equipment at neighboring property may return to source transformer via grounding electrodes at a farm thus causing a neutral-to-earth voltage problem (Surbrook & Reese, 1981). There are documented cases of submersible pump faults a half mile from a farm causing elevated neutral (Brown & Weeks, 1981).

3. Fault in Primary Equipment. A few cases of neutral-to-earth voltage have been related to breakdown of electrical components on the primary distribution system. In this situation, the voltage drop on the primary neutral has been traced to a high resistance present in splices (Surbrook & Reese, 1981).

4. Problems with Primary Grounding. Primary neutral currents return to the source transformer through the earth as well as on the primary neutral. A farm close to a distribution substation may, under unusual conditions, act as a return path for primary ground currents (Surbrook & Reese, 1981).

2.2 - Models of Neutral-to-Earth Voltages in Distribution Line

In searching the literature, three efforts in examining the neutral-to-earth voltage in distribution system through the use of models were found.

In 1982, Drache et. al. developed a numerical model to study selected aspects of neutral-to-earth voltage resulting from a single-phase rural distribution system. The model represented a 7.2 kV single-phase line 8 Km in length, with ten farms. They used a Transmission and Distribution computer modeling package (EMTP) developed at the Bonneville Power Administration of Portland, Oregon for the study. The researchers concluded that uniform changes in system loading and grounding produced nearly uniform changes in voltage. Changes in grounding or loading at one farm created localized effects most apparent on that farm and the adjacent farms.

Stetson et al (1984) developed a DC analog model to illustrate tne neutral-to-earth voltage phenomenon associated with multi-grounded single-phase distribution systems. The analog used the "true-earth" concept, wherin each connection between the neutral conductor and the true earth is represented by a resistance between the conductor and true earth. True earth is used as a voltage reference and has zero resistance and, zero potential difference exists between any two true-earth ground connections. The authors adopted the true earth model to a simple electrical analog consisting of an isolated length of multiple grounded primary neutral and two farm loads. This analog was aimed to serve as a neutral-to-earth demonstration unit to permit orderly analysis of the problem. The model can be used to demonstrate several effects, on primary and secondary lines, caused by poor connections, poor grounding, etc. The analog demonstrates that the neutral-to-earth voltage is always present on power transmission and distribution systems. However, excessive voltage can be reduced to a level that is below the animal sensitivity threshold. For the isolated line segment represented by the analog, the neutral-to-earth voltage was maximum at the end of the line and minimum near the center. The results show negative values of voltage at the beginning of the line representing instantaneous phase reversals. They concluded that the reduction can be achieved by assuming low-impedance neutral circuits and by slow resistance grounding system. Balancing loads and using correct wiring are also effective corrections.

Monroe et. al. (1984) developed a computer program able to evaluate the voltage and current distribution problems and remedial measures on a neutral network. The method presented the estimation of neutral-to-earth voltages and current flows by the use of a Y-bus network solution analysis. The program provides the means of evaluating particular situations, such a poor grounding, stray voltages, load imbalance and evaluating remedial measures necessary to alleviate field problems. This type of evaluation provides an alternative to the various trial and error remedial methods, The authors illustrated the topic considering several different situations on a rural distribution circuit. A typical rural cooperative circuit with diversified loads was used to evaluate the neutral-to-earth voltages. It was evaluated by different alternatives studying the effects of changing the neutral conductors on some segments of the line and the effects of installation of a low impedance rod or mat system. The authors concluded that changing the neutral is an expensive alternative but it might be considered since it substantially decreased the neutral-to-earth voltage along the modified segment of the line. Another conclusion was that there is significant effect of improving local grounding conditions, however, it was noted that this effect is relatively localized.

CHAPTER III

OBJECTIVES

The purpose of this research was to individually analyse the factors which cause neutral-to-earth voltage along a single-phase branch of a grounded wye electrical distribution line.

Neutral-to-earth voltage is an inherent and necessary characteristic of a multi-grounded distribution distribution system. A number of possible causes of excessive voltage on the neutral conductor have been identified as both on-farm and off-farm sources. A major source is excessive voltage drop on the neutral conductor which may be associated with poor neutral connections, poor grounds, unbalanced loads, and undersized neutrals. Another source is electrical current faulting directly to earth from an ungrounded conductor usually through high resistance.

In this study, the neutral-to-earth voltage sources were separated into single components and each one was analyzed as though it were the only source. In the field, several, or possibly all, of these sources may be superimposed, but a fruitful evaluation is difficult if the contribution from each source is not clearly distinguished and analyzed.

The first major objective was to develop a circuit network model with analogous behavior to a single-phase grounded primary electrical distribution line with and without single-phase secondary loads.

The second objective was to analyze the neutral-to-earth voltage produced along the entire length of the distribution line under specific conditions.

a) Determine the neutral-to-earth voltage profile along a single-phase grounded distribution circuit originating at the substation with the load concentrated at the end of the line, and distributed along the line.

b) Examine the influence of a neutral or transformer grounding resistance on the neutral-to-earth voltage profile along a single-phase grounded distribution circuit originating at the substation with the load concentrated at the end of the line, and distributed along the line.

c) Analyze the influence of a neutral conductor resistance over the neutral-to-earth voltage profile along a single-phase grounded distribution circuit originating at the substation with the load concentrated at the end of the line and distributed along the line.

d) Analyze the influence of enlarging a load at one location on the neutral-to-earth voltage profile along a single-phase grounded distribution circuit originating at the substation with the load distributed along the line.

e) Analyze the effect of a variation in the substation grounding resistance on the neutral-to-earth voltage profile along a single-phase grounded distribution circuit originating at the substation with the load concentrated at the end of the line and distributed along the line.

f) Analyze the effect of a sustained primary or secondary line to ground fault on the neutral-to-earth voltage profile along a single-phase grounded distribution circuit originating at the substation with the load distributed along the line.

CHAPTER IV

METHODOLOGY

An equivalent circuit for an electrical distri ution system was developed so that the neutral-to-earth voltages could be readily computed while varying neutral grounding resistance, neutral conductor resistance, loading, substation grounding resistance, and ground faults.

The computer program SPICE, developed by the Electronics Research Laboratory at the University of California, Berkeley, was used for this study. SPICE is a powerful tool and may be used to analyze both analog and digital circuits. SPICE is a general network solving program for use on mainframe computers. Refer to Appendix for more detailed information.

4.1 - Calculation Procedure

Figure 1 represents the equivalent circuit of one section of a multi-grounded single-phase electrical distribution system where V is the source voltage, R_C represents the ungrounded conductor resistance, R_L represents the load resistance, and R_N represents the neutral conductor resistance. The substation, neutral and

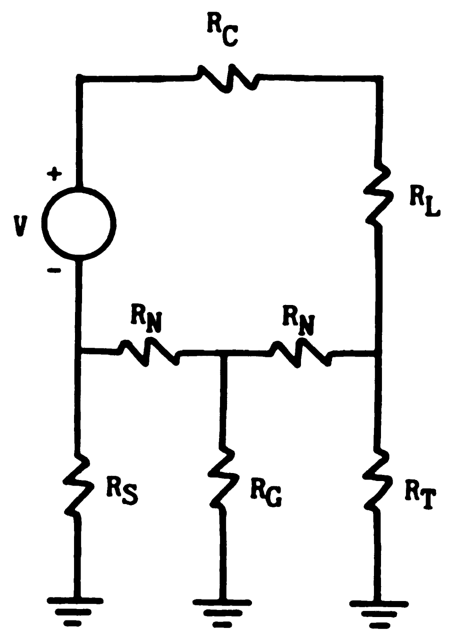


FIGURE 1. Sample multi-grounded, single-phase, electrical distribution system.

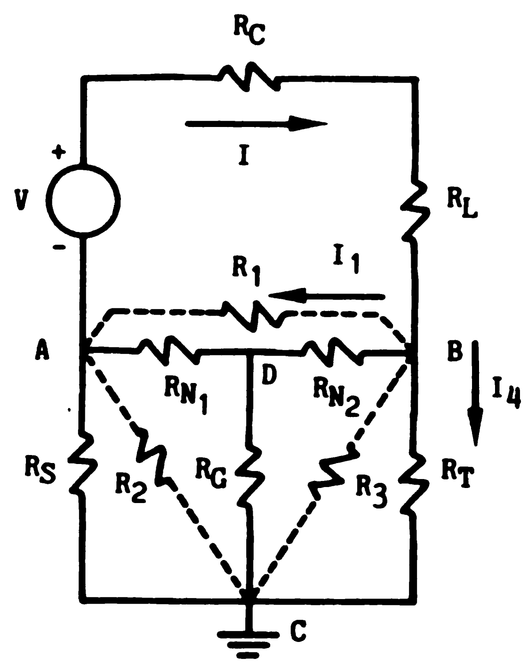


FIGURE 2. Equivalent circuit showing the star-to-delta conversion.

transformer grounding resistances are represented by R_S R_G and R_T, respectively. The network analyses of this equivalent circuit could be computed through delta-to-star conversion.

Figure 2 shows the star part of the circuit inside a delta as an aid in finding the delta resistances. From the star-delta conversion formulas of the values of R_1, R_2 and R_3 can be obtained:

$$R_1 = R_{N1} + R_{N2} + \frac{R_{N1}\ R_{N2}}{R_{G1}} \tag{1}$$

$$R_2 = R_{G1} + R_{N1} + \frac{R_{G1}\ R_{N1}}{R_{N2}} \tag{2}$$

$$R_3 = R_{G1} + R_{N2} + \frac{R_{G1}\ R_{N2}}{R_{N1}} \tag{3}$$

As a result of this conversion, the circuit becomes series-parallel and the total resistance (R_T) is easy to find throughout the following steps:

$$R_4 = \frac{R_3\ R_{G2}}{R_3 + R_{G2}} \tag{4}$$

$$R_5 = \frac{R_{GS}\ R_2}{R_{GS} + R_2} \tag{5}$$

$$R_6 = R_4 + R_5 \tag{6}$$

$$R_7 = \frac{R_1\ R_6}{R_1 + R_6} \tag{7}$$

$$R_8 = R_C + R_L \tag{8}$$

$$R_T = R_7 + R_8 \tag{9}$$

Thus $I_T = \dfrac{V}{R_T}$ (10)

The potential differential between the points B and A is:

$$V_{BA} = I\ R_7 \tag{11}$$

The current $I_1 = \dfrac{V_{BA}}{R_1}$ (12)

The current thought the parallel combination of R_{G2} and R_3 is:

$$I - I, = I_2 \tag{13}$$

$$V_{BC} = I_2 R_4 \tag{14}$$

$$I_4 = \frac{V_{BC}}{R_{G2}} \tag{15}$$

$$V_C = 0 \tag{16}$$

Finally, the voltage at the points A, B and D are:

$$V_B = I_2\ R_4 \tag{17}$$

$$V_A = V_B - V_{BA} \tag{18}$$

$$V_D = V_B - R_{N2}\left(\frac{V_{BC}}{R_{G2}}\right) \tag{19}$$

4.2 - Distribution Line Model Development

An electrical distribution system is all or part of an electric power system between the majority power source and the customers' service switches. The distribution system can, in general, be divided into six parts:

subtransmission circuits, distribution substation, primary feeders, distribution transformers, secondary circuits, and customers' services.

The model consists of the equivalent circuit of an electrical distribution system. In this study, only that part of the distribution system beginning at the secondary windings of the distribution substation transformer and extending to the end customer is investigated. Further, the model utilizes single phase circuitry exclusively, where, in actuality, a typical distribution line is made up of sections of three-phase, two-phase (open wye) and single-phase construction. This yields a conservative model because the worst neutral-to-earth voltage problems are typically found on single-phase feeders.

Typical distribution feeder voltages are 4800 volt delta, 12,470Y/7200 volt wye, 8318Y/4800 volt wye and other voltages in this general range. For this study, the more common 12,470Y/7200 volt system was selected as being representative of many rural feeders. The system modeled has the following characteristics:

a. 4.5 Km (2.8 mile) of 7.2 kV multi-grounded single phase distribution system;

b. primary conductors are number 4 AWG, ACSR (Aluminum Conductor Steel Reinforced) with a resistance of 0.424 ohm/304.8m (1000 ft);

c. secondary conductors are number 4 AWG aluminum, number 1/0 AWG aluminum, and number 4/0 AWG aluminum, with resistances of 0.424 ohm/304.8m (1000 ft), 0.168 ohm/304.8m (1000 ft), and 0.0836 ohm/304.8m (1000 ft), respectively;

d. the primary neutral conductor is grounded at the substation and also fifteen times at an equal spacing of 304.8m (1000 ft) along the line or at each load (customer transformer), whichever is closer;

e. the substation grounding system has 0.5 ohm of resistance;

f. each neutral grounding electrode or transformer grounding electrode connects to "true" earth through 20 ohms resistance;

g. resistance of each load, 6480 ohms (customer transformer) is set at a value which produces a 1 ampere load at the distribution voltage.

h. neutral wires are selected deliberately to be smaller than normal, thus creating a worst-case voltage drop situation for the model. A more common size for the neutral conductor today would be number 2 ANG, AL ACSR or larger.

The model assumes that:

a. impedances are pure resistances (very nearly true)

b. the earth is homogeneous and acts as a pure resistance. The modeled circuit carries very low currents so that the effects of inductance and capacitance of the earth may be ignored.

c. substation transformer winding resistance is negligible compared to the ungrounded conductor resistance.

In order to simplify the utilization of computer program SPICE, the distribution line systems were supplied by a DC source of voltage equivalent to the actual AC source. The voltage and current values shown are equivalent to rms values. The negative values shown represent an instantaneous phase reversals. Rough comparisons with actual field measurements show close enough agreement to confirm the validity of the DC model.

In the initial phase of modeling, a circuit was developed. Throughout the process of this experiment, modifications were made and incorporated into this initial model. The following demonstrates the steps through which the modeling process evolved:

4.2.1 - Step 1 - CIRCUIT A

The first model developed is shown schematically in Figure 3. It represents a multi-grounded primary distribution line with a concentrated load located at the end of the line.

The single-phase substation voltage is V, and has an amplitude of 7200 volts rms at the substation. R_C (6.32 ohms) represents the ungrounded conductor resistance; R_L (432 ohms) is the load resistance; R_N (0.424 ohm) is the neutral conductor resistance. Resistance R_G (20 ohms) represents the neutral grounding system, while R_S (0.5 ohm) represents the substation grounding resistance.

4.2.2 - Step 2 - CIRCUIT B

CIRCUIT A was then modified in order to represent a primary distribution line with a distributed load along the line. Fifteen loads (customer transformers) were uniformly spaced each 304.8m (1000 ft) along the line, as shown in Figure 4. Equal loading was applied to each of the fifteen

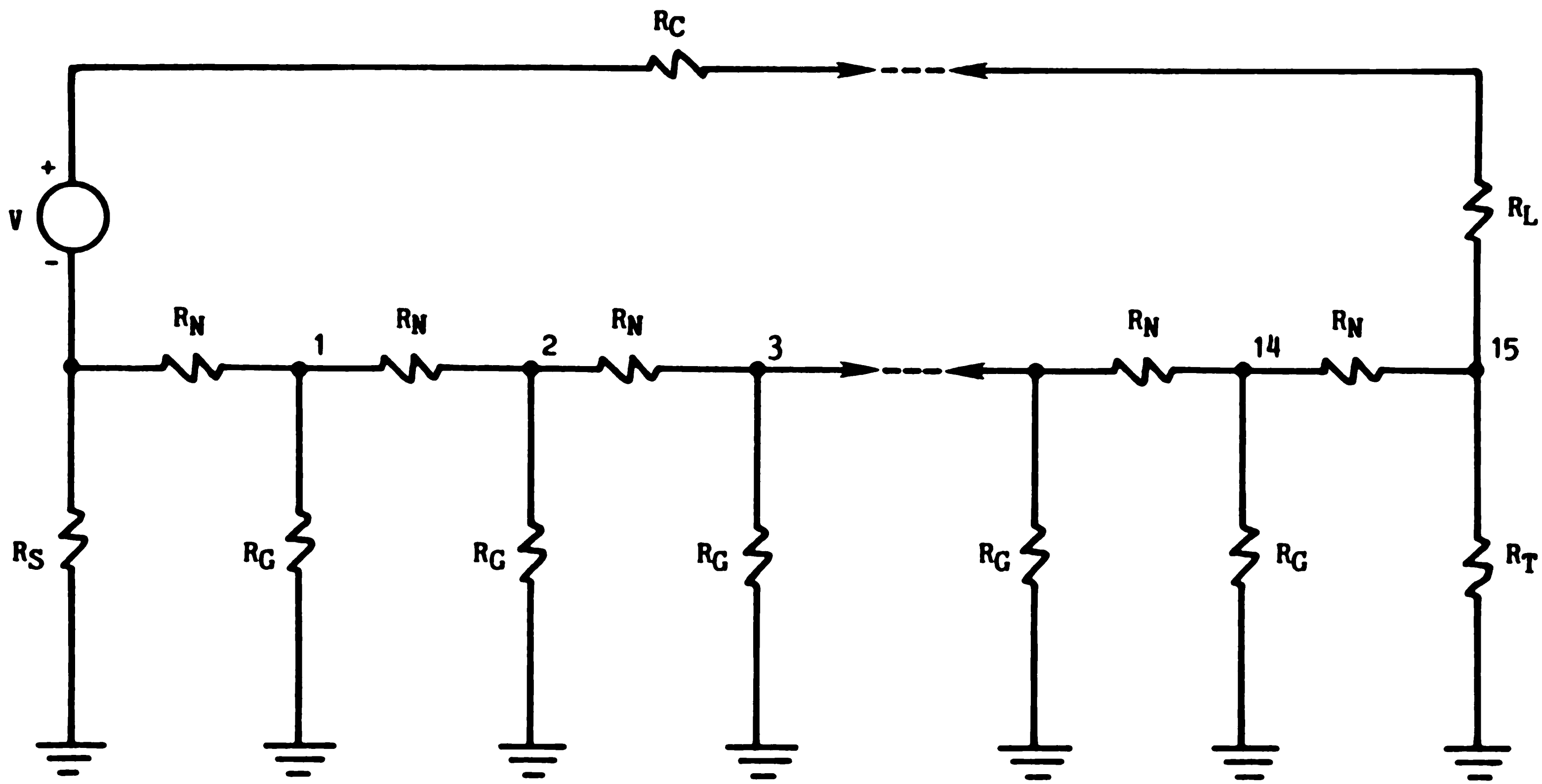


FIGURE 3. CIRCUIT A. Distribution Line Model. Concentrated load at the end of the line.

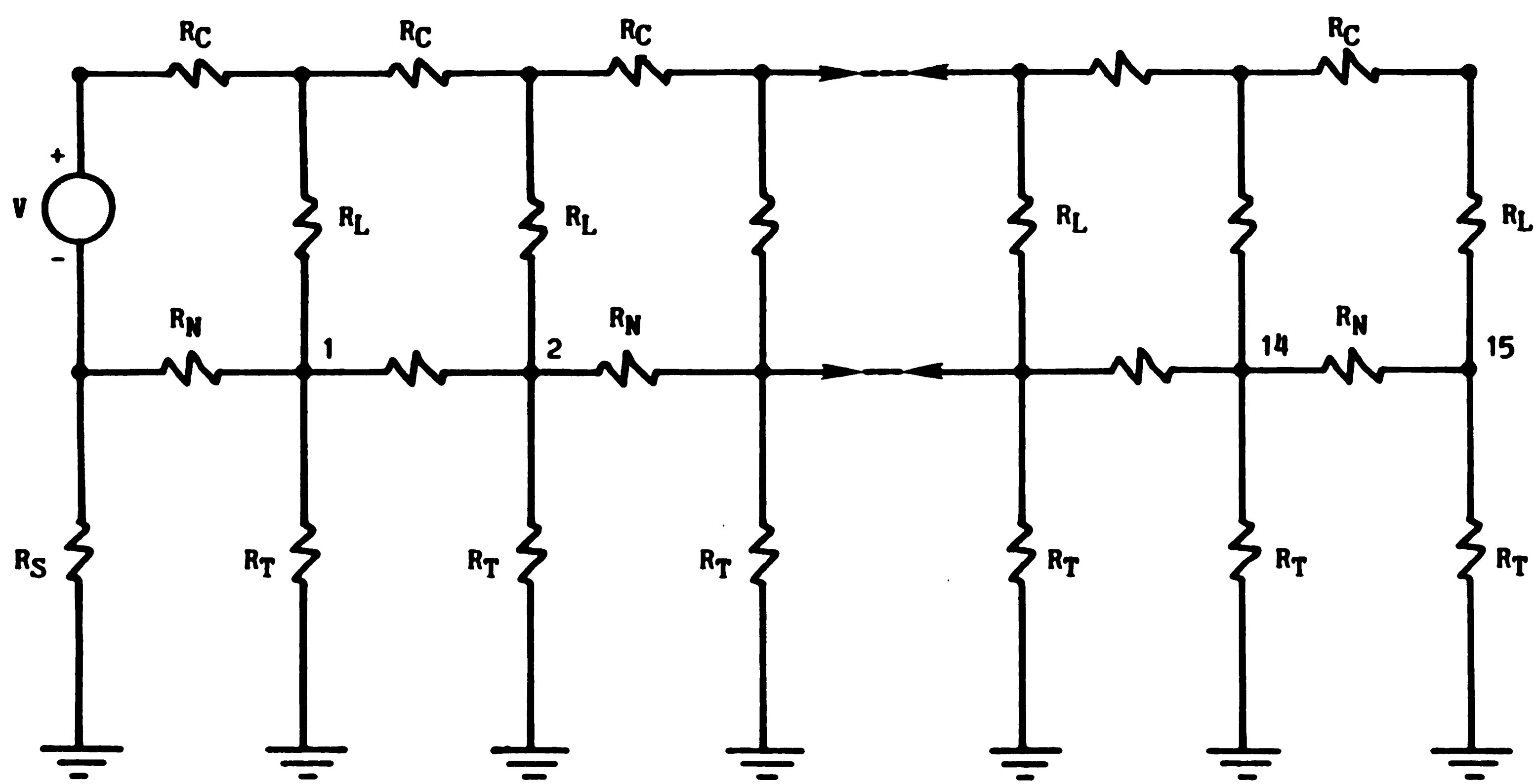


FIGURE 4. CIRCUIT B. Distribution Line Model. Distributed load along the line.

transformers by using a 6480 ohm (R_L) resistance between the primary ungrounded and neutral conductors. R_C (0.424 ohm) represents the ungrounded conductor resistance. R_T (20 ohms) represents the transformer grounding resistance.

The value of all other line parameters remained unchanged from values previously stated.

4.2.3 - Step 3 - CIRCUIT C

Figure 5 shows the circuit used in this step. CIRCUIT B was modified by adding extra grounding electrodes with 20 ohms of resistance each, at the midpoint between loads (customer transformers). R_N (0.212 ohm) represents the neutral conductor resistance between each grounding electrode.

