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ANALYSIS FOR EFFECTS OF SOME DIFFERENT OPERATIONAL CONDITIONS ON NEUTRAL-TO-EARTH VOLTAGE IN A SINGLE-PHASE ELECTRIC POWER DISTRIBUTION SYSTEM

presented by

Changming LI

has been accepted towards fulfillment of the requirements for

M.S. degree in Agricultural Engineering

Truman C Surbrook

Major professor

Date May 10, 1991

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ANALYSIS FOR EFFECTS OF SOME DIFFERENT OPERATIONAL CONDITIONS ON NEUTRAL-TO-EARTH VOLTAGE IN A SINGLE-PHASE ELECTRIC POWER DISTRIBUTION SYSTEM

By

Changming Li

A THESIS

Submitted to
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ABSTRACT

ANALYSIS FOR EFFECTS OF SOME DIFFERENT OPERATIONAL CONDITIONS ON NEUTRAL-TO-EARTH VOLTAGE IN A SINGLE-PHASE ELECTRIC POWER DISTRIBUTION SYSTEM

By

Changming Li

Neutral-to-earth voltage (NEV) on a dairy farm may affect milk production of a dairy cow. Computer models were developed to simulate NEV along a 7.2 kV multi-grounded single-phase electric power distribution line.

The computer models analyses estimated the NEV changes arising from high resistance segments with various load in the neutral of the primary line, phase-to-neutral faults, phase-to-earth faults, substation ground resistance change, different levels of the neutral ground connection, primary operating voltage change and secondary ground faults. Particular attention was paid to ground fault conditions and the relationship of level of load and abnormal resistance in the neutral conductor.

The distribution line was simulated as an AC line and compared to the DC model to determine if the DC model was a valid predictor of NEV along the distribution line.

Approved:

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LIST OF SYMBOLS

VI	Substation voltage, volt
RS	Substation grounding mat resistance, ohm
RU	Primary ungrounded phase conductor resistance, ohm
RD	Primary neutral conductor resistance, ohm
RRL	DC model residential transformer simulation resistance, ohm
RFL	DC model farm transformer simulation resistance, ohm
RRG	Residential transformer ground resistance, ohm
RFG	Farm transformer ground resistance, ohm
RSG	Secondary ground electrode resistance, ohm
RG	Ground electrode resistance between transformers, ohm
REG	Extra ground electrode resistance between transformers, ohm
RSL	Secondary load resistance, ohm
RSU	Secondary ungrounded conductor resistance, ohm
RSN	Secondary neutral conductor resistance, ohm
RF	Fault simulation resistance, ohm
RC	Neutral contact resistance with transformer and grounding electrode
TRL	AC model residential transformer simulation
TFL	AC model farm transformer simulation

I. INTRODUCTION

The most prevalent rural electric power distribution systems in the United States are multi-grounded neutral systems. These are generally single-phase two-wire or three-phase three-wire or three phase four-wire systems which are effectively grounded.

The multi-grounded primary distribution system under normal and abnormal operating conditions will produce neutral-to-earth voltage all along the distribution line. Some dairy farmers complain that milk production has been adversely affected by the neutral-to-earth voltage. In the past decade, research has elucidated neutral-to-earth voltage behavior under various operational conditions of the distribution network. Also, the solving of neutral-to-earth voltage problems has made significant progress. Neutral-to-earth voltage levels along a distribution line, however, are not clearly understood in relation to grounding, neutral resistance, primary/secondary neutral bond effect and ground fault. Guidelines have not been available for diagnosing distribution line abnormalities which cause elevated levels of neutral-to-earth voltage. It is important to understand the effect that various conditions have upon the neutral-to-earth voltage profile along the line in order to develop effective guidelines for remedying problems.

The scope of this thesis is to: (1) study the neutral-to-earth voltage profile along a single-phase multi-grounded distribution system as affected by grounding, faults, and abnormal line resistance; and (2) compare an AC model with a DC model to determine if the DC models can be a useful tool to study the factors that cause neutral-to-earth voltage along a single phase primary distribution line.