4.2.4 - Step 4 - CIRCUIT D

In order to simulate the primary electrical distribution system and the customer's secondary electrical system CIRCUIT B was modified to create CIRCUIT D. At each load, a circuit was added to the secondary side of the distribution transformer (Figure 6) which had the following characteristics: 120/240 volt, single phase, three wire, grounded system with one feeder and a balanced load. The AC voltage source V_S (120v) represents the actual AC voltage between the ungrounded and the neutral conductors.

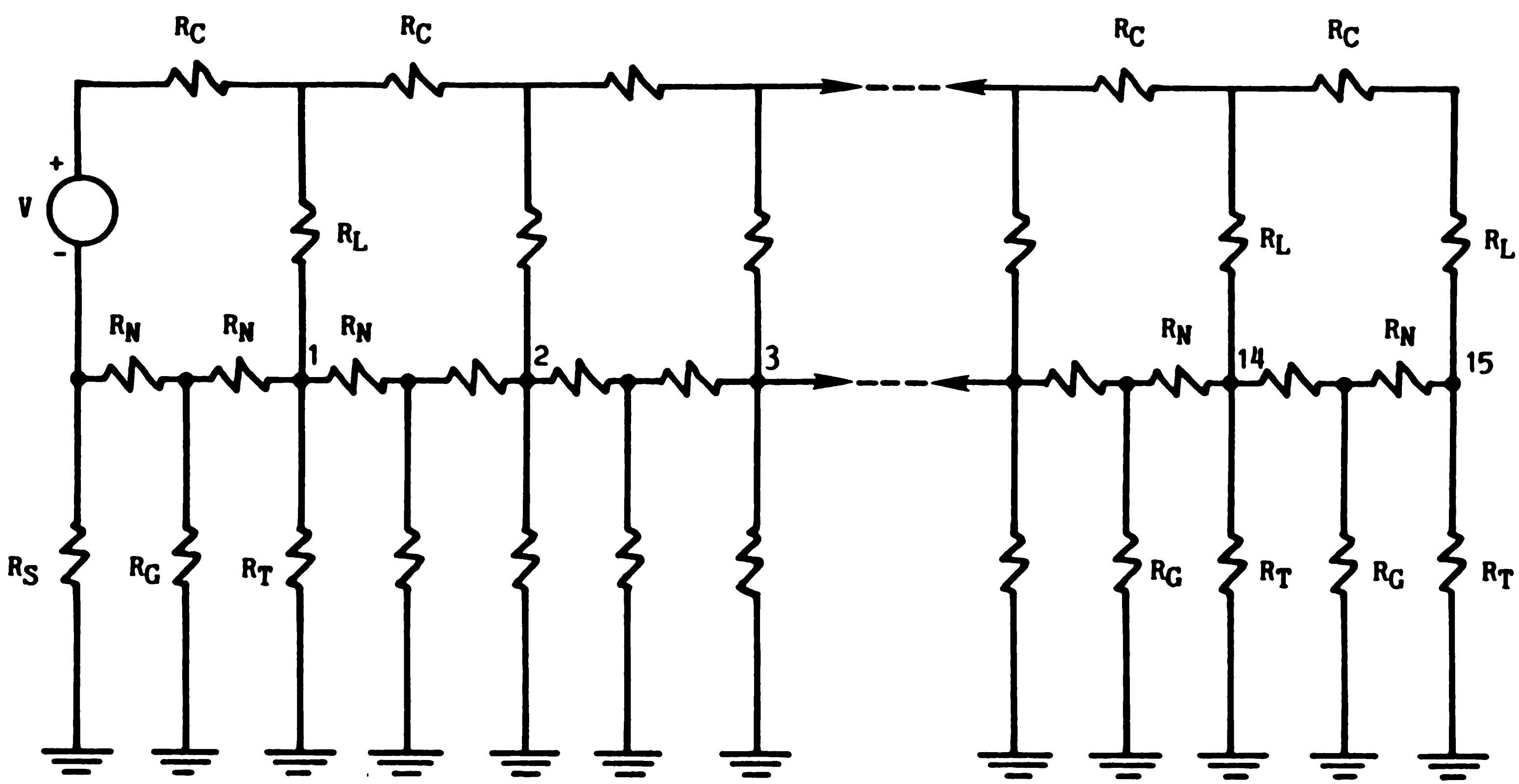
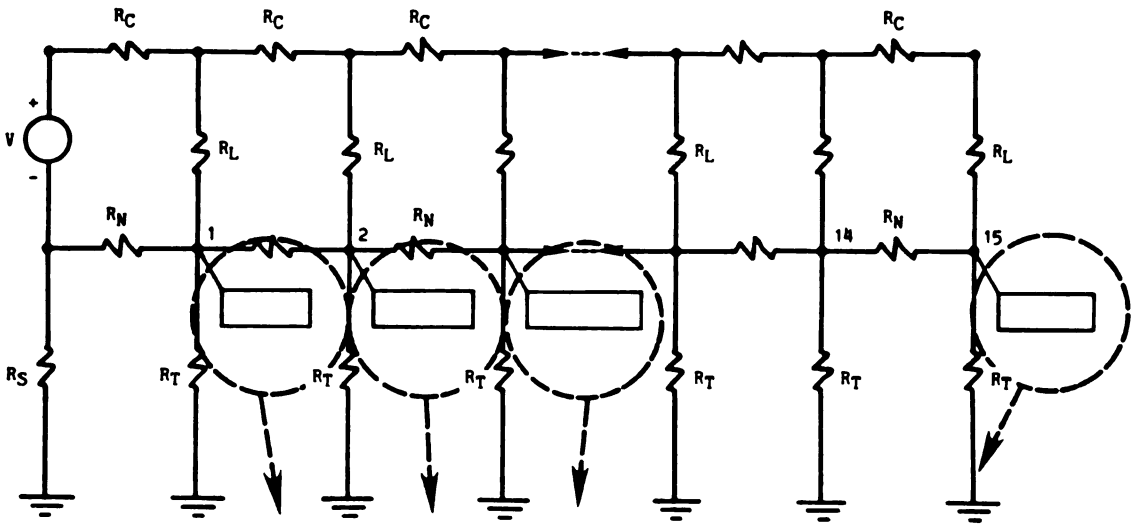


FIGURE 5. CIRCUIT C. Distribution Line Model. Distributed load along the line. Extra grounding system.



DETAIL - ONE-FEEDER SECONDARY SYSTEM

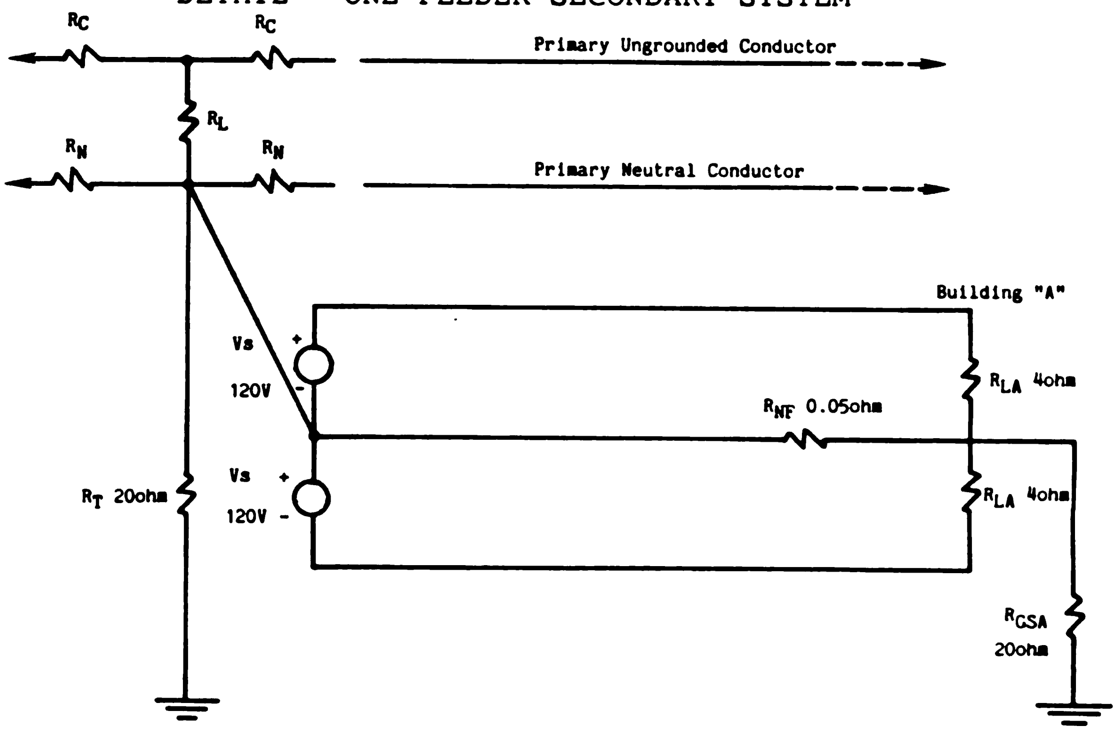


FIGURE 6. CIRCUIT D. Distribution Line Model. Distributed load along the line. Primary and one-feeder secondary systems.

The grounding electrode system consists of 20 ohm resistances. The 7.2 kW load used implied 4 ohms (R_{LA}) per leg loading on the secondary system. R_{NF} (0.05 ohm) represents the secondary neutral conductor resistance.

4.2.5 - Step 5 - CIRCUIT E and CIRCUIT F

In order to create CIRCUITS E and F, the equivalent circuit of the secondary side of the distribution transformer, utilized in the step before, was modified. Here, it represents a customer secondary distribution system with three feeders, each having a balanced load grounded system. It is a typical farm electrical distribution system with a central metering point and three wire, single-phase feeders to each building.

Building A had a current load of 30 Amperes that implied 4 ohms (R_{LA}) per leg in the secondary system. Buildings B and C each had current loads of 15 Amperes that implied 8 ohms (R_{LB} and R_{LC}) per leg in the secondary system.

The grounding electrode system consisted of grounding electrode, bonded to the neutral at the transformer and another at the central metering point, both with 20 ohms of resistance. The grounding electrode system of buildings A, B and C had 12 (R_{GSA}), 20 (R_{GSB}), and 12 (R_{GSC}) ohms of resistance, respectively. The secondary neutral resistances had the values 0.005 ohm (R_{NS}) and 0.02 ohm (R_F) from the transformer to the metering point and from the metering point to the buildings, respectively.

The resistance of 6480 ohms between the primary ungrounded and primary neutral conductors was lowered to 3240 ohms, in order to maintain the balance of energy, between primary and secondary transformer.

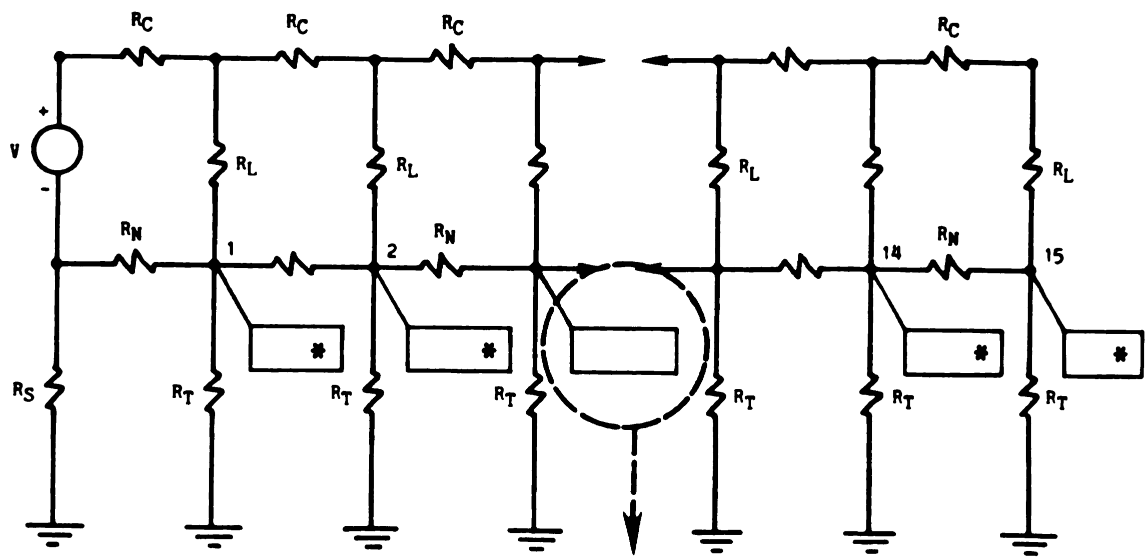
Figures 7 and 8 show distribution line models with three feeders secondary circuits, located at the center of the line in the case of CIRCUIT E (Figure 7) or at the end of the line in the case of CIRCUIT F (Figure 8). All other loads, for both systems, were of the one-feeder type detailed in Figure 6.

4.3 - Simulation

In the process of modifying CIRCUITS A through E, certain parameters were simulated and are explained as follows:

4.3.1 - Study of Neutral/Transformer Grounding Resistance

In the primary neutral/transformer grounding resistance study, the value of grounding resistance (R_G or R_T) was changed at one location. A smaller resistance was located near the substation (location 1), and then near the middle of the line (location 8), and then at the end of the line



*one-feeder secondary system

DETAIL - THREE-FEEDER SECONDARY SYSTEM

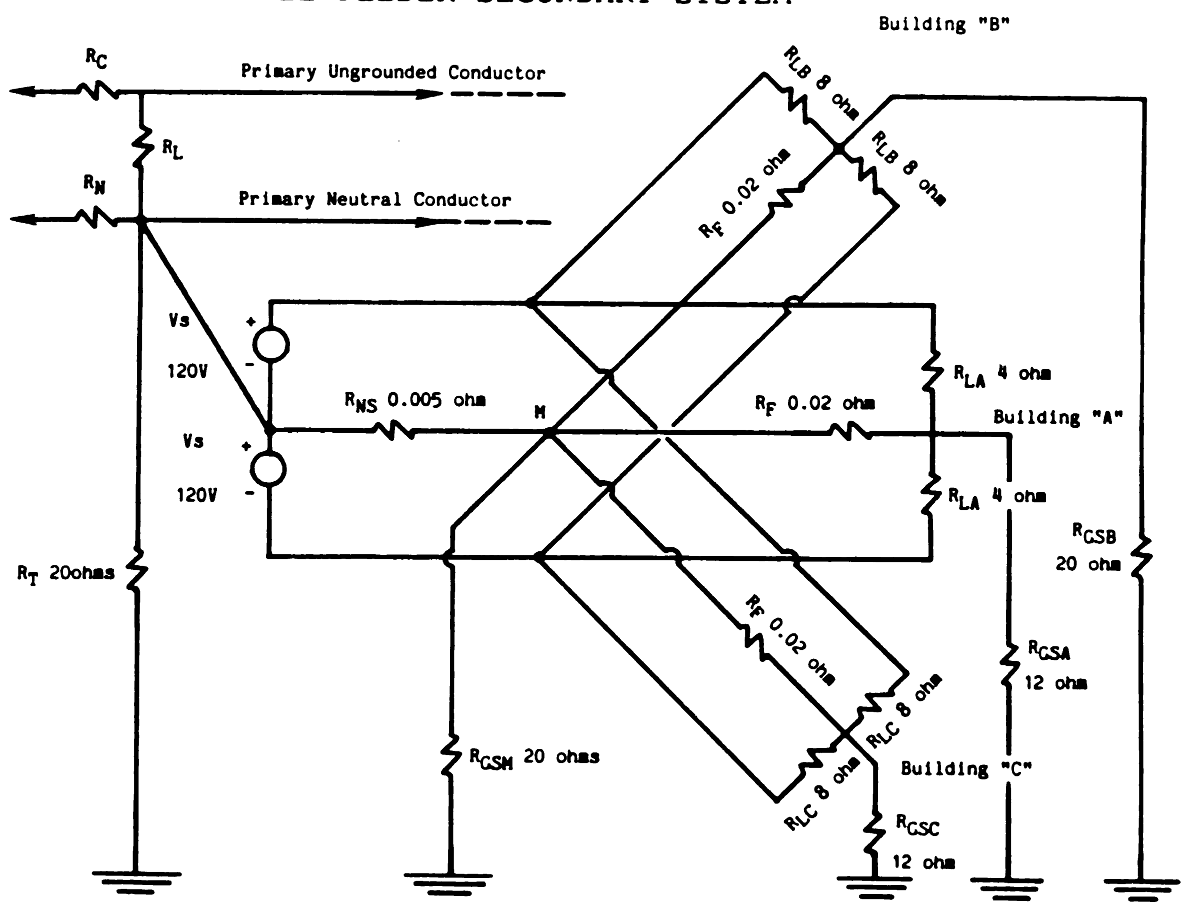
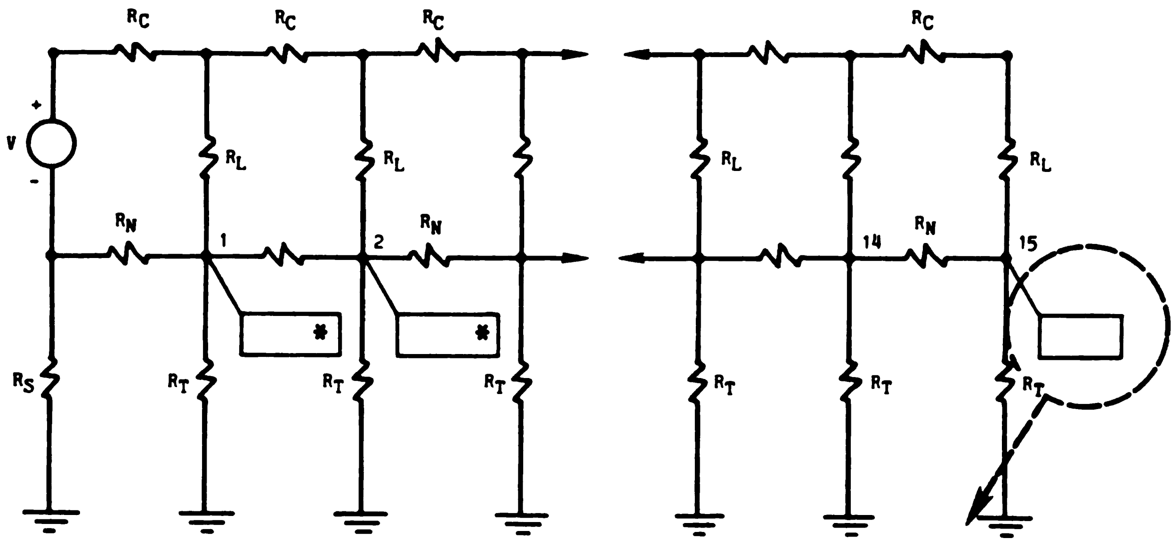


FIGURE 7. CIRCUIT E. Distribution Line Model. Distributed load along the line primary and secondary systems. Center load with three-feeders while all others are of one-feeder type.



*one-feeder secondary system

DETAIL - THREE-FEEDER SECONDARY SYSTEM

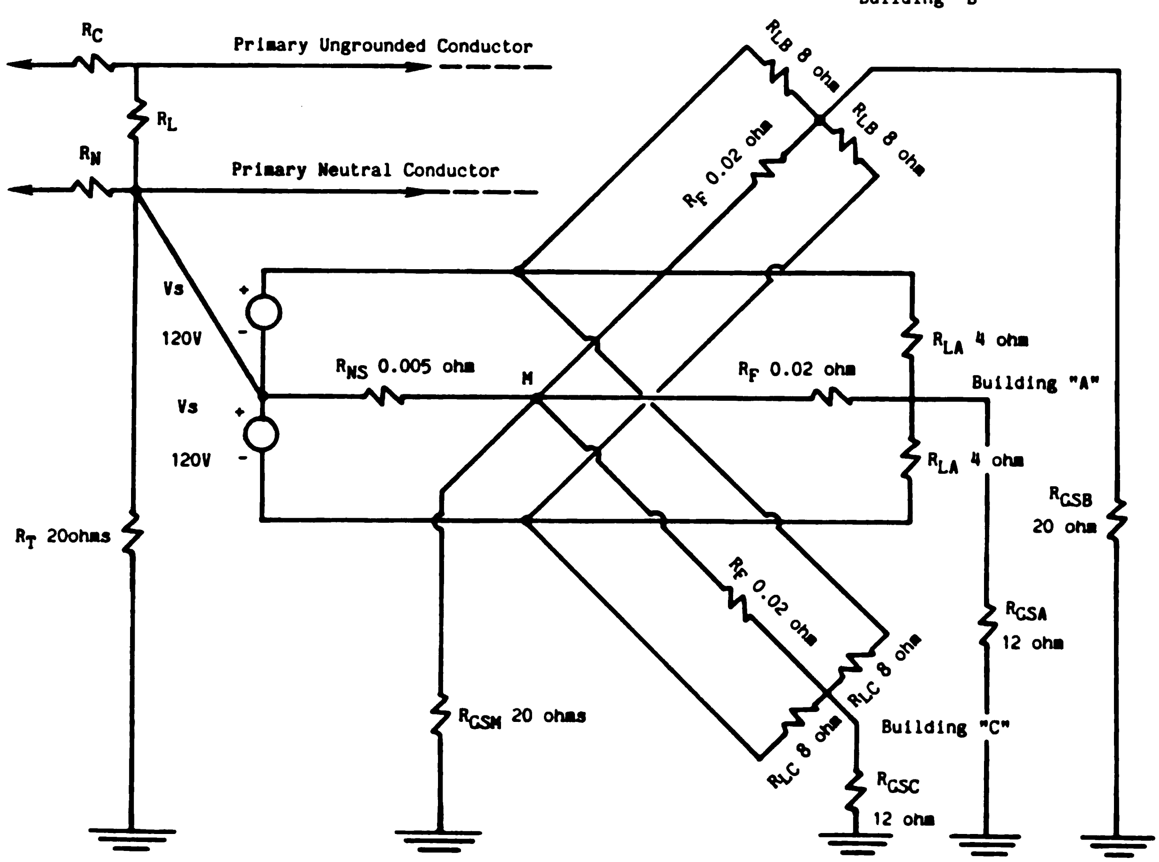


FIGURE 8. CIRCUIT F. Distribution Line Model. Distributed load along the line. Primary and secondary systems. End load with three-feeders while all other loads are of one-feeder type.

(location 15). For CIRCUIT A, the new value of resistance studied was 1 ohm. For CIRCUITS B and D, different values of transformer grounding resistance was examined at locations 1, 8, and 15. At each of these locations the transformer grounding resistance values were 0.5 ohm, 1 ohm, 5 ohms, 10 ohms, 50 ohms, and 100 ohms. The substation grounding resistance was held constant at 0.5 ohm and all other transformer grounding resistances along the lien were held constant at 20 ohms.

CIRCUIT C was used to simulate the effects of increasing number of primary neutral grounding electrodes along the line.

4.3.2 - Study of Neutral Conductor Resistance

This study demonstrated the effects of variation in the neutral conductor resistance (R_N) on the neutral-to-earth voltage along the line using the following circuit:

a. Primary neutral conductor: In CIRCUIT A (Figure 3), neutral conductor resistance, between points 7 and 8 (R_{N8}), was chosen for study because it was located in the center of the line. Its value was raised in 3 stages -- 1, 2, and 5 ohms, respectively. In CIRCUIT B, three points along the line were studied. The value of R_N was changed at each location. Larger resistance values were positioned near the substation between the substation and location 1 (R_{N1}), and then at the middle of the line between locations 7 and 8 (R_{N8}), and then at the end of the line between locations 14 and 15 (R_{N15}). The values studied were 1 ohm, 2 ohms, and 5 ohms. In CIRCUIT E, the value of R_N was changed in the segment between locations 4 and 5, and then in the segment between locations 9 and 10, and then in the segment between locations 14 and 15. Values of 0.624, 0.924, 2.0, 5.0 ohms were studied at each location.

b. Secondary neutral conductor: In this case, the loading resistance effect was studied simultaneously with secondary neutral conductor resistance effects. Secondary neutral conductor resistance of feeder A (R_{FA}), secondary system with three-feeders, (CIRCUIT E and CIRCUIT F) was changed to 0.1 ohm. This 0.1 ohm resistance simulated an excessive resistance in the secondary feeder neutral. This value was used for all loading alternatives examined (Table 1).

TABLE 1. Load in Resistance Applied at Each Building from the Ungrounded Conductor to Neutral in Figures 7 and 8

	SECONDARY UNGROUNDED CONDUCTOR TO NEUTRAL LOAD RESISTANCE					
CURVES OF FIGURES 25 - 26	BUILDING A		BUILDING B		BUILDING C	
	R_{LA1}	R_{LA2}	R_{LB1}	R_{LB2}	R_{LCA}	R_{LC2}
1	4	4	8	8	8	8
2	3	6	8	8	8	8
3	6	3	8	8	8	8
4	4	4	∞	∞	∞	∞
5	3	6	∞	∞	∞	∞
6	6	3	∞	∞	∞	∞

4.3.3 - Study of Loading Resistances

The purpose of this study was to analyze the effects of the secondary loading on the neutral-to-earth voltage. CIRCUITS E and F were examined. The feeders were simulated with balanced load, unbalanced load, and without load, according to the alternatives described in Table 1.

4.3.4 - Study of Substation Grounding Resistance

The objective was to study the effects of variations in substation grounding resistance on the profile of neutral-to-earth voltage along the distribuition line. In CIRCUIT A, CIRCUIT B, and CIRCUIT D, the values of R_S, substation resistance-to-earth, were raised in four stages: 1 ohm, 3 ohms, 5 ohms, and 10 ohms respectively.

4.3.5 - Study of Ground Faults

The purpose of this study is to demonstrate the effects of a sustained primary or secondary line-to-ground fault. CIRCUITS E and F were again examined.

In this case, a ground fault was introduced by inserting different fault resistances from the ungrounded conductor of the primary or the secondary ungrounded conductor to the earth. The following cases were simulated.

a. Primary system fault:

Primary ungrounded conductor to earth faults of 10, 50, and 100 Amperes were created at location 1, location 9, and location 15 respectively.

b. Secondary system fault:

A ground fault was created from the secondary ungrounded conductor of feeder A in Figure 7 (CIRCUIT E) on each secondary leg. Also, the simulated form with the ground fault was placed at location 2 near the substation and at location 15 at the end of the line. The faults were created with a resistance of 50 ohms, 200 ohms, and 500 ohms from the secondary ungrounded conductor to earth.

CHAPTER V

RESULTS AND DISCUSSIONS

The purpose was to study neutral-to-earth voltage effects on a single phase primary distribution line.

The objective of this study was to analyze the profile of neutral-to-earth voltage along the distribution line and to observe the influence of various sources that produce neutral-to-earth voltage.

In this chapter the simulation results are presented and analyzed.

5.1 - Simulation Results

A series of simulations were performed using circuits developed for each specific case and the computer circuit analysis program SPICE.

For each study, a base case was used; that is, line parameters, such as neutral resistance and grounding resistance were uniform along the line. A uniform base model allowed the examination of effects of changes in one variable by comparing its results to the base case results.

The neutral-to-earth voltage examined for each comparison was determined at each grounding electrode connection along the primary or secondary neutral conductor.

The results of this study are presented in the following order: (1) primary neutral grounding resistance, (2) primary neutral conductor resistance, (3) loading, (4) substation grounding resistance, (5) ground faults.

Before the results being presented, two points need to be clarified: (a) despite being plotted as continuous curves, the graphs represent discrete points of neutral-to-earth voltage along the line; (b) the changes in the direction of the neutral-to-earth voltage polarity will not be observed when one is measuring neutral-to-earth voltage along the line, because AC voltmeters give readings in effective or rms values. The curves representing neutral-to-earth voltage in this thesis are shown with an instantaneous polarity of one end of the line as compared to the other. For instance, the neutral-to-earth curve shown in Figure 9, will be observed as the curve shown in Figure 10.

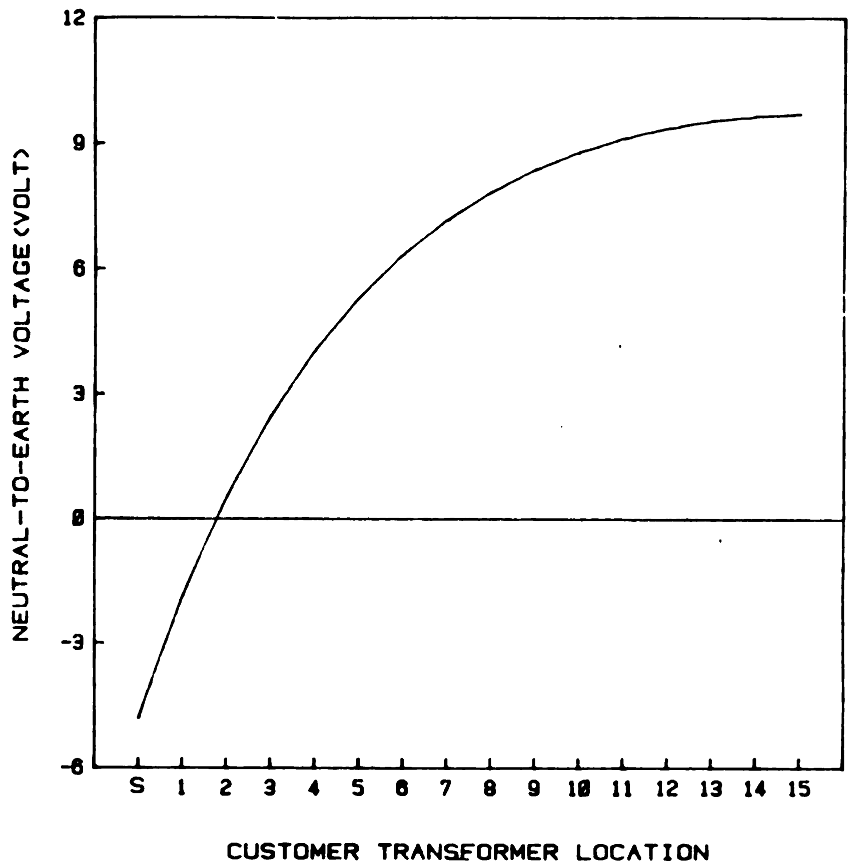


FIGURE 9. Profile of the neutral-to-earth voltage along the distribution line from the substation to the last customer-instantaneous values.

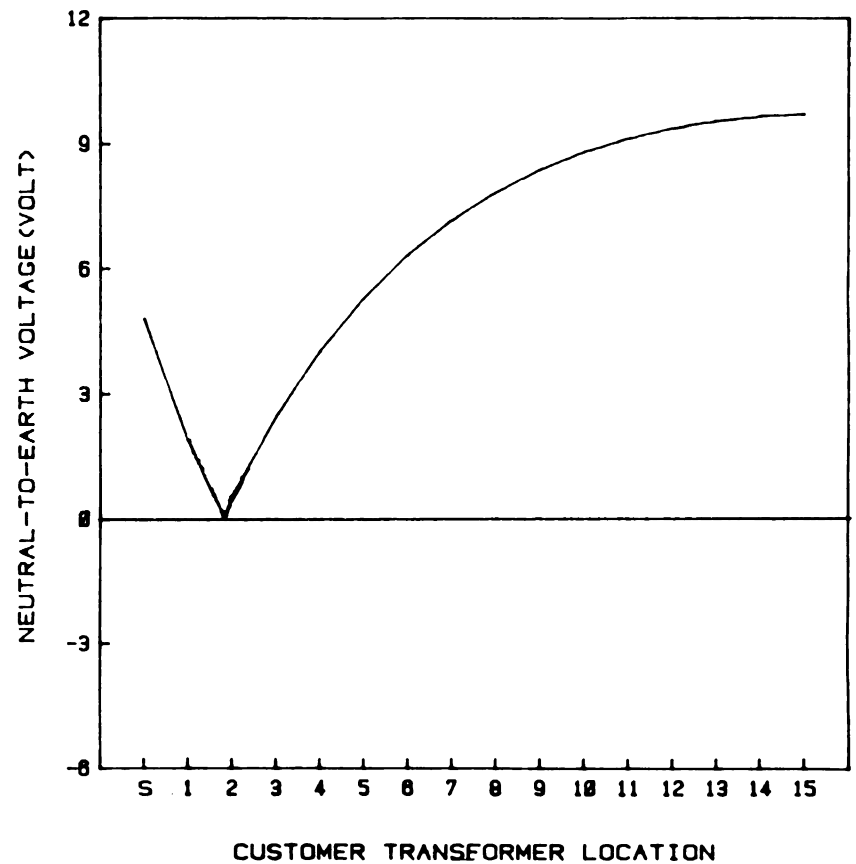


FIGURE 10. Profile of the neutral-to earth voltage along the distribution line from the substation to the last customer-rms value.

5.1.1 - Neutral/Transformer Grounding Resistance

The purpose of this study was to evaluate the effects of grounding resistance on the electrical system; that is, the effects of (R_G or R_T) changes on neutral-to earth voltage. This represents installation of a low or high impedance grounding electrode in different locations along a distribution line.

Figures 11 through 16 show the resulting simulation curves when a value of primary neutral/transformer grounding resistance was varied at one location in the following systems:

> Multi-grounded primary distribution line with a concentrated load located at the end of the line (CIRCUIT A -- Figure 3)

Figure 11 shows the primary neutral-to-earth voltage for variable neutral transformer grounding electrode resistance. For the base case, neutral/transformer grounding resistances were uniform along the line with 20 ohms each while the substation grounding resistance was 0.5 ohm. The ungrounded conductor resistance was 6.32 ohms and the primary neutral conductor resistance was 0.424 ohm between grounding electrodes. A load resistance of 432 ohms at the end of the line produced a 16.30 Amperes load. The profile shows the neutral-to-earth voltage near the substation is lower (5.59 volts) than at the end of the line (41.98 volts). The voltage reverses the polarity at

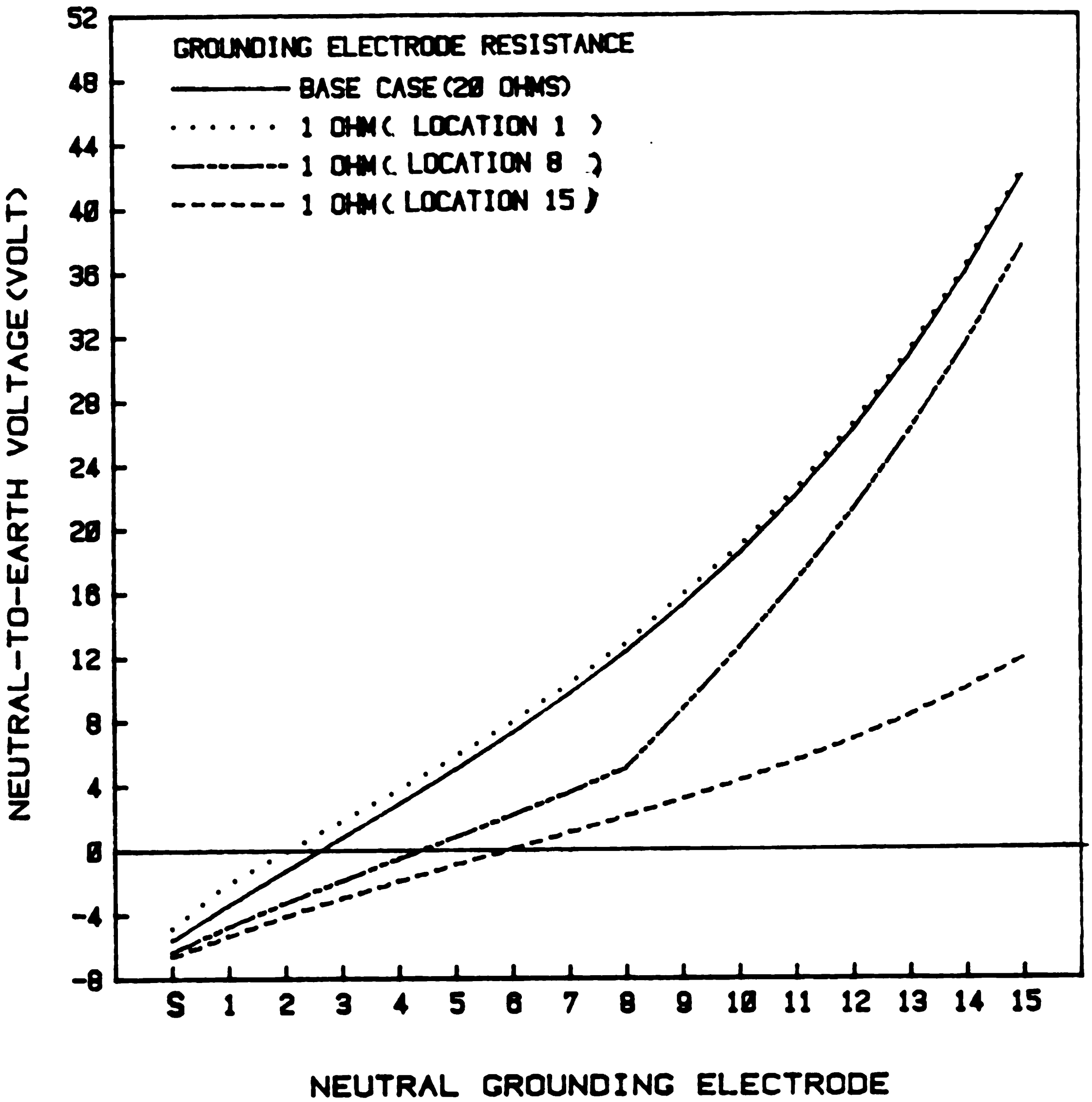


FIGURE 11. Profile of the neutral-to-earth voltage along the distribution line from the substation to a customer, at the end of the line, for variable neutral grounding electrode resistance (Distribution line model, CIRCUIT A).

or near point 3. The magnitude of neutral-to-earth voltage decreases from the substation, reaches zero near point 3, and then rises sharply to reach the maximum value at the end of the line. The neutral-to-earth voltage at point 15 is eight times greater than at the substation and has a 180^{o} phase relationship to the voltage-to-earth at the substation.

The neutral-to-earth voltage profile for the system shows minimal changes when neutral grounding resistance is lowered near the substation. Consequently, neutral-to-earth voltage was reduced at the beginning of the line, and the voltage increased at the opposite end. However, in no case was the change greater than 1.3 volts, as compared to the base case.

Lowering neutral grounding resistance near the middle of the line reduced the voltage at point 8 from the base case of 12.3 volts to 5.1 volts (59%). The effects on the distribution line diminished with distance from point 8. There was only 24% reduction at point 11 and 10% reduction at point 15. Near the substation there was an increase in the magnitude of the neutral-to-earth voltage.

When transformer grounding resistance was lowered at the end of the line, the voltage at points 4-15 was reduced; but slightly increased the magnitude of voltage near the substation. At point 15 the neutral-to-earth voltage was reduced by 30.0 volts (72%) from the base case.

Note that when the grounding resistance was lowered point 1, point zero neutral-to-earth voltage was shifted in the direction of the substation; but when the grounding was lowered at points 8 and 15, point zero neutral-to-earth voltage was shifted in the direction of the end of the line.

This study shows that for the case when primary load is applied at the end of the line, neutral-to-earth voltage is significantly reduced by lowering neutral-to-earth resistance near the load. When the neutral-to-earth resistance was reduced near the middle of the line, significant neutral-to-earth voltage reduction occurred in the local area of the reduced grounding resistance.

Multi-grounded primary distribution system with the load distributed along the line (CIRCUIT B -- Figure 4).

Figures 12 and 13 present the neutral-to-earth voltage profiles when the CIRCUIT B was studied. For the base case, equal loading was applied to each of the fifteen customer transformers by using a 6480 ohms resistances which produced 1 Ampere load. The primary ungrounded and neutral conductor resistance were 0.424 ohm between customers. The substation resistances was 0.5 ohm and each customer transformer grounding resistance had 20 ohms. The base case profile, neutral-to-earth rises sharply at first, then levels off toward the end of the line. The neutral-to-earth voltage at the substation was 4.1 volts and at the end of the line 16.6 volts. This profile can be represented with a logarithmic curve defined by the equation $y = -1.96 + 7.04 \ln X$.

Note that primary neutral-to-earth voltage asymtotically reaches a maximum voltage for this case when the load is distributed along the multigrounded line.

The customer transformer grounding resistance was altered at one location. Different values of resistances were located near the substation (location 1), and then near the middle (location 8), and then at the end of the line (location 15).

When customer grounding resistance was changed near the substation (location 1) no significant effects on the neutral-to-earth voltage, was observed.

Figure 12 shows the profile when only one transformer gounding resistance near the middle of the line (location 8) was examined. Lowering customer grounding resistance from 20 ohms to 1 ohm, decreased the neutral-to-earth voltage by 59% at that point and by 28% at the end of the line (location 15); however, when the grounding resistance was changed to 5.0 ohms, the voltage was only reduced by 18%. Increasing the customer grounding resistance from 20 ohms to 100 ohms (5 times greater) raised the neutral-to-earth voltage at this customer by only 0.8 volt.

Note that a significant reduction in neutral-to-earth voltage occured only when the resistance to earth at

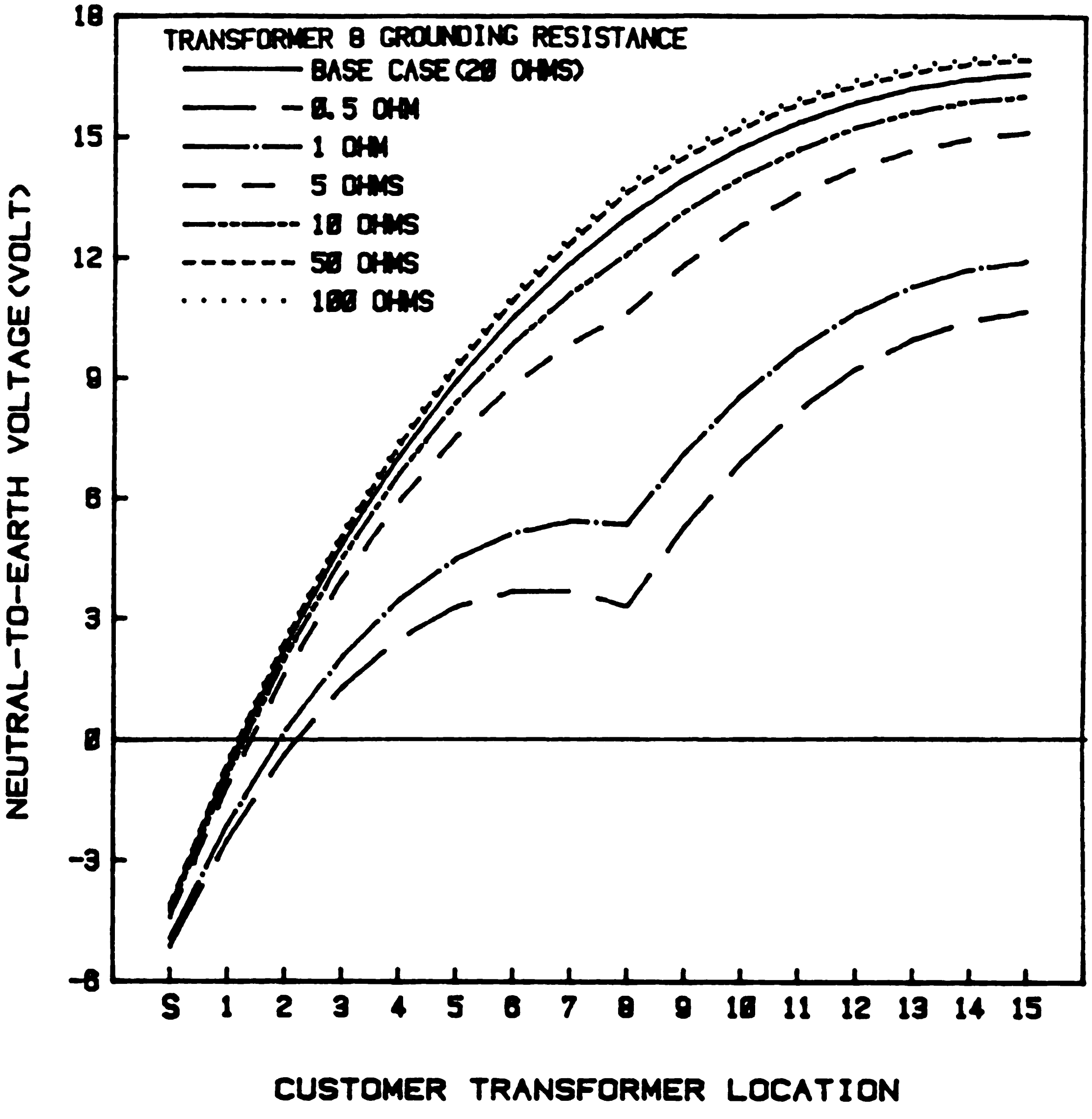


FIGURE 12. Profile of the neutral-to-earth voltage along the distribution line from the substation to the last customer for variable customer transformer grounding resistance at location 8 (Distribution line model, CIRCUIT B) with a 1 ampere primary load at each transformer.

location 8 was reduced to less than 5 ohms. The greatest reduction was in the local area of the transformer.

Figure 13 shows the voltage profiles for the system when customer grounding resistance was examined at the end of the line (location 15). Modifying the grounding resistance from 20 ohms to 1.0 ohm, reduced the neutral-to-earth voltage by 72% at this location and by 31% at location 8. For grounding resistance equal to 100 ohms,the neutral-to-earth voltage increased by 2.0 volts.

It should be noted that a significant reduction in neutral-to-earth resistance at the end of the line will result in a significant reduction in neutral to-earth voltage at the end of the line with negligible inverse in neutral-to-earth voltage magnitude at the substation.

Multi-grounded primary distribution and secondary system (CIRCUIT D -- Figure 6).

In this case, the secondary side of the distribution transformer was added at each load. It represents a 120/240 volts, single-phase, three wire, grounded system with one feeder and a balanced load. Each secondary grounding system consists of 20 ohms resistance. For the base case the customer transformer grounding resistance was kept at 20 ohms each and the value of all other line parameters remained unchanged from values of the previous study. This change had the effect of lowering the resistance to earth at each transformer location.