Computer models were developed to study the neutral-to-earth voltage profiles produced by different grounding condition, types of ground faults and neutral resistance under specific operational or loading conditions. Actual data from an operating distribution line is important to be considered, but controlled experiments are difficult to conduct and in some cases may create dangerous conditions. Computer simulation of a primary distribution system provides the opportunity to study conditions whose field data are not available or not practical to obtain.

The following operational conditions were studied to determine their effect on the neutral-to-earth voltage along a distribution line: (1) different levels of abnormal resistance in the neutral conductor at a particular point along the line, and different levels of line loading near the point of abnormal neutral resistance; (2) a high resistance connection between the neutral and the primary winding of the transformer; (3) a 7.2 kV phase-to-neutral fault at different points along the line; (4) a 7.2 kV phase-to-earth fault at different points along the line; (5) different levels of resistance-to-earth of the substation; (6) different levels of resistance-to-earth of the distribution neutral; (7) different levels of phase-to-neutral voltage; and (8) a secondary

ungrounded conductor to earth fault at one point along the distribution line.

II. LITERATURE REVIEW

Since early this century, extensive research has been conducted concerning the effect of electrical voltage and current on humans. The lethal threshold value of continuous alternating current through the human body was determined by several researchers. Based on the results of Dalziel's studies[12], 99.5% of all persons can safely withstand, without ventricular fibrillation, the passage of a current not exceeding a magnitude I_B (in amperes) for duration t_s (in seconds) determined by the formula $I_B = k\, t_s^{-0.5}$. For 50 kg body weight, k=0.116.

Since the 1960's, extensive research has also found the effect of the electric voltage and current on animals as well as general indications of levels of voltage that bothered cows. Phillips (1963, 1969) and Woolford (1971, 1972) studied the effects of voltage and current on milk production (New Zealand). In the past decade, significant research concerning the farm stray voltage problem has also been conducted in the United States.

Since the late 1970's, the major concerns of stray voltage researchers in the U. S. and other countries were focused on: (1) How, and to what extent, does the neutral-to-earth voltage affect cows' milk production? (2) What is the source of the stray voltage? How is the neutral-to-earth voltage produced? What is its changing trend under the various operational conditions of the distribution network system? (3) Is it possible to mitigate or avoid neutral-to-earth voltage problems on farm? If yes, how? The literature will be reviewed from the three aspects just mentioned above.

2.1 Stray Voltage and Electric Current Effect on Dairy Cows

Borcherding (1979) reported work by a veterinarian that linked mastitis in cows to voltage irritation. Britten (1980) reported that a herd of cows milked faster, with higher production and lower leukocyte counts after a voltage problem was eliminated.

Appleman and Gustafson (1985) classified the observed effects of stray voltage on dairy cows into four general areas: effect on milking performance and behavior; effect on herd health; effect on nutritional intake; and, effect on production. Nevertheless, it was reported that any negative effects of electrical shock on milk production or mammary gland health most likely were not directly related to shock, i.e., physiological responses to shock were minimal and milk yield was generally maintained at normal levels during the shock period. However, the severe behavioral responses to shock usually caused management problems. In addition, the degree to which milk production would be affected depended on how dairy producers would deal with the abnormal behavior.

Gustafson et al. (1985) indicated that the effect of a stray voltage on a dairy cow was influenced by many factors: (a) voltage magnitude and waveform; (b) the resistance of a cow's body pathway; (c) condition of concrete, soil and metallic conductors affecting resistance to "true earth"; (d) resistance of the cow's contact points; (e) resistance of the electrical pathway to the cow's contact points; and (f) impedance of the source. When combined, these factors determine the current flow through the cow's body.

It is known that a current above some level flowing through the cow's body directly affects the cow's behavior or health. A voltage drives the current in the circuit with the cow body pathways as resistances.