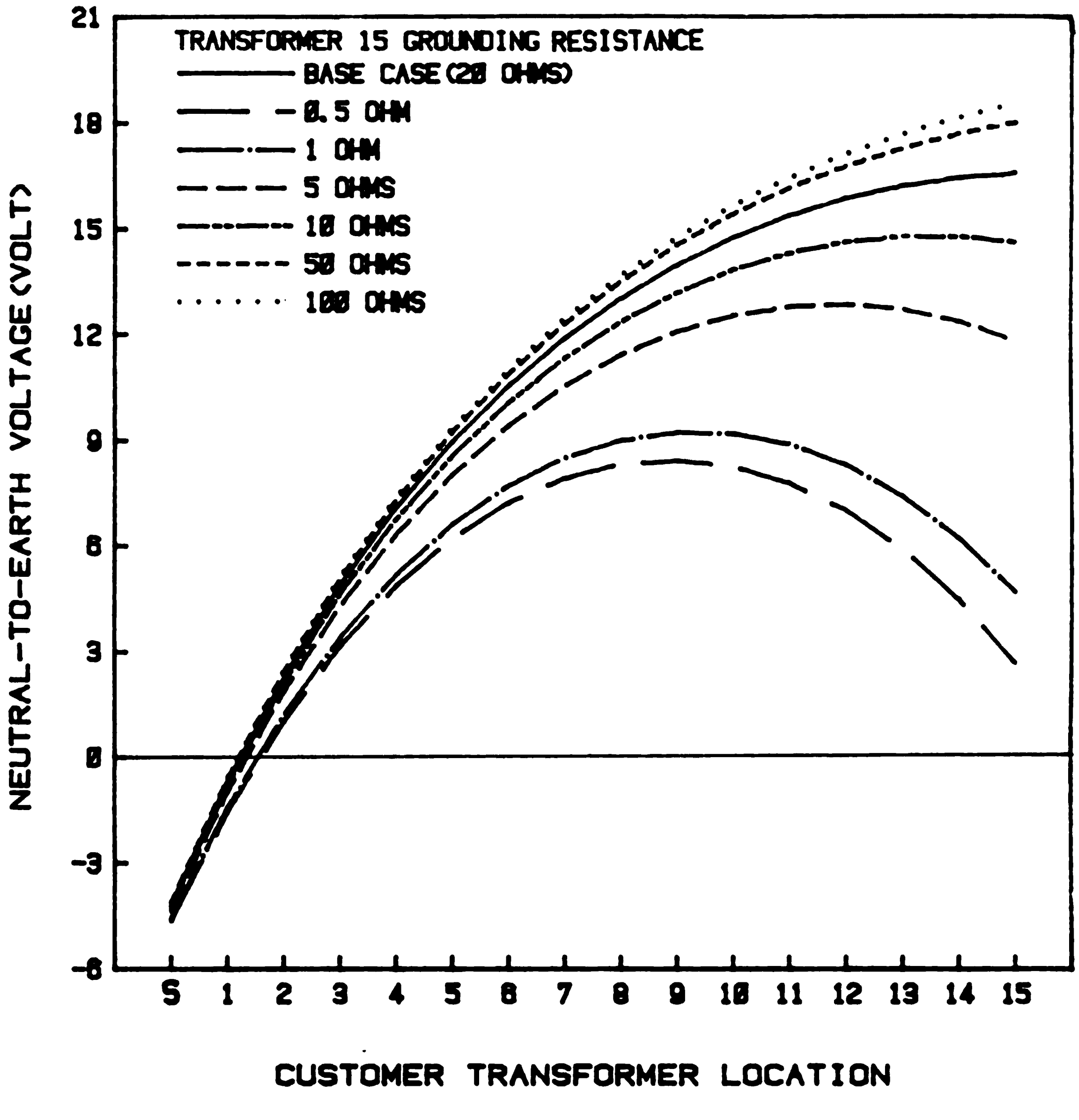


FIGURE 13. Profile of the neutral-to-earth voltage along the distribution line from the substation to the last customer for variable customer transformer grounding resistance at location 15. (Distribution line model, CIRCUIT B) with a 1 ampere primary load at each transformer.

Simulated results are presented in Figures 14 and 15, the presence of a secondary grounding system altered the neutral-to-earth voltage profile. The magnitude of the voltage at the substation 4.81 volts and at the end of the line (location 15) is 9.71 volts. It still resembles a logarithmic curve defined by expression: $y = -2.19 + 4.63 L_n X$ with an asymtotic maximum voltage. The added grounding electrodes reduced the end of line neutral-to-earth voltage by 42% as compared with the case, Figure 12.

The value of the customer grounding resistance was altered, at one location, to 0.5 ohm, 1.0 ohm, 5.0 ohms and 100 ohms, respectively.

Figure 14 shows the results when a customer grounding resistance, near the substation (location 1), was examined for the resistance value of 1.0 ohm and 0.5 ohm the magnitude of neutral-to-earth voltage, at that location, was decreased by 0.7 volts and 0.2 volts respectively. From location 2, the voltage increased at all points along the line; but always with values smaller than 1.0 volt. For the resistance value of 100 ohms, the profile is identical to the base case profile. This indicates that lowering grounding resistance near the substation has little effect on the overall neutral-to-earth voltage line.

The system profile when customer grounding resistance was altered near the middle of the line (location 8) is shown in Figure 15.

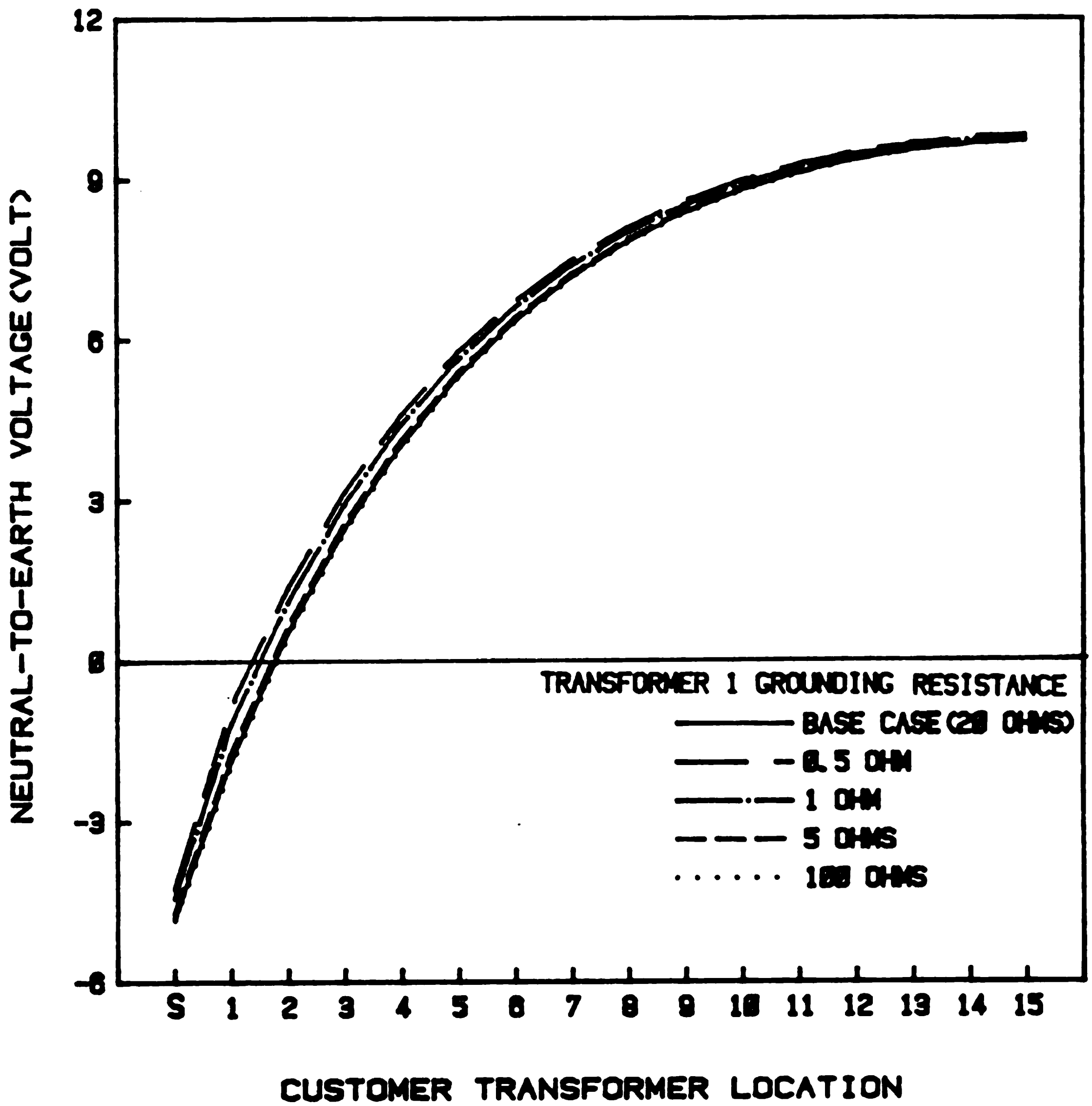


FIGURE 14. Profile of the neutral-to-earth voltage along the distribution line from the substation to the last customer for variable customer transformer grounding resistance at location 1 (Distribution line model, CIRCUIT D) with a 1 ampere primary load at each transformer.

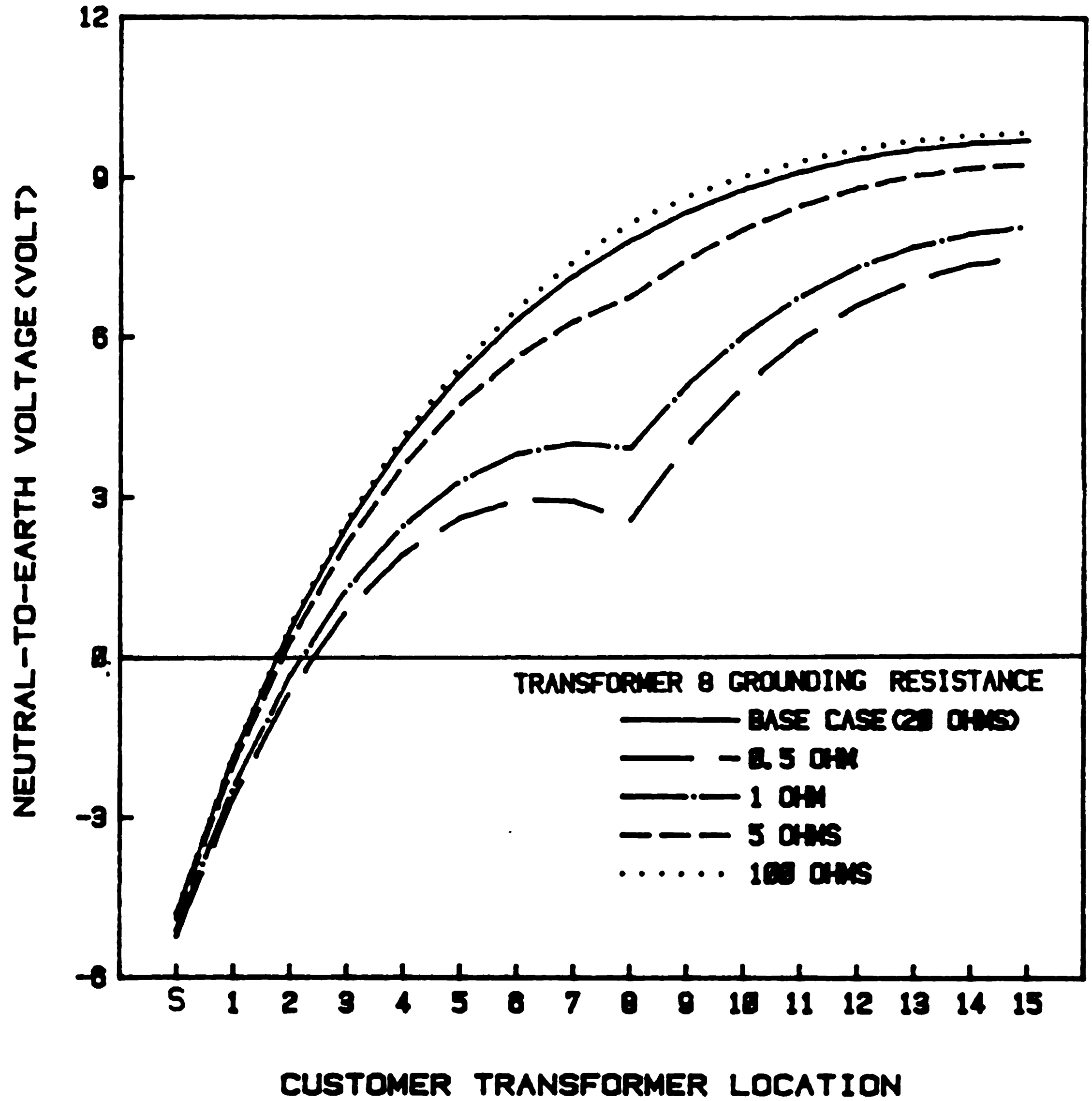


FIGURE 15. Profile of the neutral-to-earth voltage along the distribution line from the substation to the last customer for variable customer transformer grounding resistance at location 8 (Distribution line model, CIRCUIT D) with a 1 ampere primary load at each transformer.

Lowering the grounding resistance from 20 ohms to 1.0 ohm, decreased the neutral-to-earth voltage by 3.9 volts (49%) at this location, and by 1.61 volts (16%) at the end of the line (location 15). When the grounding resistance was lowered from 20 ohms to 5 ohms (25% reduction), the neutral-to-earth voltage decreased 1.1 volts. In both cases from location 2 the neutral-to-earth decreased along the line. With the customer grounding resistance equal to 100 ohms, that is, the resistance value is raised 5 times, the neutral-to-earth voltage increased from location 2 to location 15 but never greater than 0.4 volt.

Figure 16 shows the profile when transformer grounding resistance at the end of the line (location 15) was examined. Lowering the resistance from 20 ohms to 1.0 ohm, decreased the neutral-to-earth voltage, at this location by 6.2 volts (64%) and by 1.4 volts (18%) at location 8.

Changing the resistance to 5.0 ohms, the voltage decreased by 2.0 volts (20%). At the same point, the neutral-to-earth voltage increased by only 0.8 volt when the grounding resistance was 5 times greater (100 ohms).

The effect of significantly lowering the resistance-to-earth at the middle of the line and at the end of the line had the same effect as discussed earlier.

Figure 17 presents the resulting neutral-to-earth voltage profiles when CIRCUIT C (Figure 5) was examined. In this case, the number of primary grounding electrodes along the line was increased, that is, was added grounding

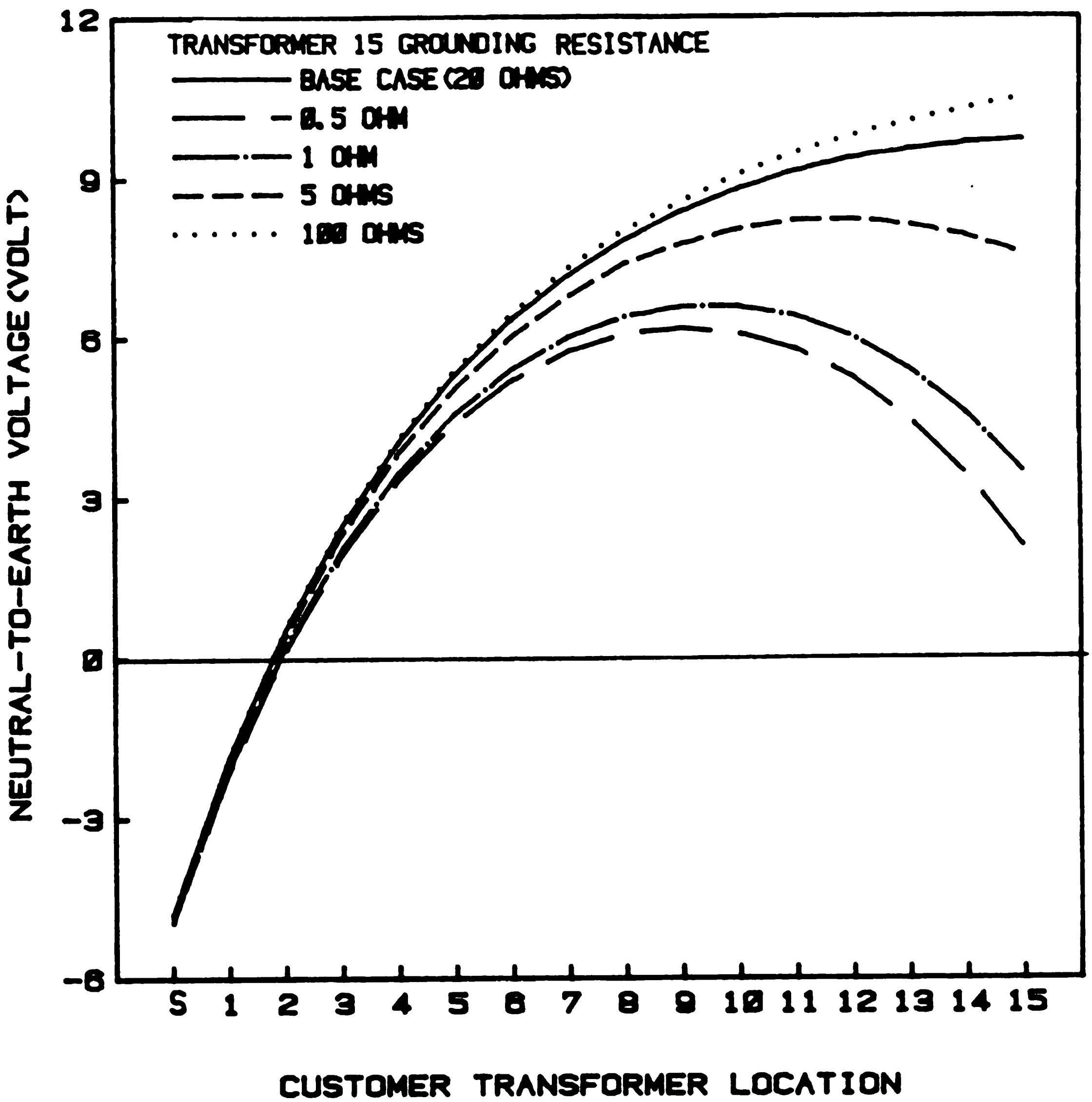


FIGURE 16. Profile of the neutral-to-earth voltage along the distribution line from the substation to the last customer for variable customer transformer grounding resistance at location 15 (Distribution line model, CIRCUIT D) with a 1 ampere primary load at each transformer.

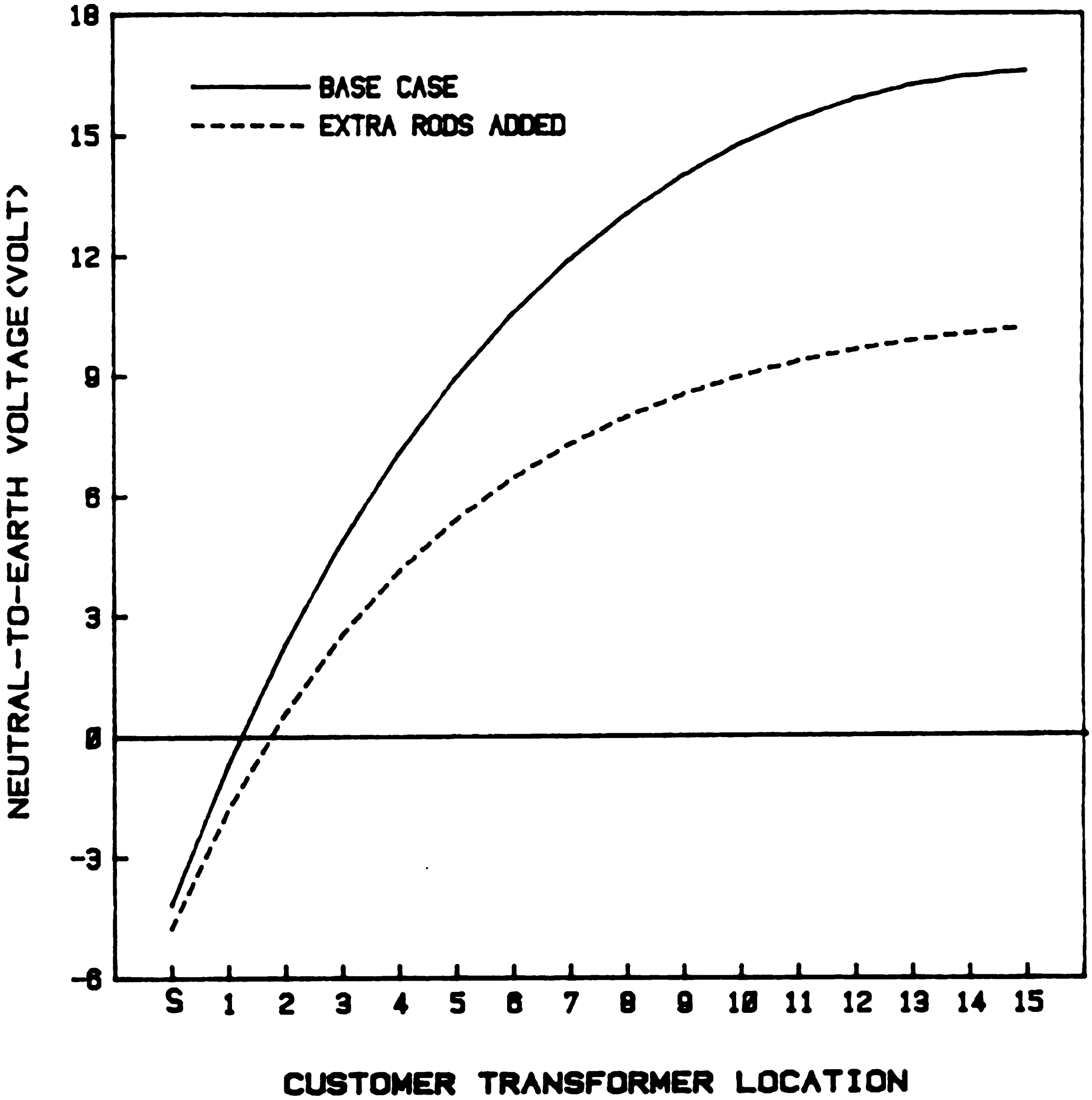


FIGURE 17. Profile of the neutral-to-earth voltage along the distribution line from the substation to the last customer with extra grounding electrodes added along the line (Distribution line model, CIRCUIT C).

resistance of 20 ohms between customers. The neutral conductor resistance was 0.212 ohms between grounding electrodes. The graph shows that the zero point of neutral-to-earth voltage, consequently, shifted away from the substation and the maximum value of neutral-to-earth voltage was reduced from 16.56 volts to 10.20 volts. Near the substation the magnitude of voltage increased by 1 volt. Lowering the grounding resistance along the line will lower the neutral-to-earth voltage.