Norell et al. (1982) reported the electrical resistance data for eight pathways through a dairy cow. The mean resistances of a cow ranged from 359 to 877 ohms, with the lowest for a mouth-all hooves path. Some pathways were selected in order to model the common cow stray voltage problem on farm. For example: the pathway of front-to-rear hooves was to model the cows that stood or walked across an area of the barn or parlor where a floor voltage gradient existed; the pathway of mouth-to-all hooves was to model the cows that bridged the gaps between metallic feeders or water bowls and ground; and the pathway of body-to-all hooves was to model the cows that bridged the gaps between metal pipeworks connected to the grounded neutral systems and concrete floor or earth. They found that the hoof-to-earth contact resistance was a large component of the pathway resistance but they did not evaluate the hoof-to-earth contact resistance quantitatively. So far, there has been little research reported on the quantitative analysis of the resistance.

Gustafson et al. (1985) studied 3 dairy cow-body pathways' behavioral sensitivity to DC and 30 seconds on-off AC current. They reported that the pathway front-to-rear hooves response rate (ratio of responding cows to total test cows) became statistically significant above 2.0 mA AC and 1.0 mA DC. Mouth-to-all hooves response rate became significant above 2 mA AC and 4 mA DC. Response rate for a body-to-all hooves pathway with currents from 0-7.5 mA AC and 0-9 mA DC were inconclusive. Appleman and Gustafson (1985) reported for AC 60 Hz source, the cow's behavioral sensitivity threshold currents are different with the different body pathways, ranging from 0.75 to 7.1 mA. Gustafson et al. (1985) reported that the cow's behavioral sensitivity threshold to the DC current was about 30 percent higher than AC.

Drenkard et al. (1985) did the experiment which exposed six multiparous non-pregnant Holstein cows to electric current to assess its effects on cow's behavior, health, milking performance, and endocrine responses. Three treatments (0, 4 and 8 mA) were applied in a changeover design over three consecutive one week periods. They concluded that behavioral responses to regularly applied AC current treatment decreased in frequency and intensity with time. Changes of milking performance and milk composition were not significant. Changes of milking related cortisol responses during 8 mA current experiment were significant. Oxytocin release was delayed during 8 mA treatments. Current treatments did not affect prolactin.

Aneshansley et al. (1987) reported their experiment which had fifteen first-calf heifers and fifteen 2nd to 4th lactation cows exposed to five voltages (0-4 volts) while drinking. Exposure was continuous for 21 days. They reported no significant difference in water consumption, feed intake, milk production, or concentration of fat or protein in the milk. Drinking behavior (number of drinks/day and time/drink) did change significantly.

Over the past decade, most studies of the cows' behavioral sensitivity response have been conducted with continuous, fixed and steady state current/voltage levels and various duration. However, one area that has not been adequately studied is dairy cow sensitivity to short duration currents.

Currence et al. (1987) used three durations (1, 10 and 100 cycles at 60Hz) of AC electrical current with the left front-left rear hoof pathway to determine the magnitude of short bursts of 60 Hz current that were required to cause a physical reaction in dairy cows. The conclusion was that the magnitudes of 60-Hz AC currents required to cause dairy cows to respond were essentially the same for current duration of 1.67 and 0.17 seconds (100 and 10 cycles at 60 Hz) with a value equal to about 3.5 mA (rms). The magnitude required for current duration of 0.017 second (1 cycles at 60 Hz) was approximately 50% higher. The similar tests were also given to twelve human volunteers to determine the magnitude of short bursts of 60 Hz current that were required to cause their "perception" and "equal level of discomfort".

The conclusion was that the difference in mean current magnitudes due to current duration were statistically insignificant.

Gustafson et al. (1988) conducted the electric strength/duration experiments to six Holstein cows by using the square current wave-form (about 11 mA in height and 38 mS in width) to cows' mouth-to-all hooves pathways. They processed their experimental data statistically to verify the model of Pearce et al. in 1982 and their own exponential model. They concluded that the model of Pearce et al. did not fit their experimental data as well as might be desired and their own statistical model was better. Their model was: $I_S = 11.02 \times t^{-0.16}$. Where I_S was the current strength of the stimulation needed to evoke the response in mA and t was duration of stimulation in mS. In the empirical formula above, the time ranged from 0.1 to 300 mS and the current strength ranged within 3 to 14 mA.

2.2 Possible Sources of the Farm Neutral-to-Earth Voltage

Surbrook and Reese (1981) defined the terminologies regarding the farm stray voltage as follows: (1) **Neutral-to-Earth Voltage** -- A voltage difference measured between the neutral of an electrical system and the earth. Metallic structures and equipment bonded to the neutral will also be at a difference in potential from the earth. (2) **Transient Voltage** -- A voltage that is not constant. It can be a sudden voltage spike or a gradual rise and fall of the voltage. This voltage is usually measured between earth and the neutral. (3) **Tingle Voltage** -- A term sometimes used to describe a very slight voltage that causes a slight shock or tingle when encountered by a human. A 120 V supply may only cause a tingle if the person is well insulated. (4) **Stray Voltage** -- A general term often used to include all sources of voltages found on the farm that may be encountered by humans and animals between a metal object and the adjacent earth on floor. It includes the three previous voltages encountered.

Surbrook and Reese (1981) traced the origins of farm stray voltage from two sources -- on-farm and off-farm. They indicated that common on-farm stray voltage sources were: (1) ground faults on the farm; (2) voltage gradient across the ground or floor arising from wires faulted in the earth; (3) electric fencer wires shorting direct to equipment or inducing a charge in pipes and equipment; (4) grounding conductor intentionally used as a neutral and a neutral used as a grounding conductor; and (5) voltage drop on the secondary neutrals. Typical off-farm stray voltage sources were: (1) voltage drop on the primary neutral; (2) a ground fault on a neighbor's property; and (3) a fault in primary equipment or a problem with primary grounding.

Gustafson and Cloud (1982) indicated that in the field, several or possibly all of these sources would interact. However, unless the contribution from each source could be clearly distinguished and analyzed, successful diagnosis was difficult. So, a good understanding of the sources and their interaction, the electric nature of the problem, and the effects of the electrical characteristics of the system were important to proper diagnosis and solution.

Gustafson and Cloud (1982) further proposed the solutions to stray voltage problems: (a) eliminate or minimize the voltage causing the problem; (b) isolate the voltage from any equipment in the vicinity of all potential animal contact points; or (c) install an equipotential plane that will keep all possible animal contact points at the same potential. The solution or solutions selected depends on (a) the source or sources of the stray voltage; (b) the magnitude of the stray voltage; (c) the cost of alternative solutions; (d) the physical facilities involved; and (e) the policies of the power supplier. The solutions can be relatively simple if the problem is clearly diagnosed and the alternatives evaluated and explained to the farmer.

Several researchers have contributed to the identification of the sources of the neutral-to-earth voltage in the past decade based on experimental circuit measurement and circuit calculation by computer

Stetson et al. (1984) developed an analog model of the neutral-to-earth voltage in a single-phase distribution system. They used resistors, conducting wires, switches, and a DC power source to build up the physical circuit experiment model of a single-phase distribution system. Their analog used the DC power source to simulate the substation transformer and resistors to simulate the load transformers. The analog assumed that each connection between the neutral conductor and earth ground could be represented by a resistance between the conductor and true earth. True earth had zero resistance, and zero potential difference existed between any two true earth ground connections regardless of their physical spacing. By taking physical measurement of their circuit model, they revealed the neutral-to-earth voltage phenomenon associated with multi-grounded single-phase distribution systems.

Their analog could be used to demonstrate the effects on primary lines of magnitude and location of loads with respect to the substation, poor neutral connections, and poor grounds. On the secondary lines the effects of poor connections, poor grounds, and undersized neutrals could be illustrated with two farmstead loads. These loads could be connected to illustrate the effects of loads in-phase and out-of-phase with the primary line, and the influence of one farm on another. The effect of separating primary and secondary neutrals could be illustrated.