From all results presented it is evident that changes made at one location along the line, may increase, decrease or have minimal effects on neutral-to-earth voltage at other locations. The effect is, for the most part, location-dependent; a significant reduction in one grounding resistance had a lower effect upon the total neutral-to-earth voltage of the line and a large change at the specific location. Changes made near the substation do not affect general neutral-to-earth voltage conditions over the entire line. However, when alterations were made at the end of the line, net voltage change at that point were maximized, illustrating the great sensitivity of the final location. Uniform changes made in the primary grounding system along the line implied uniform changes in the neutral-to-earth voltage levels over the whole line.

Due to a small resistance of the neutral conductor, the network of a neutral grounding system tends to behave as a set of resistances in parallel which is more apt to decrease than increase the value of each resistance.

In short, reducing resistance to earth at one customer location did have an effect upon neutral-to-earth voltage when the reduction occurred away from the substation. Customers near the substation did, however, see a slight increase in neutral-to-earth voltage.

5.1.2 - Neutral Conductor Resistance

This case evaluates the effects of a high resistance at some location along the primary or secondary neutral conductor, that is, the effects of a high resistance splice or connection. The simulated results will be presented as follows: (a) Primary Neutral Conductor Resistance and (b) Secondary Neutral Conductor Resistance.

(a) Primary Neutral Conductor Resistance

In this part the primary neutral-to-earth voltage profiles will be present when a value of primary neutral conductor resistance was altered at one location. Figure 18 shows the results when the effects in CIRCUIT A (Figure 3) were analyzed. In this case the neutral conductor resistance, between points 7 and 8 was changed to 1 ohm, 2 and 5 ohms and all other neutral conductor resistances are left at 0.424 ohm. At the location of the high resistance

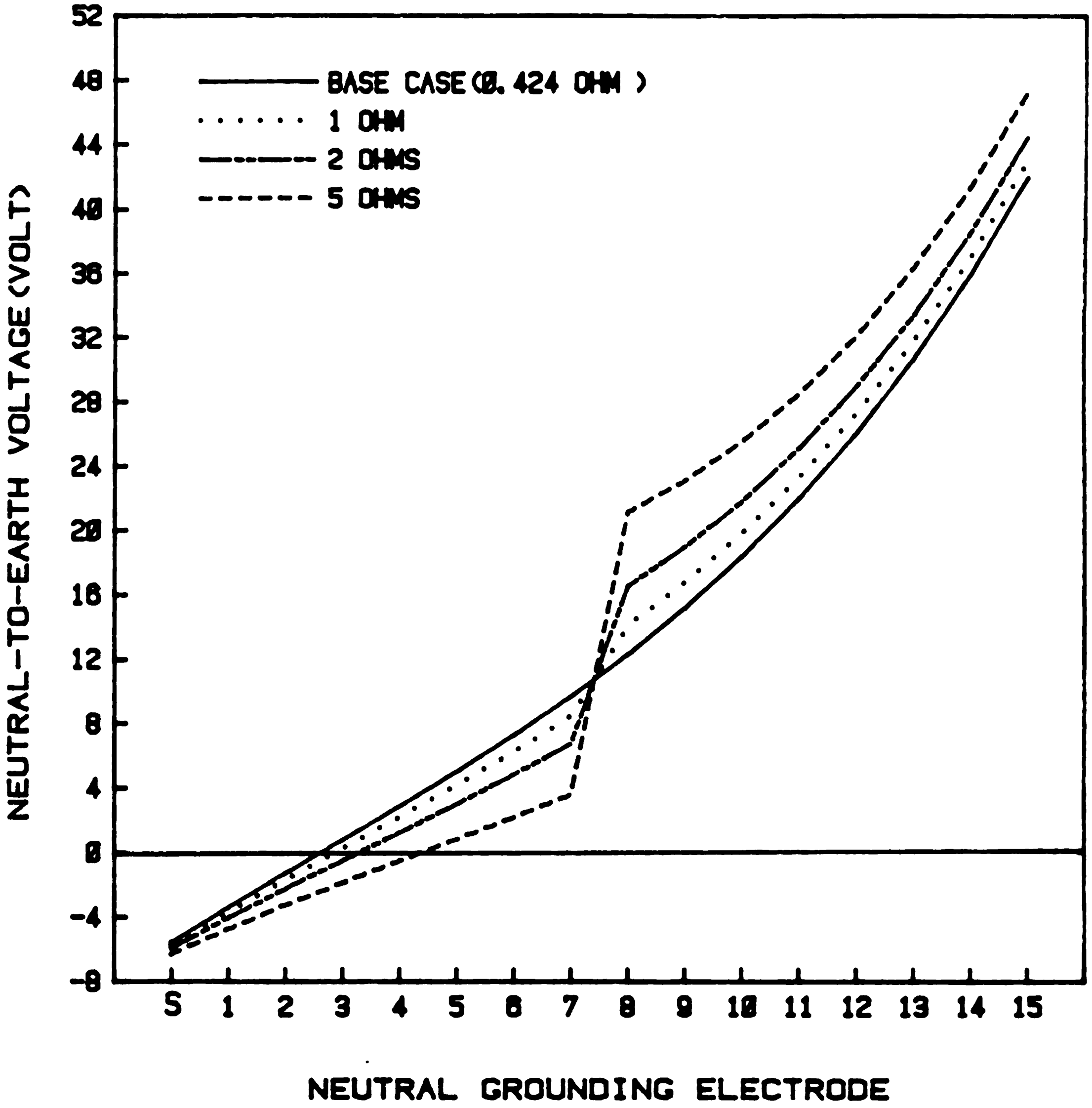


FIGURE 18. Profile of the neutral-to-earth voltage along the distribution line from substation to a cuatomer at the end of the line with variable neutral conductor resistance between locations 7 and 8 (Distribution line model, CIRCUIT A).

the voltage drop across the points 7 and 8 increased. The effects were diminished away from those points. When the resistance was increased to 5 ohms, the voltage sharply changed; decreased the neutral-to-earth voltage by 6.0 volts at point 7 and increased the voltage by 9.0 volts at point 8. The total voltage drop across the line was increased for all values studied.

The simulation results, when the effects of variation in the neutral conductor resistance (R_N) was studied, using the CIRCUIT B (Figure 4) are shown in Figures 19 and 20. The new values of resistances studied were 1 ohm, 2 and 5 ohms.

Figure 19 shows the results when neutral conductor resistance between substation and location 1 was changed. The neutral-to-earth voltage increased at all points along the line. When the value of neutral conductor resistance is increased, the point zero neutral-to-earth voltage is shifted in direction to the source. When the R_{N1} was changed to 5.0 ohms the magnitude of voltage increased by 2.2 volts at the substation, and by 11.2 volts at location 1. The voltage drop across this segment of the line is 18.0 volts.

The results when the conductor neutral resistance between locations 7 and 8 was examined are shown in Figure 20. For the base case, the voltage drop across the segment between locations 7 and 8 is 1.1 volts. When the resistance value was changed to 5 ohms, the voltage drop

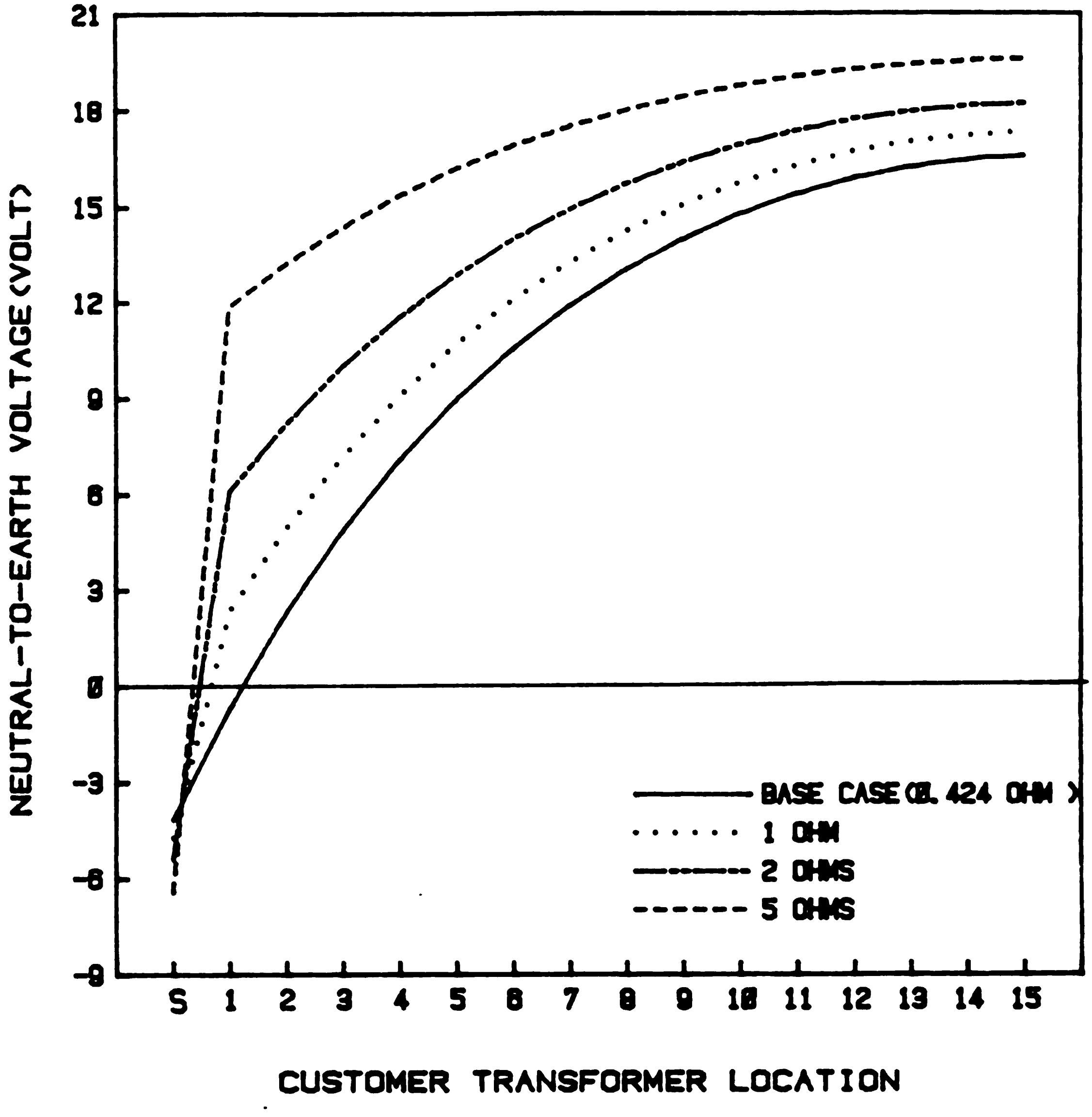


FIGURE 19. Profile of the neutral-to-earth voltage along the distribution line from substation to the last customer with variable neutral conductor resistance between the substation and location 1 (Distribution line model, CIRCUIT B).

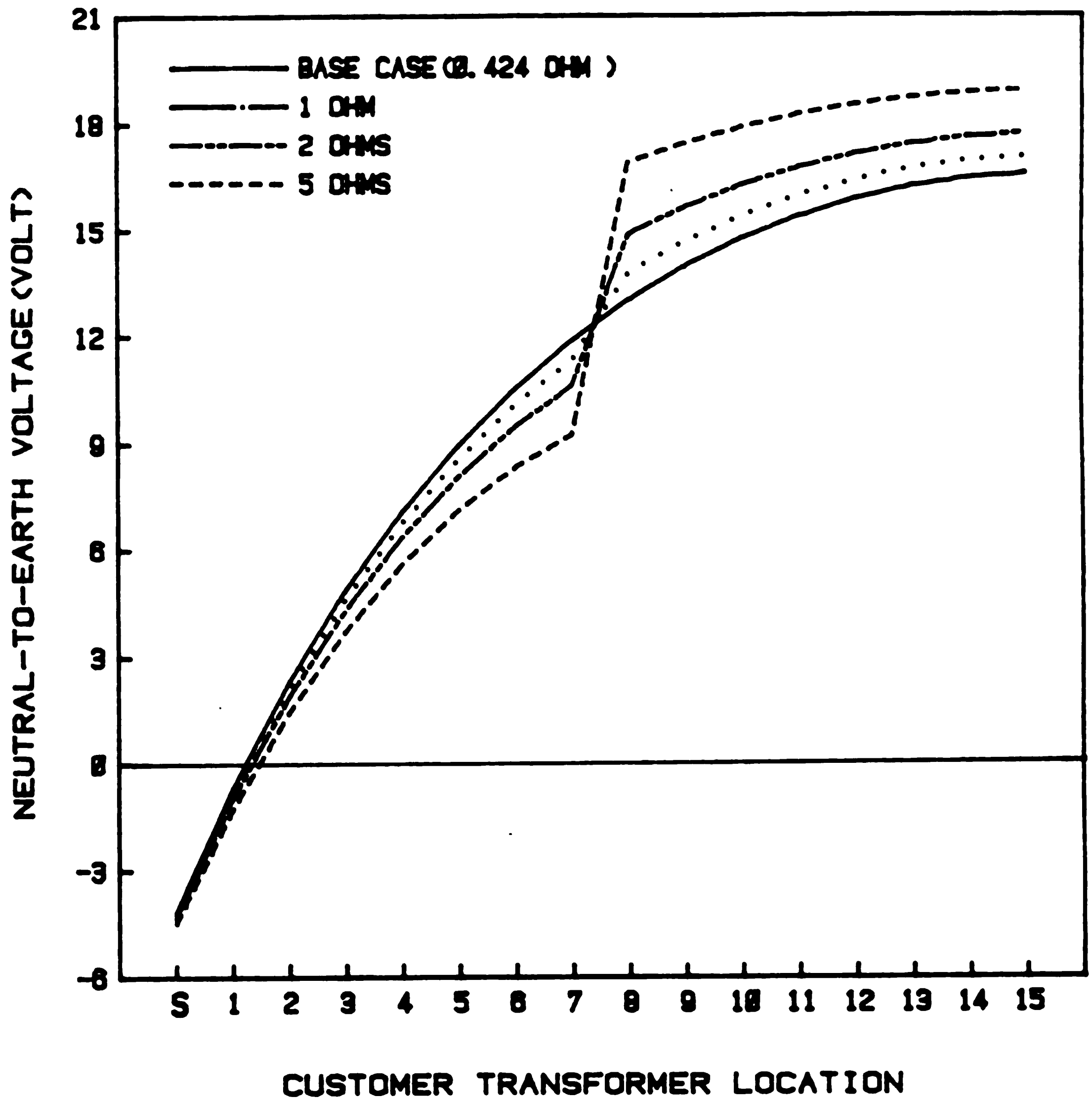


FIGURE 20. Profile of the neutral-to-earth voltage along the distribution line from the substation to the last customer for variable neutral conductor resistance between the locations 7 and 8 (Distribution line model, CIRCUIT B).

across the same segment changed to 7.6 volts. The voltae decreased by 3.0 volts at location 7 and increased by 4.0 volts at location 8.

When the neutral resistance between locations 14 and 15 was changed to 1 ohm, 2 and 5 ohms the voltage profile for the system was almost identical to the base case profile. At locatins 14 and 15 more effect occurred. However, in no case was the change greater than 0.9 volt.

Figures 21 and 22 present the resulting profiles when CIRCUIT D (Figure 6) was utilized for study. Again, the resistance values used were 1 ohm, 2 and 5 ohms.

When neutral conductor resistance between the substation and location 1 (Figure 21) was changed to 5 ohms the magnitude of the neutral-to-earth voltage increased by 2.2 volts at the substation and 4.3 volts at location 1. The neutral-to-earth voltage increased at all locations along the line. The voltage drop across the segment between the substation and location 1 is 13.2 volts.

Figure 22 shows the results when the neutral resistance between locations 7 and 8 was changed. The neutral-to-earth voltage decreased by 1.4 volts at location 7 and increased by 1.7 volts at location 8. The voltage drop across the segment between locatins 7 and 8 is 3.8 volts.

When the neutral resistance was changed at the last span of the line (between locations 14 and 15, the

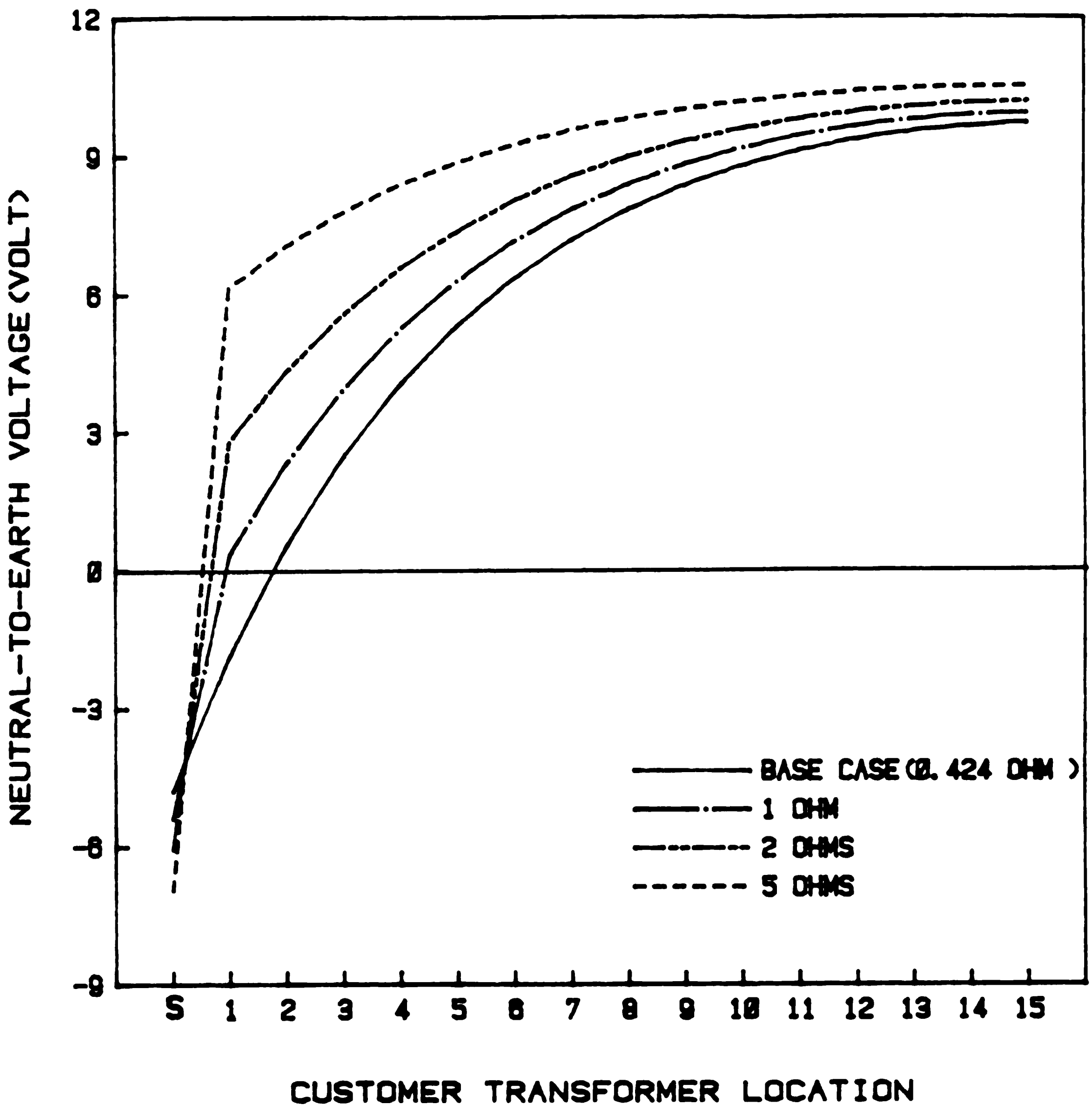


FIGURE 21. Profile of the neutral-to-earth voltage along the distribution line from the substation to the last customer for variable neutral conductor resistance between the substation and location 1 (Distribution line model, CIRCUIT D).

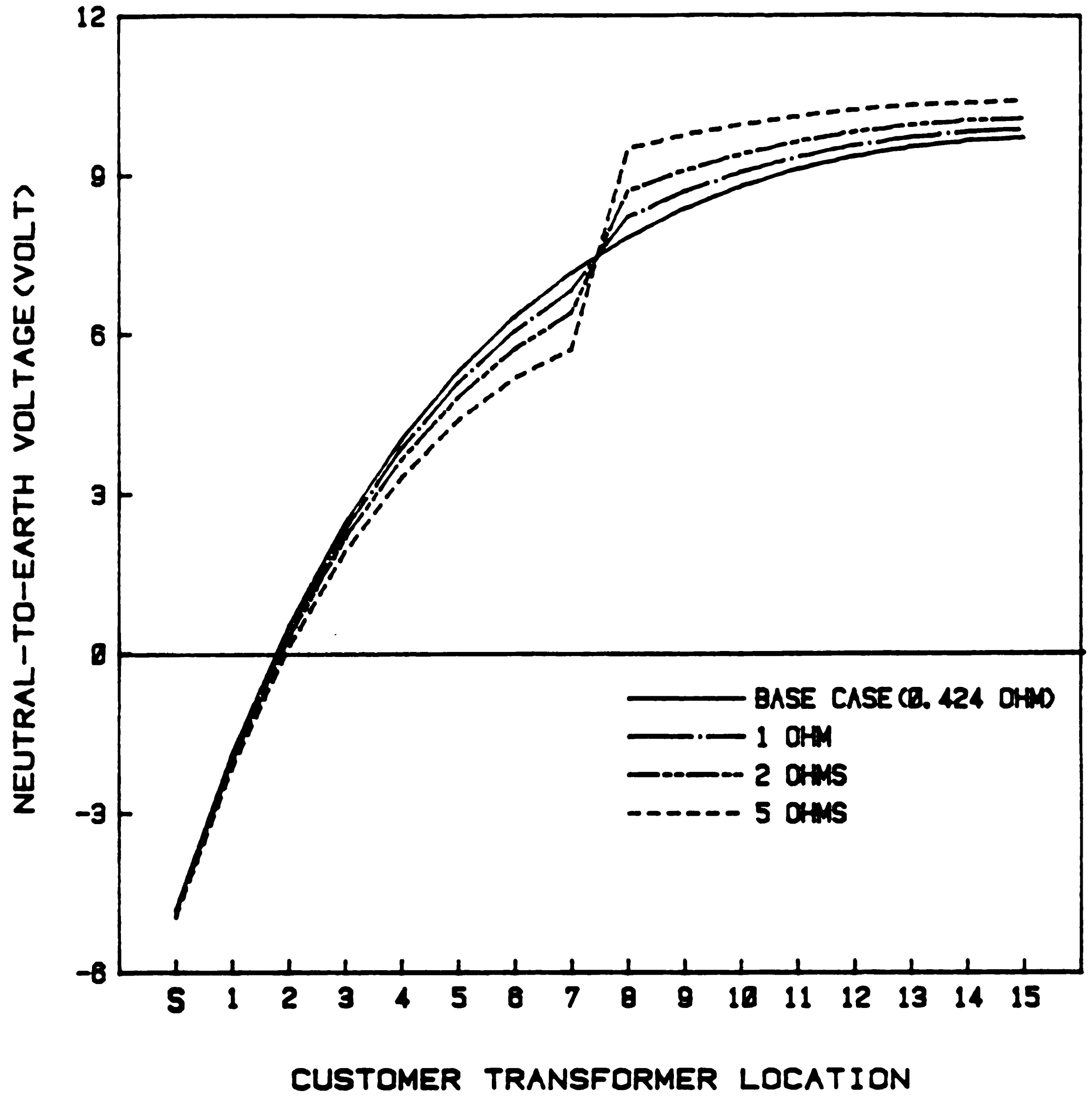


FIGURE 22. Profile of the neutral-to-earth voltage along the distribution line from the substation to the last customer for variable neutral conductor resistance between the locations 7 and 8 (Distribution line model, CIRCUIT D)

neutral-to-earth voltage profiles were almost identical to the base case profile.

CIRCUIT E (Figure 7) was analyzed with different resistance values (0.624, 0.926 ohm, 2 and 5 ohms). The results are shown in Figures 23 and 24.

Figure 23 shows the results when the neutral resistance between the locations 4 and 5 was changed. When the resistance value was altered to 5 ohms the voltage decreased 2.5 volts at location 4 and increased 2.8 volts at location 5. The voltage drop across this neutral segment is 5 times greater than the voltage drop across the same segment for the base case. The voltage at the end of the line increased by only 0.6 volt. When the resistance was changed to 0.924 ohm the voltage drop across the same segment is only 2 times greater than the voltage drop for the base case.

Figure 24 presents the results when the neutral resistance was changed between locations 9 and 10. For resistance value of 5 ohms, the neutral-to-earth voltage at location 9 decreased by 1.0 volt and at location 10 the voltage increased by 1.3 volts. The drop across this location is 5.6 times greater than the voltage drop for the base case. The voltage at the end of the line increased by only 0.8 volt. When the resistance was changed to 0.924 ohm the voltage drop was only 2 times greater than the voltage drop across this segment for the base case.

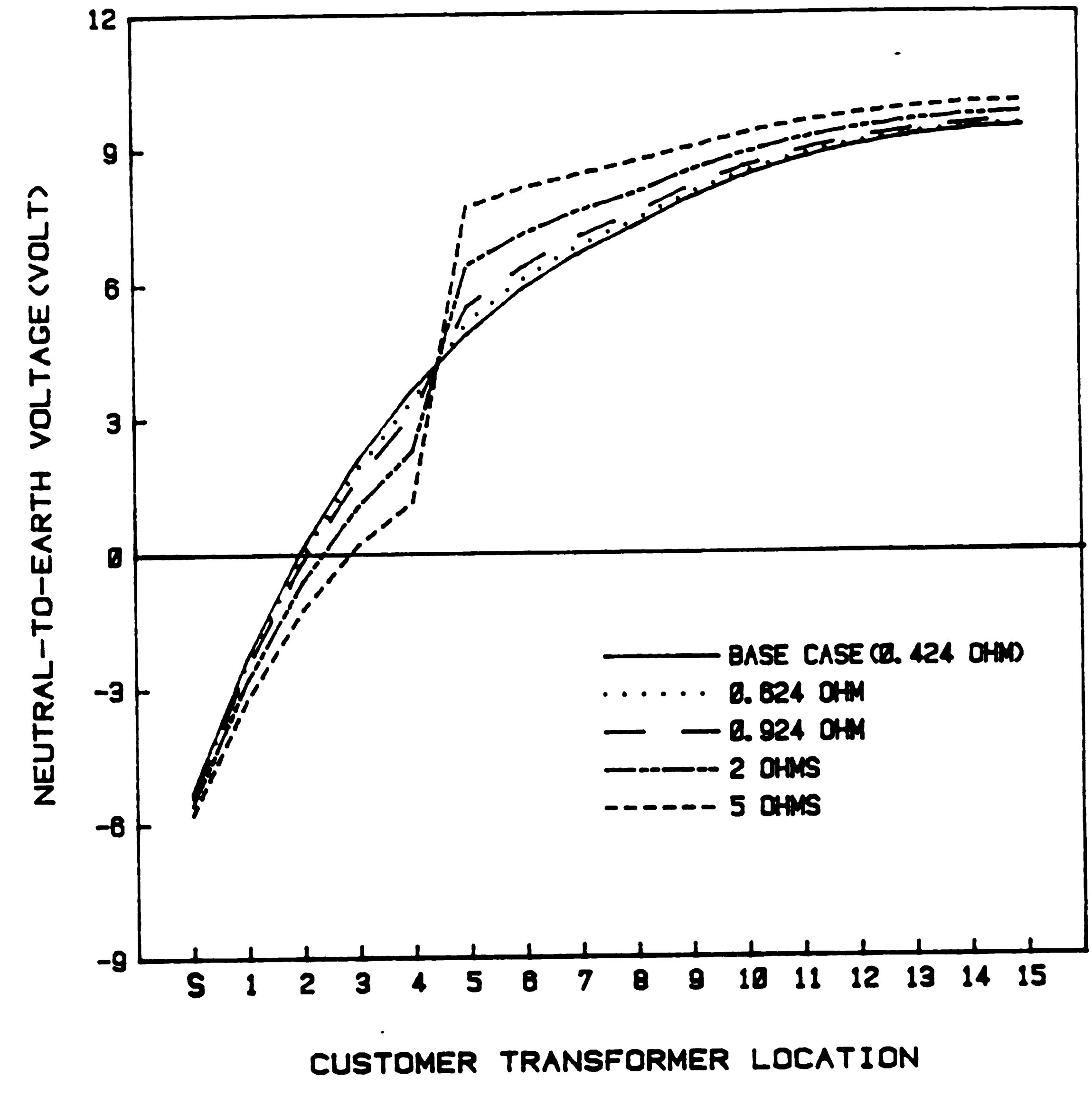


FIGURE 23. Profile of the neutral-to-earth voltage along the distribution line from the substation to the last customer for variable neutral conductor resistance between locations 4 and 5 (Distribution line model, CIRCUIT E, center load with three feeders).

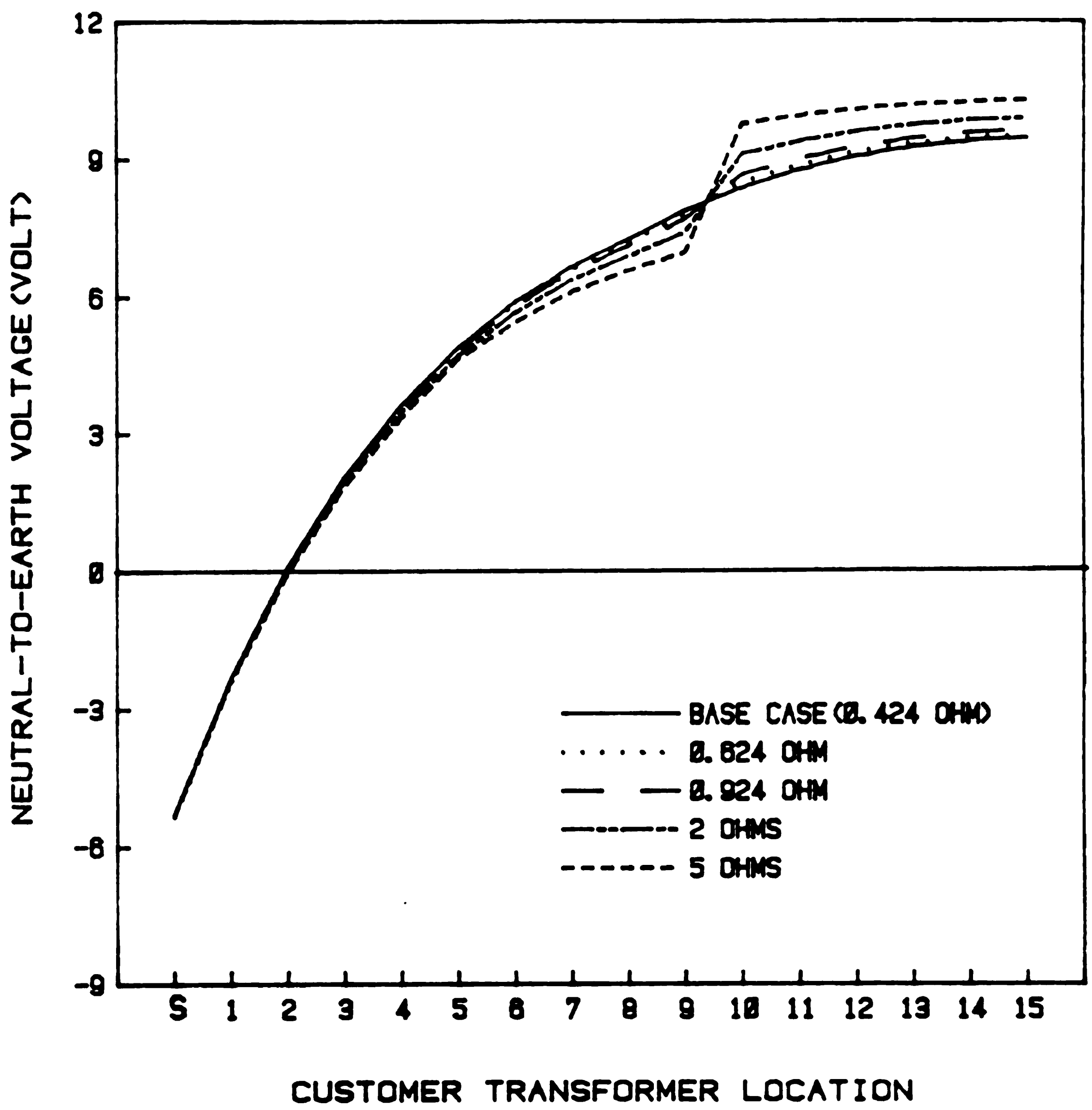


FIGURE 24. Profile of the neutral-to-earth voltage along the distribution line from the substation to the last customer for variable neutral conductor resistance between location 9 and 10 (Distribution line model, CIRCUIT E, center load with three feeders).

Again, the profile remained almost identical to the base case profile when the neutral resistance at the last span of the line was altered.

(b) Secondary Neutral Conductor Resistance

The CIRCUIT E (Figure 7) and CIRCUIT F (Figure 8) were utilized in this study. In both circuits, for the base case the neutral conductor resistances between the metering point and buildings A, B, and C were 0.02 ohms. The neutral conductor resistance at feeder A was changed to 0.10 ohm. As this study was done simultaneously with the loading study, the secondary neutral conductor was examined using the three feeder circuits with a balanced load, an unbalanced load and without a load, following the alternatives stated in Table 1.

For all load cases studied, the primary neutral-to-earth voltage along the line essentially did not differ from the values of their correspondent base case profile as shown in Table 2.

Tables 3 and 4 summarize the results of neutral-to-earth voltages at the transformer (VTE), meter (VME), building A (VAE), building B (VBE), and building C (VCE) with different farm building loads, and different values of neutral conductor resistance at building A.

Effects more significant were presented at buidling A (VAE) when feeder A was simulated with an unbalanced load.

TABLE 2. Effects of secondary neutral voltage drop on neutral-to-earth voltage along the line with the secondary voltage drop created at location 8.

LOCATION	CUSTOMER BUILDING LOADS					
	BALANCED		UNBALANCED 1		UNBALANCED 2	
	NEUTRAL RESISTANCE (OHM) - BUILDING A					
	0.02	0.1	0.02	0.1	0.02	0.1
SUBSTATION	-5.30	-5.30	-5.30	-5.31	-5.30	-5.30
1	-2.31	-2.31	-2.32	-2.33	-2.30	-2.29
2	.11	.11	.10	.07	.12	.14
3	2.06	2.06	2.05	2.01	2.08	2.11
4	3.63	3.63	3.61	3.57	3.65	3.70
5	4.89	4.89	4.86	4.81	4.91	4.97
6	5.89	5.89	5.85	5.79	5.92	5.99
7	6.66	6.66	6.62	6.54	6.71	6.79
8	7.26	7.26	7.21	7.10	7.31	7.41
9	7.89	7.89	7.84	7.76	7.93	8.02
10	8.38	8.39	8.35	8.28	8.42	8.49
11	8.77	8.77	8.74	8.68	8.80	8.86
12	9.06	9.06	9.03	8.98	9.08	9.14
13	9.27	9.27	9.24	9.20	9.29	9.34
14	9.40	9.40	9.38	9.33	9.42	9.47
15	9.47	9.47	9.44	9.40	9.49	9.53

* see CIRCUIT E - Figure 7 (loaded three-feeders)

TABLE 3. Neutral-to-Earth Voltage for Different System Loading and Neutral Conductor Resistances Three Feeders Secondary System at the Middle of the Line

CUSTOMER BUILDING LOADS			NEUTRAL RESISTANCE BUILDING A	NEUTRAL-TO-EARTH VOLTAGES (V)				
A	B	C		VTE	VME	VAE	VBE	VCE
BAL	BAL	BAL	.02	7.26	7.25	7.24	7.24	7.24
			.10	7.26	7.25	7.23	7.24	7.24
UNB1	BAL	BAL	.02	7.21	7.30	7.68	7.29	7.28
			.10	7.10	7.20	9.02	7.20	7.20
UNB2	BAL	BAL	.02	7.31	7.20	6.79	7.19	7.19
			.10	7.42	7.31	5.37	7.31	7.30
BAL	NONE	NONE	.02	6.39	6.39	6.34	6.38	6.38
			.10	6.39	6.39	6.34	6.38	6.38
UNB1	NONE	NONE	.02	6.34	6.43	6.82	6.43	6.42
			.10	6.24	6.33	8.16	6.32	6.32
UNB2	NONE	NONE	.02	6.44	6.34	5.93	6.33	6.33
			.10	6.55	6.45	4.51	6.44	6.44

<u>NOTE:</u> See List of Symbols and

CIRCUIT E - Figure 7

TABLE 4. Neutral-to-Earth Voltage for Different System Loading and Neutral Conductor REsistance Three Feeders Secondary System at the End of the Line

FARM BUILDING LOADS			NEUTRAL RESISTANCE	NEUTRAL-TO-EARTH VOLTAGES (V)				
A	B	C	BUILDING A	VTE	VME	VAE	VBE	VCE
BAL	BAL	BAL	.02	8.36	8.34	8.33	8.34	8.33
			.10	8.36	8.35	8.30	8.34	8.34
UNB1	BAL	BAL	.02	8.28	8.36	8.74	8.36	8.35
			.10	8.12	8.20	10.00	8.20	8.20
UNB2	BAL	BAL	.02	8.43	8.32	7.92	8.32	8.31
			.10	8.60	8.50	6.50	8.50	8.50
BAL	NONE	NONE	.02	6.93	6.92	6.91	6.92	6.91
			.10	6.94	6.93	6.89	6.92	6.92
UNB1	NONE	NONE	.02	6.85	6.94	7.33	6.94	6.93
			.10	6.70	6.78	8.60	6.77	6.77
UNB2	NONE	NONE	.02	7.01	6.90	6.50	6.90	6.89
			.10	7.08	7.08	5.13	7.07	7.06

<u>NOTE:</u> See List of Symbols and

CIRCUIT F - Figure 8

However, effects were much less significant at the other points, and when the circuit had a balanced load. It suggests that the effect on neutral-to-earth voltage of a high resistance in the secondary neutral conductor is aggravated when the circuit has an unbalanced load.

Changes made on primary neutral conductor resistance at one location resulting in improving on neutral-to-earth voltage at some locations, worsen at other locations or do not affect neutral-to-earth voltage conditions along the line. The voltage drop across the section which has the high resistance greatly increases. The effects are more pronounced near the substation than at the end of the line, where changes imply minimal alterations.

Changes made on the secondary neutral conductor does not affect the primary neutral-to-earth voltage along the line. The effect is localized and the presence of an unbalanced system can increase or decrease the secondary neutral-to-earth voltage. The effects at other points on the circuit are negligible.

5.1.3 - Loading Resistance

CIRCUIT E (Figure 7) and CIRCUIT F (Figure 8) were used in this study. Six different alternatives of loading (presented in Table 1) were used to test the effects of changing secondary load on the neutral-to-earth voltage. The results are presented in Figures 25 and 26. The six

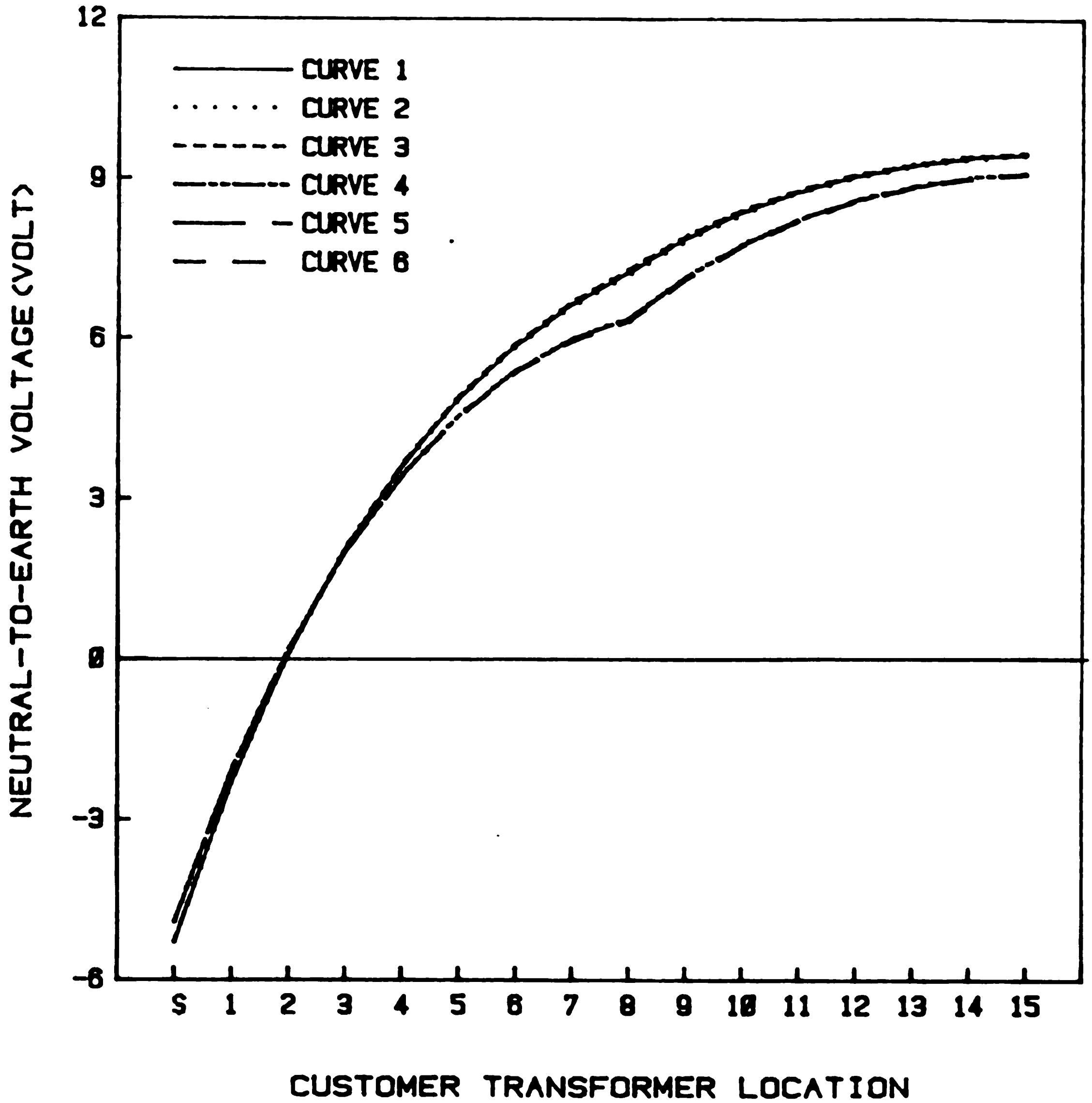


FIGURE 25. Profile of the neutral-to-earth voltage along the distribution line from the substation to the last customer for variable single customer loading at location 8 (Distribution line model, CIRCUIT E, center load with three feeders).

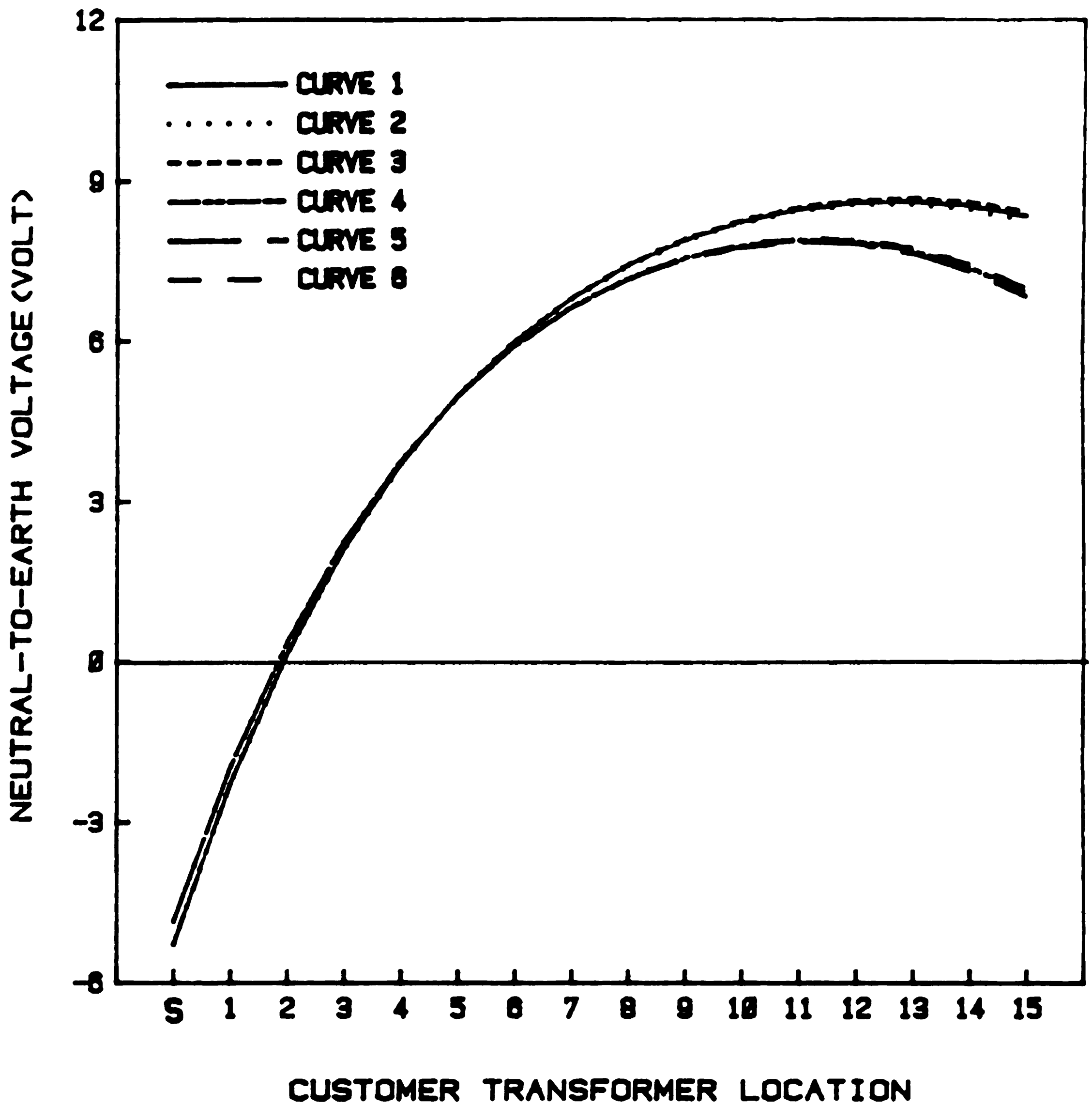


FIGURE 26. Profile of the neutral-to-earth voltage along the distribution line from the substation to the last customer for variable single customer loading at location 15 (Distribution line model, CIRCUIT E, end load with three feeders).

curves presented in those figures are defined in Table 1, according to customer building loads. Curves 1, 2, and 3 correspond to the secondary system with three loaded feeders (transformer primary current equal to 2 Amperes) and curves 4, 5, and 6 correspond to the secondary system with one loaded feeder and two unloaded feeders (transformer primary current equal to 1 Ampere).