They reported their six demonstrations: (1) The effect of primary conductor resistance on the neutral-to-earth voltage demonstrated the influence of neutral wire size. The voltage increased as neutral conductor resistance increased. For the isolated line segment represented by the analog, the voltage was a maximum at the ends of the line and minimum at or near the center. (2) The effect of a high resistance at some location along the primary or secondary neutral conductor demonstrated the effect of a high-resistance splice or connection. The voltage drop across the high-resistance splice or connection was much higher than across any of the other neutral segments. (3) The effect of different neutral-to-earth resistance on neutral-to-earth voltage demonstrated the effect of good and poor grounding. Ground resistance changes could cause the neutral-to-earth voltage changes, but the effect was location-dependent. (4) The effect of connecting a farmstead neutral at different locations along the primary neutral demonstrated that the farm neutral-to-earth voltage could be location-dependent as well as farm-load-dependent. With no secondary neutral current, an off-farm source was responsible for the farm neutral-to-earth voltage. With both on-farm neutral and an off-farm source, the phase relationship between the primary and secondary neutral currents and the line location affected the voltage on farm. (5) With identical neutral current at each farm and farms at the different taps, the interaction magnitude decreased as the distance between farms increased. (6) The effect of connecting or disconnecting the farmstead neutral from the primary neutral demonstrated connecting the primary and secondary neutrals sometimes reduced and sometime increased the measured neutral-to-earth voltage. They summarized that to solve the problem of excessive neutral-to-earth voltage, an orderly approach was essential because of the difficulties of analysis necessary to identify its source.

Kehrle (1984) developed the DC circuit model of 7.2 kV single-phase distribution power system to facilitate the analyses of the neutral-to-earth voltage on farm. The computer program of circuit simulation was used to perform the theoretical calculations and analyses of the neutral-to-earth voltage along the distribution line. The 8 conclusions were reached. (1) The results obtained from the theoretical analyses showed many similarities to the measurement results of the DC physical analog model of Stetson et al. in 1984. (2) The effect of a neutral/transformer grounding resistance was location-dependent. A significant reduction of the grounding resistance at a specific point resulted in a significant reduction of neutral-to-earth voltage at that point, and to a less extent elsewhere in the system. Also, the resistance changes made near the substation did not affect the general neutral-to-earth voltage over the entire line. However, when changes were made at the end of the line, net voltage changes at that point were maximized. (3) The effects of a primary neutral conductor resistance was also location-dependent. Increasing the resistance of the neutral conductor in a segment located at the beginning of the line resulted an increase of the 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 location ahead of that segment in the direction of the substation. and an increase of neutral-to-earth voltage resulted at all points behind that segment in the direction toward 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 did 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 effect 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. The effect of a sustained secondary line to ground fault at a location was more apparent at that location than at the adjacent locations.

Surbrook et al. (1986, 1987) reported that the stray voltage was caused by the voltage drop and ground faults and might have its origin in certain parameter changes of the primary electrical distribution system or in the customer's secondary electrical system. The voltage rms value of the neutral-to-earth voltage along a primary distribution line might be at a value of zero some distance from the substation, depending on the condition of the conductor resistances and of the loads.

Gustafson (1985) used the computer program to find the neutral-to-earth voltages in a DC circuit model. Some of his findings revealed basic parameters that caused a rise in neutral-to-earth voltage levels. 3 of his findings listed as follows. (1) Increased neutral wire resistance resulted in the largest percentage effect (on the neutral-to-earth voltage) in the central portion of the distribution line. (2) Poor connection in the primary neutral conductor can dramatically change the apparent resistance of the conductor. When poor connection was near the substation, the effect on neutral-to-earth voltage was largest on those farms near the substation. The highest value, at the end of the line, was not changed significantly. When the additional resistance was placed near the midpoint of the line, some farms ahead of the poor connection had reduced levels of the neutral-to-earth voltage, while those further along saw increased levels. (3) As the substation grounding resistance was increased, the voltage near the substation increased and the zero point along the line was moved further down the line. The effect diminished with distance from the substation.

2.3 Field Test and Diagnosis of Farm Neutral-to-Earth Voltage

Beside theoretical analyses of the neutral-to-earth voltage problem, Several researches have made contributions to the field testing and diagnosis of farm neutral-to-earth voltage in the past decade.