It can be seen, for both circuits, that decreasing the load of customer 8 or customer 15, the neutral-to-earth voltage decreased (comparing curves 1 and 4). The effects on the distribution line diminished with the distance from the transformer which had its load altered.

5.1.4 - Substation Grounding Resistance

This case evaluates the effects of substation grounding resistance (R_S) on neutral-to-earth voltage along the distribution line.

Figure 27 shows the results when the CIRCUIT A (Figure 3) was examined with different values of substation grounding resistance (1, 3, 5, and 10 ohms). When the resistance was changed form 0.5 ohm to 10 ohms, that is, it was increased 20 times, the magnitude of neutral-to-earth voltage increased 20.1 volts (5 times bigger) at the substation. However, the voltage at the end of the line decreased 5.5 volts.

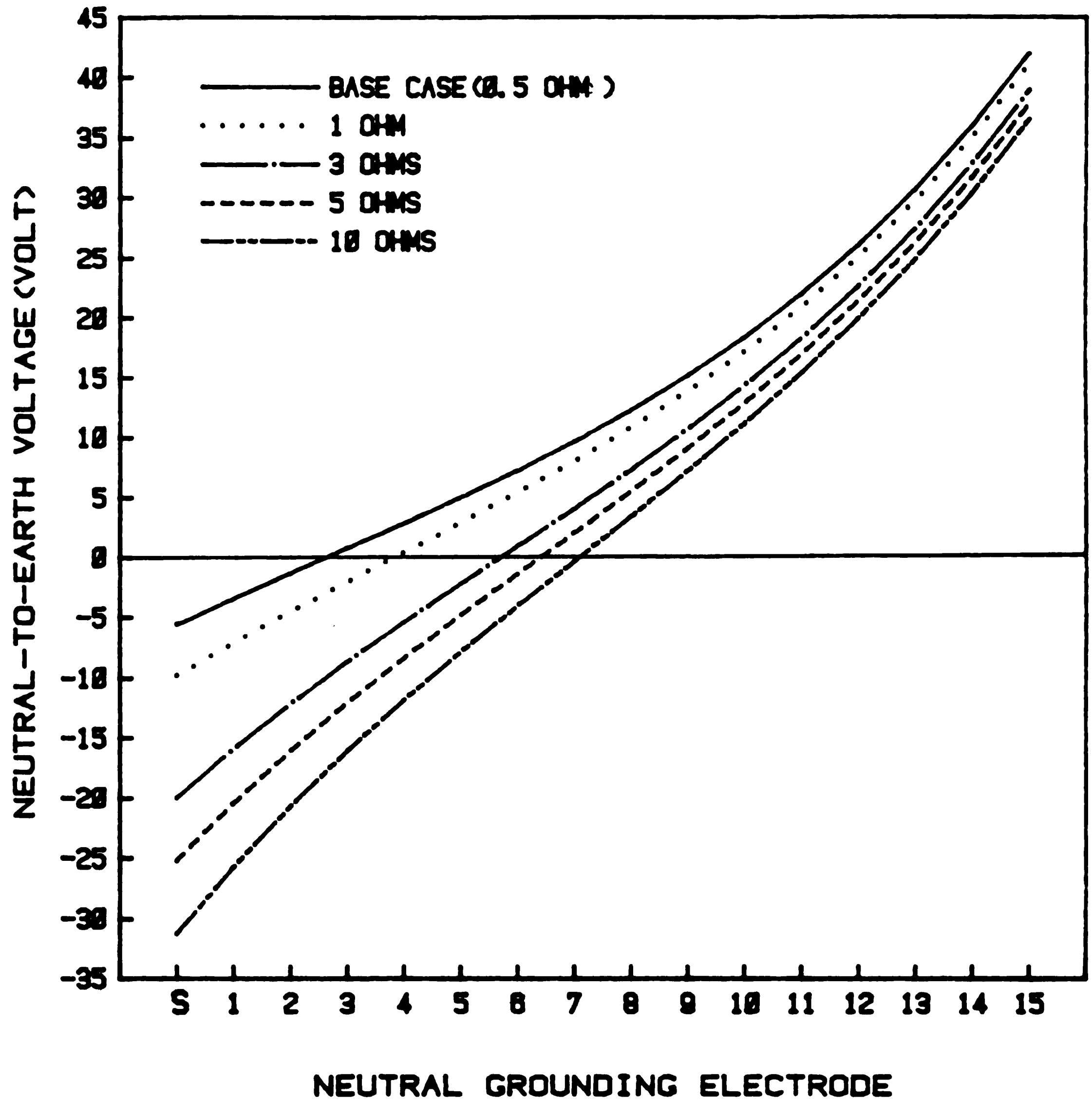


FIGURE 27. Profile of the neutral-to-earth voltage along the distribution line from the substation to a customer at the end of the line for variable substation grounding resistance (Distribution line model, CIRCUIT A).

Figure 28 presents the results when the new values of resistance were simulated using CIRCUIT B (Figure 4). For resistance equal to 10 ohms, the magnitude of neutral-to-earth voltage increased 19.2 volts (almost 6 times bigger) at the substation and decreased 4.0 volts at the end of the line.

CIRCUIT D (Figure 6) was also used and the effects of changing R_S on neutral-to-earth voltage are shown in Figure 29. When the resistance value was changed to 10 ohms (20 times bigger) the neutral-to-earth voltage at the substation increased by 17.0 volts (almost 5 times greater) and at the end of the line the voltage decreased by 1.4 volts.

Note that, the effect of improving the substation grounding mat system is relatively localized since voltages at other locations were altered by much smaller percentages. For values of R_S greater than 3 ohms (CIRCUIT B and CIRCUIT D) the profiles show the maximum magnitude of neutral-to-earth voltage at the substation.

5.1.5 - Ground Faults

CIRCUIT E (Figure 7) was used to study the effects of sustained line-to-ground faults. The results are presented as the following:

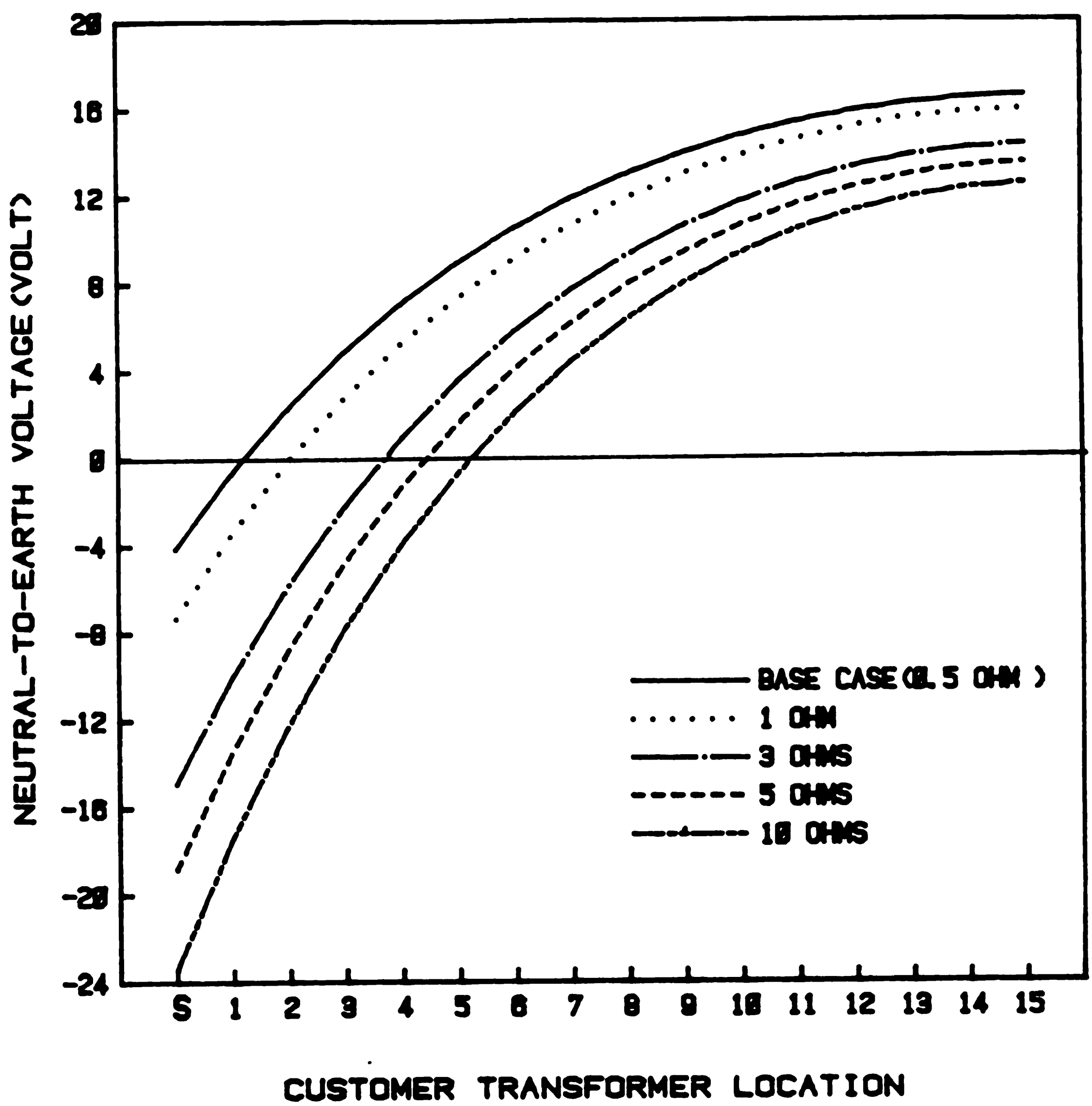


FIGURE 28. Profile of the neutral-to-earth voltage along the distribution line from the substation to the last customer for variable substation grounding resistance (Distribution line model, CIRCUIT B).

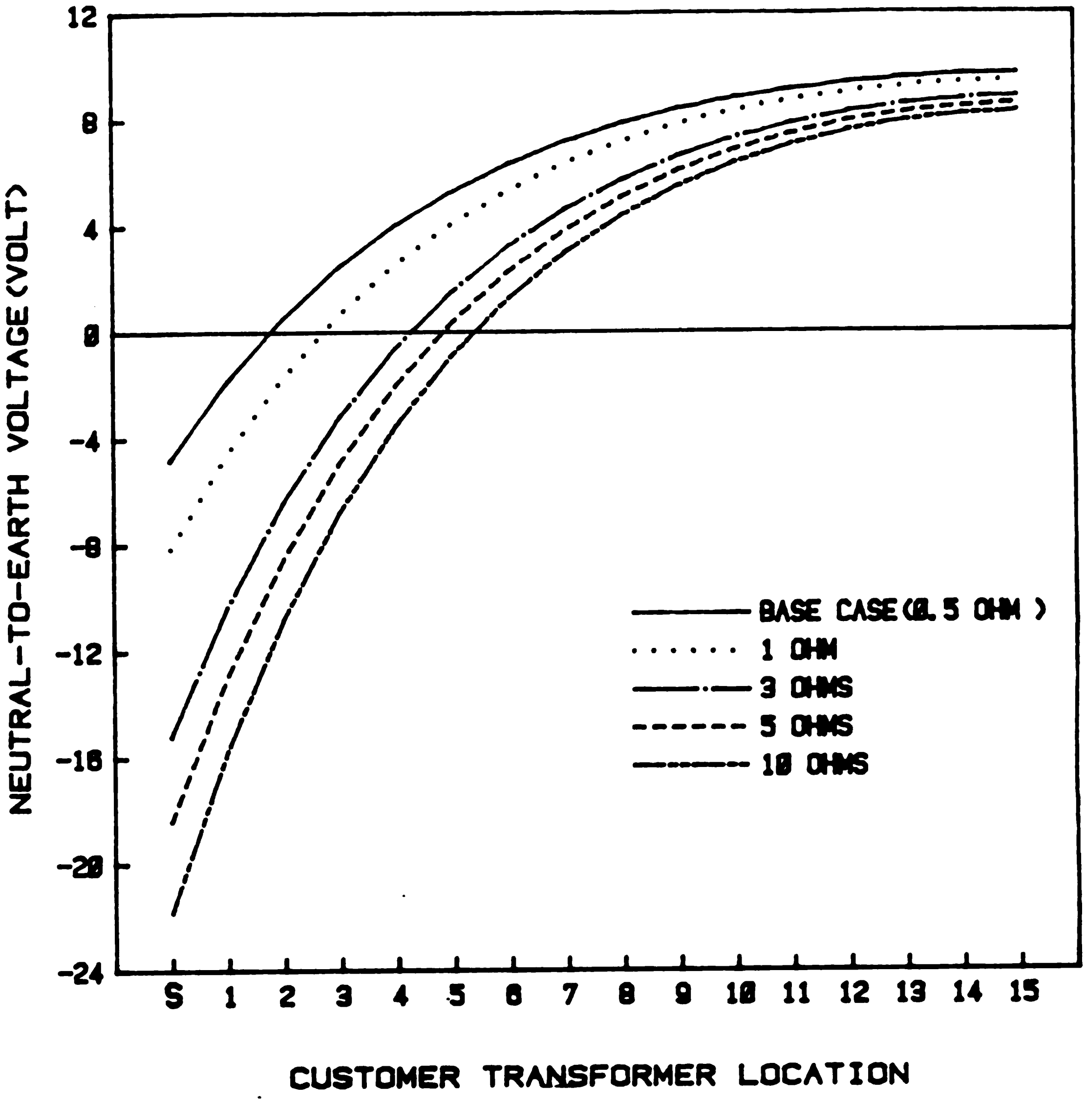


FIGURE 29. Profile of the neutral-to-earth voltage along the distribution line from the substation to the last customer for variable substation grounding resistance (Distribution line model, CIRCUIT D).

a) Primary Ground Fault

Figure 30 presents the neutral-to-earth voltage profiles along the distribution line when 10, 50, and 100 Amperes primary line-to-ground fault were created at location 1., using the above mentioned circuit. It can be seen that the level of magnitude of neutral-to-earth voltage, at the substation, increased as the fault resistance-to-earth decreased. A low substation grounding resistance (0.5 ohm) and 20 ohms of resistance at each ground rod ensured that a high proportion of fault current returns via the ground path and the substation grounding resistance has the major impact on the distribution of fault current. When the ground faults were created at locations 9 and 15 respectively, the neutral-to-earth voltage profiles for both cases did not have much difference from the values when the ground fault was created at location 1. In this comparison, the 100 Ampere primary line-to-ground fault presented the greatest changes on the neutral-to-earth voltage. The magnitude of voltage at the substation decreased 2.2 volts and 3.5 volts when the faults were created at locations 9 and 15, respectively.

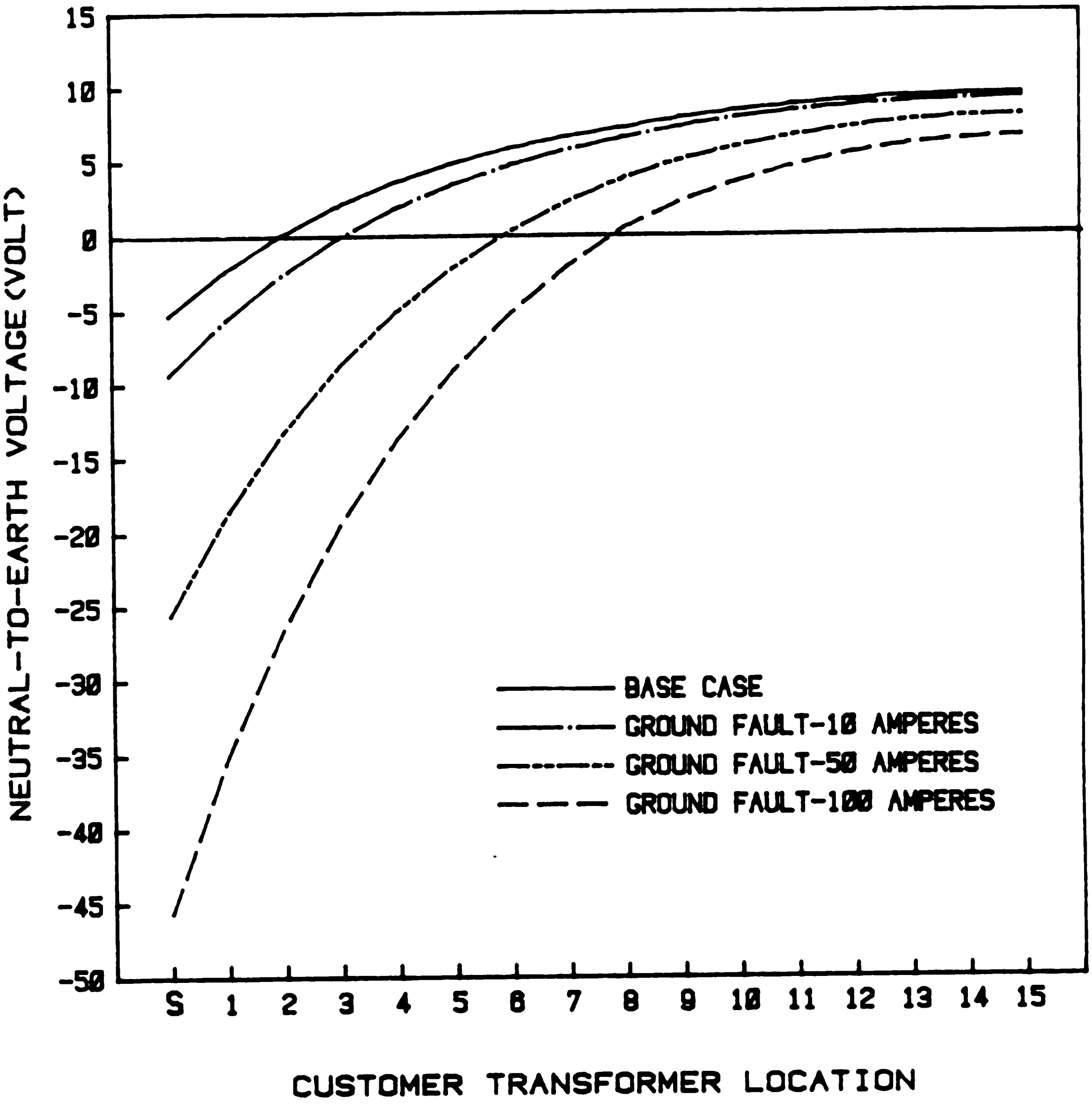


FIGURE 30. Profile of the neutral-to-earth voltage along the distribution line from the substation to the last customer with primary Ground Faults (Distribution line model, CIRCUIT E, center load with three feeders).

b) Secondary Ground Fault

Using CIRCUIT E (Figure 7) a ground fault was introduced on the secondary wiring systems of customers 2 and 15, respectively. The fault was created at the in-phase leg. Figure 31 presents the results. When the fault was created at customer 2, the magnitude of neutral-to-earth voltage increased near that location. The effect is much less significant thereafter. Customers located near the middle of the line see a slight decrease (0.5 volts) on neutral-to-earth voltage.

When the fault was created at customer 15, the neutral-to-earth voltage at that location has a significant reduction. However, near the substation , the magnitude of the voltage had no significant increase. At the middle of the line, the neutral-to-earth voltage decreased by 0.9 volt.

Using CIRCUIT E (Figure 7) and CIRCUIT F (Figure 8), a ground fault was introduced at one of the three feeders (Building A) in customer 8 and customer 15, respectively. A resistance was inserted between one ungrounded conductor of the secondary system and ground. The effect of the ground fault appears different for the in-phase and 180^{o} out-of-phase legs of the secondary system. The effect of the fault current returns to the transformer's center tap through the grounded neutral system and may be either

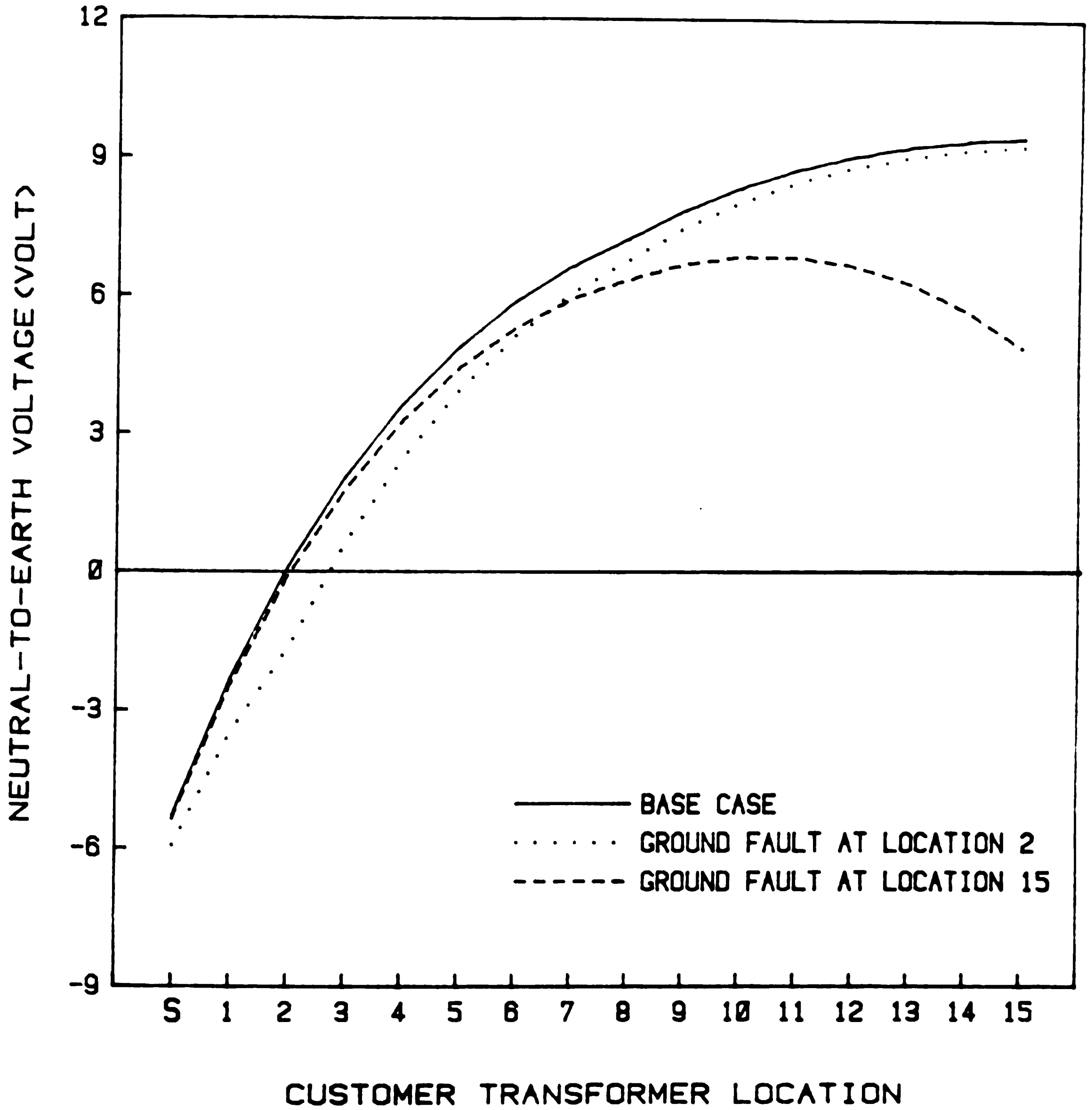


FIGURE 31. Profile of the neutral-to-earth voltage along the distribution line from the substation to the last customer with 50 amperes secondary Ground Faults, at two locations (Distribution line model, CIRCUIT E, center load with three feeders)

in-phase or 180° out-of-phase with the normal load current, depending on the leg to which the effect is related. Table 5 and Table 6 summarize the results. When the fault was inserted at the in-phase leg of the feeder the level of neutral-to-earth voltage decreases as the fault resistance-to-earth decreases.