Soderholm (1982) discussed the possible sources of stray voltage, measurement techniques to determine their cause, and corrective measures that could be applied. He indicated that proper choice of a meter or recording device for measuring stray voltage was essential if misleading indications were to be avoided. He suggested 6 specifications for voltmeters used for these measurements. (1) The meter scale should be such that AC voltage levels of 0.1 to 1.0 V can be observed. (2) The meter must be capable of separating AC and DC. (3) A low input impedance equivalent to an animal mouth-to-hoof resistance (approximately 300 ohms) should be used to evaluate voltages with a low source impedance and avoid misleading measurements due to stray pick-up. (4) The meter should be capable of high impedance input (1 megohm or greater) for use in measuring induced voltage. (5) The speed of response should be fast enough to give an indication of transient voltages. (6) In addition to a voltmeter, other measurement tools such as graphic recorder, oscilloscope or clamp-on ammeter capable of measuring current levels from 1 mA to 20 A have been found valuable in monitoring and determining causes of stray voltage.

Stetson et al. (1982) reported a test method developed to electrically evaluate an operating primary neutral connector, or splice. Their method required only a digital voltmeter and was not dependent upon a constant or given line load. Connections could be evaluated both before and after adjustment or replacement. They described specific step by step measurement procedures as follows. (1) Proper safety procedures should be followed. (2) An insulated aerial lift was the safest and quickest method to reach the connections in question. (3) All connections and tests should be made using insulated electrical safety gloves. (4) A digital voltmeter was preferred since precise, low-level voltage readings were more quickly and easily obtained. (5) A clamp-on ammeter could be used to determine the level and monitor any changes in current. (6) Attach the voltmeter leads to the conductor near the connection with leads approximately 1/3 meter apart and note the readings. (7) Move to one side or the other of the splice and take a voltage measurement across a 1/3 meter section of the wire without a splice. If the voltage reading across the splice was greater than the voltage reading on the wire without the splice, then there is resistance in the splice which should be eliminated. (8) In all cases prior to installing any connector, dirt or corrosion on the conductors must be removed with steel brush, steel wool or emery cloth. They reported their procedure had been verified by field tests and worked well on primary neutral or secondary neutral lines with bare conductors.

Surbrook et al. (1988) developed a stray voltage diagnostic procedure with a minimum number of measurements. They described the minimum instrumentation needed was voltmeter, reference ground rod, wire and a 120 V load. Their procedure was: (1) Start at the main meter location or transformer pole. Measure between the transformer ground wire and a reference ground at least 15 feet away and not under the primary right of way. (2) Make the voltage measurement near the building or area on the farm where the voltage was suspected to be affecting the animals. (3) Determine if there was an excessive voltage drop on the neutral wire to any building on the property. (4) Check ground faults on the farm. If other sources were not found in steps 1 and 3, then it was possible that a ground fault was present. (5) The power supplier line crew would open the bond between the primary and secondary neutrals at the farm transformer. At this point, telephone personnel and cable television personnel must check the grounding of their lines at the farm to make sure they did not themselves form a bond from the farm neutral to the electrical power supplier primary neutral. This was because that if the previous tests did not lead to an identification of the neutral-to-earth voltage, then it was possible that the source may be due to a ground fault some place other than on the farm.

Prothero et al. (1988) studied the primary neutral-to-earth voltage levels impacted by various wiring system treatments through taking the field measurements. The test circuit that they chose was a radial two phase 3-wire tap, from a three-phase 4-wire multi-grounded neutral feeder beginning approximately 2.5 miles from the source substation. Through analyzing the field measurement data, they reported that the present preferred method of solidly bonding primary and secondary neutrals was consistent with the goal of minimizing primary neutral-to-earth voltage on rural feeders. And the large amounts of supplemental primary neutral grounding, as well as load balancing and line reconstruction accomplished during their investigation, could not reduce the primary neutral-to-earth voltage to zero.