When the fault current occurred in the 180° out-of-phase leg of the feeder, the neutral-to-earth increases as the fault resistance-to-earth decreases.

Figures 32 and 33 show the effects of the secondary ground faults, described above, along the distribution line. For both cases, the fault resistance was 50 ohms. The inserted faults on one customer's secondary transformer created localized effects on the neutral-to-earth voltage that were most apparent on that location and the adjacent locations. It can be seen that CIRCUIT F presented slightly greater changes on neutral-to-earth voltage than did the CIRCUIT E.

TABLE 5. Neutral-to-Earth Voltage for Secondary Ground Faults - Three Feeders Secondary System at the Middle of the Distribution Line

FAULT RESISTANCE	NEUTRAL TO EARTH VOLTAGE (VOLT)				
	VTE	VME	VAE	VBE	VCE
FAULT IN THE IN-PHASE LEG					
NONE	7.26	7.25	7.24	7.24	7.24
500	7.04	7.03	7.02	7.02	7.02
200	6.72	6.71	6.70	6.70	6.70
50	5.12	5.12	5.11	5.11	5.11
FAULT IN THE OUT-OF-PHASE LEG					
500	7.45	7.44	7.43	7.43	7.43
200	7.74	7.72	7.71	7.72	7.71
50	9.15	9.14	9.12	9.13	9.12

<u>NOTE:</u> See List of Symbols and

CIRCUIT E - Figure 7

TABLE 6. Neutral-to-Earth Voltage for Secondary Ground Faults - Three Feeders Secondary System at the End of the Line

FAULT RESISTANCE	NEUTRAL-TO-EARTH VOLTAGE (VOLT)				
	VTE	VME	VAE	VBE	VCE
FAULT IN THE IN-PHASE LEG					
NONE	8.36	8.34	8.33	8.34	8.33
500	8.02	8.01	8.00	8.00	8.00
200	7.51	7.50	7.50	7.50	7.50
50	5.04	5.04	5.03	5.03	5.03
FAULT IN THE OUT-OF-PHASE LEG					
500	8.65	8.64	8.62	8.63	8.62
200	9.09	9.08	9.06	9.07	9.06
50	11.23	11.22	11.20	11.21	11.20

NOTE: See List of Symbols and

CIRCUIT F - Figure 8

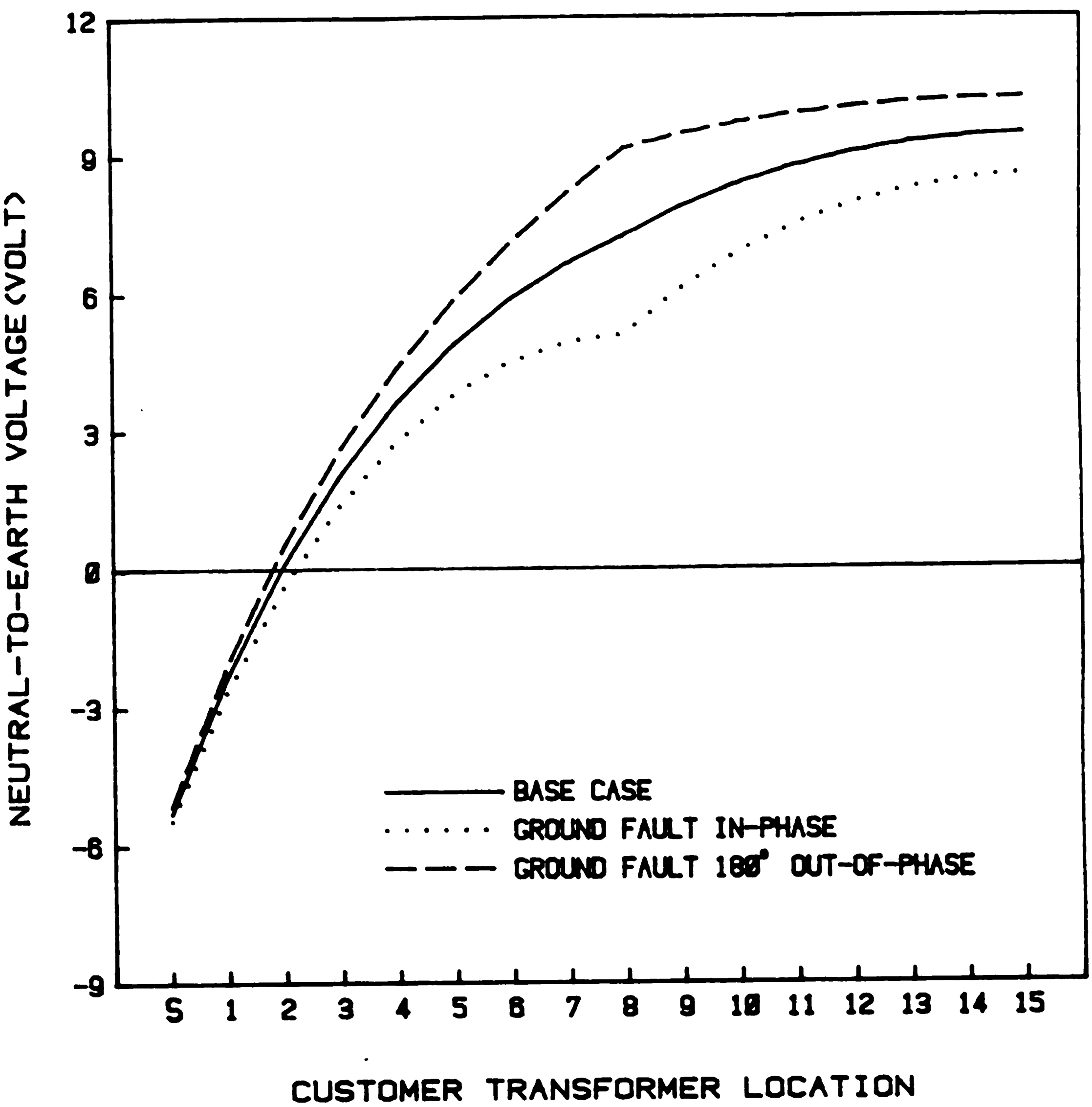


FIGURE 32. Profile of the neutral-to-earth voltage along the distribution line from the substation to the last customer with secondary Ground Faults at location 8 (distribution line model CIRCUIT E, center load with three feeders).

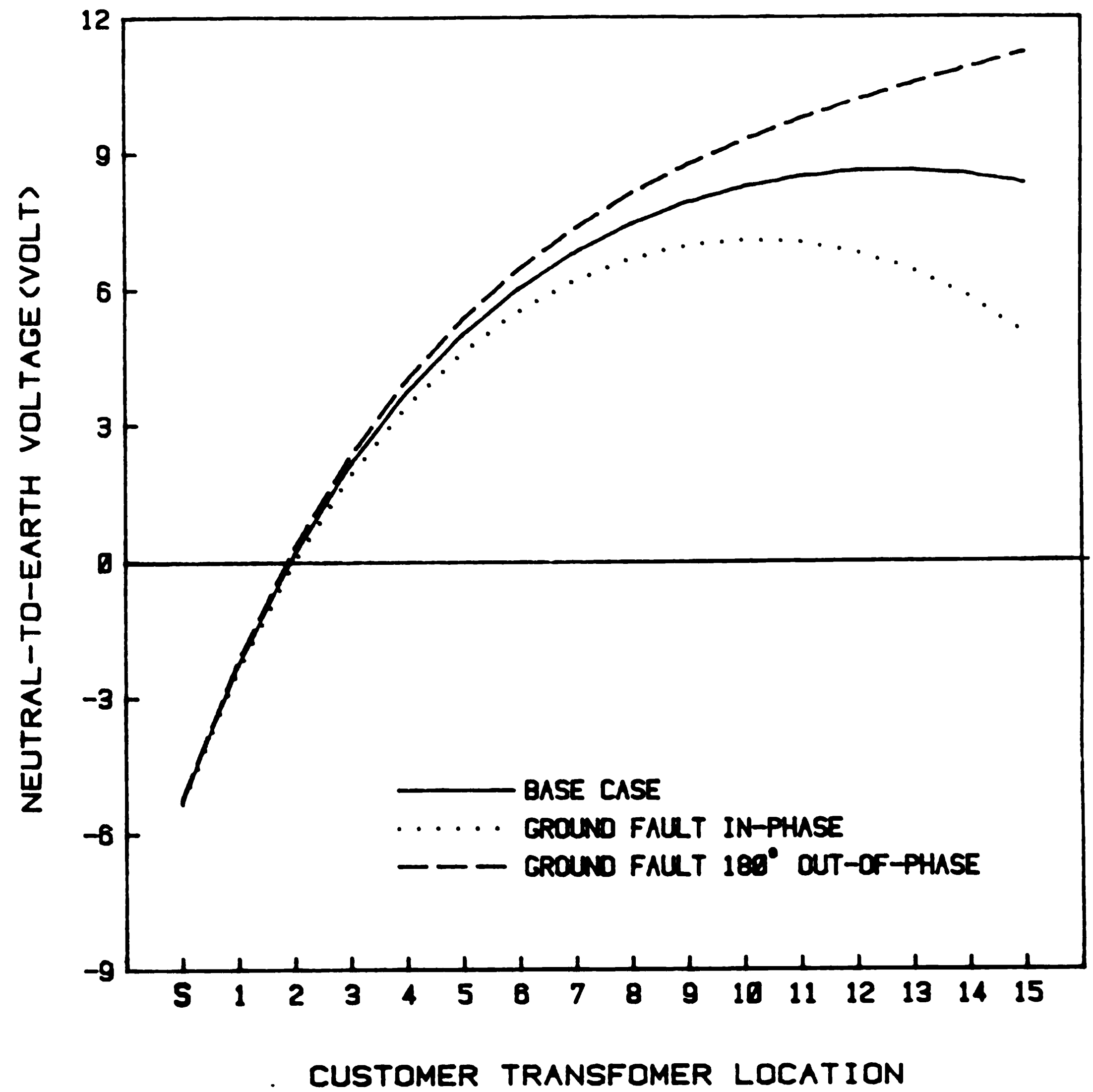


FIGURE 33. Profile of the neutral-to-earth voltage along the distribution line from the substation to the last customer with secondary Ground Faults at location 15 (Distribution line model, CIRCUIT F, end load with three feeders).

CHAPTER VI

CONCLUSION

The presence of excessive neutral-to-earth voltage on multi-grounded, single-phase, distribution systems has been implicated as causing uncomfortable conditions in confined livestock structures. This kind of voltage may have one source, or there may be several sources.

An equivalent circuit model representing a multi-grounded, single-phase overhead distribution systems was developed and successfully applied to evaluate the effects of sources of neutral-to-earth voltage.

The conclusions drawn from this study are:

1) The results obtained from the utilization of the model developed showed many similarities to a DC analog model of neutral-to-earth voltage in a single-phase distribution system presented by Stetson et. al. (1984).

2) The effect of a neutral/transformer grounding resistance is location-dependent. A significant reduction of the grounding resistance in a specific point resulted in a significant reduction of neutral-to-earth voltage in that

point, and to a lesser extent in the immediate area, but has no significant effect over the neutral-to-earth profile along the line. Also, changes made near the substation do not affect the general neutral-to-earth voltage conditions over the entire line. However, when changes are made at the end of the line, net voltage changes at that point were maximized.

3) The effects of a primary neutral conductor resistance is also location-dependent. Increasing the resistance of the neutral conductor in a segment located at the beginning of the line resulted in increased neutral-to-earth voltage at all points along the line. Increasing the resistance in a segment located at the middle of the line resulted in a decrease of the neutral-to-earth voltage at some locations ahead of that segment in the direction of the substation. An increase of neutral-to-earth voltage resulted at all points behind that segment in the direction towards the end of the line. However, an increase in the conductor resistance in a segment located at the end of the line did not have a significant effect along the line.

4) Changes made on the secondary neutral conductor resistance does not affect the primary neutral-to-earth voltage along the line.

5) Changing the load at one location resulted in a change of neutral-to-earth voltage at that point, but the change was much less significant as the distance increased away from that point.

6) The effects of varying the resistance of the substation grounding mat was more apparent at the substation and adjacent locations.

7) The effect of primary ground fault was found to be location-independent; a sustained primary line to ground fault near the substation, or at the middle, or at the end of the line had the same effects on the neutral-to-earth voltage along the line.

8) The effect of a secondary ground fault was found to be location-dependent; a sustained secondary line to ground fault at a location was more apparent at that location than at the adjacent locations.

CHAPTER VII

SUGGESTIONS FOR FUTURE STUDY

This work is a fundamental study which explains neutral-to-earth voltage on a single-phase, grounded distribution line. It can be used as a starting point for more in depth theoretical and practical research in this area.

It is suggested that future studies on this topic represent AC single-phase and three-phase distribution lines and that values for grounding and load be obtained from actual field measurements. There should also be an investigation to see if transmission lines can in any way produce neutral-to-earth voltages on farms.

APPENDIX

DESCRIPTION OF SPICE PROGRAM

APPENDIX

DESCRIPTION OF SPICE PROGRAM

SPICE is a circuit analysis program developed in the Electronics Research Laboratory at the University of California, Berkeley. It can be executed interactively or from batch using the MSU Computer Laboratory's Control Data Corporation Computer System.

SPICE may be used to analyze both analog and digital circuits. It performs DC, AC, and transient analyses on both linear and nonlinear circuits. It readily accepts linear and nonlinear device models for resistors, capacitors, inductors, diodes, transistors, etc.

The circuit to be analyzed is described to SPICE by a set of element cards, which define the circuit topology and element values, along with a set of control cards, which define the model parameters and the run controls.

Each element in the circuit is specified by an element card that contains the element name, the circuit nodes to which the element is connected, and the value of the parameters that determine the electrical characteristic of the element. Following a sample of SPICE input and output:

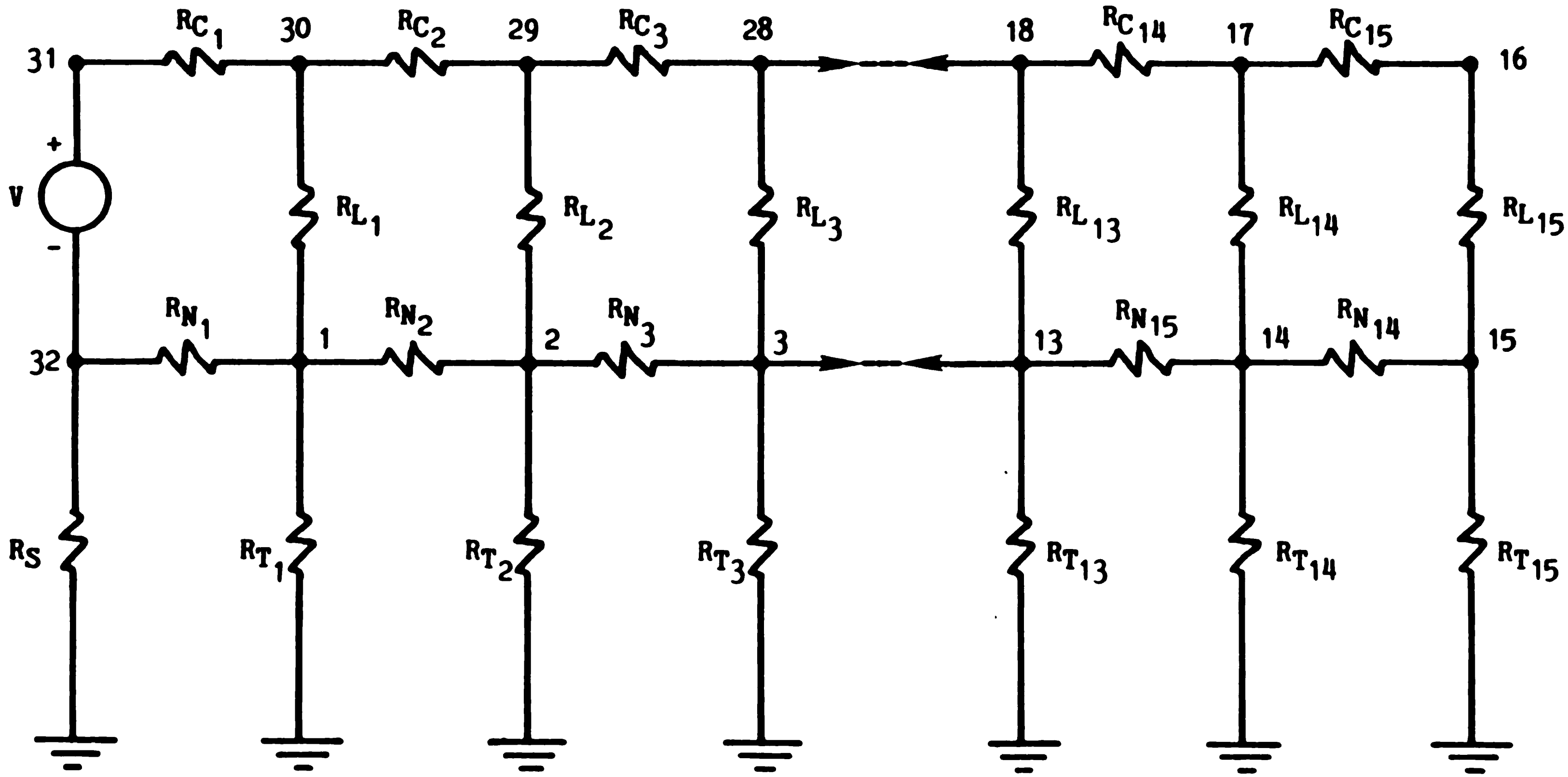


FIGURE 4. CIRCUIT B. Distribution Line Model. Distributed load along the line.

```
1******* 12/03/84  *******  SPICE 2G.2 (15APR81)  *******.15.55.18.*****
0+*CIRCUIT B DISTRIBUTION LINE MODEL
0****     INPUT LISTING                       TEMPERATURE =   27.000 DEG C
0***********************************************************************

 .WIDTH  IN=80  OUT=80
 VIN    31  32   DC  7200
 RC1    31  30             .424
 RC2    30  29             .424
 RC3    29  28             .424
 RC4    28  27             .424
 RC5    27  26             .424
 RC6    26  25             .424
 RC7    25  24             .424
 RC8    24  23             .424
 RC9    23  22             .424
 RC10   22  21             .424
 RC11   21  20             .424
 RC12   20  19             .424
 RC13   19  18             .424
 RC14   18  17             .424
 RC15   17  16             .424
 RL1    30   1        6480
 RL2    29   2        6480
 RL3    28   3        6480
 RL4    27   4        6480
 RL5    26   5        6480
 RL6    25   6        6480
 RL7    24   7        6480
 RL8    23   8        6480
 RL9    22   9        6480
 RL10   21  10        6480
 RL11   20  11        6480
 RL12   19  12        6480
 RL13   18  13        6480
 RL14   17  14        6480
 RL15   16  15        6480
 RN1    32   1             .424
 RN2     1   2             .424
 RN3     2   3             .424
 RN4     3   4             .424
 RN5     4   5             .424
 RN6     5   6             .424
 RN7     6   7             .424
 RN8     7   8             .424
 RN9     8   9             .424
 RN10    9  10             .424
 RN11   10  11             .424
 RN12   11  12             .424
 RN13   12  13             .424
```

```
RN14   13   14            .424
RN15   14   15            .424
RS     32    0            .5
RT1     1    0          20
RT2     2    0          20
RT3     3    0          20
RT4     4    0          20
RT5     5    0          20
RT6     6    0          20
RT7     7    0          20
RT8     8    0          20
RT9     9    0          20
RT10   10    0          20
RT11   11    0          20
RT12   12    0          20
RT13   13    0          20
RT14   14    0          20
RT15   15    0          20
.PRINT  DC
.END
1******* 12/03/84  *******  SPICE 2G.2 (15APR81)  *******.15.55.18.*****

0+*CIRCUIT B DISTRIBUTION LINE MODEL

0****     SMALL SIGNAL BIAS SOLUTION       TEMPERATURE =   27.000 DEG C

0***********************************************************************
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NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE
(1)	-.7039	(2)	2.2831	(3)	4.8487	(4)	7.0478
(5)	8.9277	(6)	10.5285	(7)	11.8847	(8)	13.0253
(9)	13.9749	(10)	14.7539	(11)	15.3790	(12)	15.8637
(13)	16.2183	(14)	16.4506	(15)	16.5655	(16)	7139.7994
(17)	7140.2655	(18)	7141.1977	(19)	7142.5961	(20)	7144.4609
(21)	7146.7921	(22)	7149.5900	(23)	7152.8547	(24)	7156.5867
(25)	7160.7861	(26)	7165.4534	(27)	7170.5889	(28)	7176.1932
(29)	7182.2667	(30)	7188.8101	(31)	7195.8238	(32)	-4.1762

VOLTAGE SOURCE CURRENTS

NAME	CURRENT
VIN	-1.654E+01

TOTAL POWER DISSIPATION   1.19E+05 WATTS

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