2.4 Mitigation of Farm Neutral-to-Earth Voltage Problem

Gustafson (1985) proposed three possible approaches to mitigate and avoid the neutral-to-earth voltage problem on farm. The first recommendation was **voltage reduction** -- by either elimination of the voltage source (e.g., by removing bad neutral connections, faulty loads or improving or correcting wiring and loading), or by active suppression of the voltage by a nulling device. (2) When the voltage could not be reduced to acceptable levels, the suggestion was **gradient control** -- by use of equipotential planes and transition zones to maintain the animal's step and touch potential at an acceptable level. (3) A final suggestion was **isolation** of a portion of the grounding or grounded neutral system accessing the animals, so that they will not be subjected to objectionable currents due to stray voltages existing on the remainder of the grounded neutral system.

Surbrook et al. (1989) proposed a number of mitigation techniques for the farm neutral-to-earth voltage problem. They indicated that common mitigation techniques can be applied once the sources were positively identified. On-farm sources usually responded to one or more of the techniques described in their report. (1) Elimination of resistance at splices and terminations of the neutral conductors on the farm was necessary when this was found to be the source. (2) Increasing neutral conductor size may reduce the voltage. (3) Reducing the length of feeder conductors to a building was effective during initial layout of the farm buildings. (4) Balancing the 120 V loads in a building to maintain neutral current at or near zero was important. (5) A four-wire feeder, separating the neutral from equipment grounding conductor, may be installed to a building where animals may be affected. (6) Elimination of the interconnections between neutral conductors and equipment grounding conductors in a building. (7) Providing all electrical equipment with an equipment grounding conductor that was continuous from the equipment to the grounding bus of the circuit supply panel increased the safety and reduced the chances of neutral-to-earth voltage. (8) Elimination of any fault in equipment or wiring, or any wiring that potentially could cause a fault from an ungrounded conductor to the equipment or the earth was extremely important.

Surbrook et al. (1989) also indicated that off-farm source mitigation normally handled by the power supplier included: (1) separating the primary and secondary neutral conductor; (2) repairing corroded neutral conductor splices; (3) increasing the neutral conductor size; (4) increasing the primary line operating voltage; (5) reducing neutral-to-earth resistance at one or more locations along a distribution line; and (6) elimination of ground faults on the primary system, or at another customer location.

They indicated that there were some mitigation techniques that were an attempt to lower the cow contact voltage regardless of the source. These mitigation approaches included: (1) Equipotential planes installed in the floor of milking areas, at watering devices and feeding areas were intended to put everything within reach of the cow at the same electric potential so there would be no contact voltage. (2) Installing an active suppression device counteracting the neutral-to-earth voltage condition may be effective where the voltage could not be eliminated.

Althouse and Surbrook (1990) proposed and physically realized the design of equipotential plane on farm. They reported the step potential for a cow's contact could be reduced to below 1 volt when neutral-to-earth voltage was as high as 5 volts, measured from equipotential plane to reference ground.

III. OBJECTIVE

The primary goal of this study was to develop an effective computer model to simulate and analyze the neutral-to-earth voltage profile along a primary distribution line under some operational conditions. The computer model developed was then used to investigate the neutral-to-earth voltage problem on farm which has not been studied enough to explain in relation to the behavior of real distribution lines. The specific objectives of this study were as follows:

1. Develop a network model of a single-phase, multi-grounded primary electrical distribution system which provides the neutral-to-earth voltage at every grounding electrode and the current in each neutral, grounding electrode, and other network element.
2. Simulate the primary circuit network model with the computer program and analyze the computer numerical solutions of the neutral-to-earth voltages and some currents under the control of the following system operating conditions in a network model: (1) different levels of abnormal resistance in the neutral conductor at a particular point along the line, and different levels of line loading near the point of abnormal neutral resistance; (2) a high resistance connection between the neutral and the primary

winding of the transformer; (3) a 7.2 kV phase-to-neutral fault at different points along the line; (4) a 7.2 kV phase-to-earth fault at different points along the line; (5) different levels of resistance-to-earth of the substation; (6) different levels of resistance-to-earth of the distribution neutral; (7) different levels of phase-to-neutral voltage; and (8) a secondary ungrounded conductor to earth fault at one point along the distribution line.

3. Compare the operations of DC and AC base cases to determine if a DC model is accurate in studying neutral-to-earth voltage along a single-phase distribution line.

IV. METHODOLOGY

The electrical network simulation program SPICE running on Michigan State University mainframe IBM-3090 computer was employed to simulate the DC base case and other DC cases used to study effects of some other different operational conditions on the neutral-to-earth voltage along the single-phase power distribution line. Then the SPICE computer program was employed to simulate the AC base model for verifying the effectiveness of the simpler DC model and for studying primary and secondary neutral separated/bonded effects on neutral-to-earth voltage. The results from the simulation runs with the SPICE program were used as the input data to the personal computer software SUPERCALC-3 to draw the corresponding neutral-to-earth voltage profiles of all the models and case studies.

4.1 The DC Single-Phase Distribution Simulation Model

A DC base model has been developed for simulation of a neutral-to-earth voltage of distribution line. Figure 1 shows the circuit network for this single-phase electrical primary distribution line system model. The parameter values in the DC base model are shown in Table 1. The following scenario was modeled:

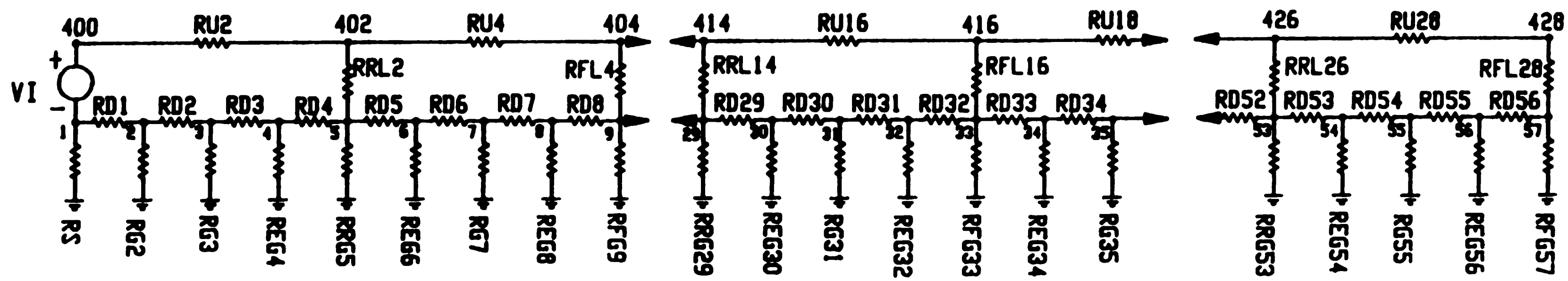


Figure 1. DC circuit model for single-phase electrical distribution system (input voltage 7,200 V)

Table 1. Parameters for Base DC Circuit Model in Figure 1.

Ungrounded Wire		Neutral Wire		Earth Ground		Load Resistance	
Symbol	**Ohms**	**Symbol**	**Ohms**	**Symbol**	**Ohms**	**Symbol**	**Ohms**
				RS	0.5		
RU2	0.32	RD1	0.08	RG2	25.0		
		RD2	0.08	RG3	25.0		
		RD3	0.08	REG4	100 K		
		RD4	0.08	RRG5	15.0	RRL2	7,200
RU4	0.32	RD5	0.08	REG6	100 K		
		RD6	0.08	RG7	25.0		
		RD7	0.08	REG8	100 K		
		RD8	0.08	RFG9	5.0	RFL4	3,600
RU6	0.32	RD9	0.08	REG10	100 K		
		RD10	0.08	RG11	25.0		
		RD11	0.08	REG12	100 K		
		RD12	0.08	RRG13	15.0	RRL6	7,200
RU8	0.32	RD13	0.08	REG14	100 K		
		RD14	0.08	RG15	25.0		
		RD15	0.08	REG16	100 K		
		RD16	0.08	RFG17	5.0	RFL8	3,600
RU10	0.32	RD17	0.08	REG18	100 K		
		RD18	0.08	RG19	25.0		
		RD19	0.08	REG20	100 K		
		RD20	0.08	RRG21	15.0	RRL10	7,200
RU12	0.32	RD21	0.08	REG22	100 K		
		RD22	0.08	RG23	25.0		
		RD23	0.08	REG24	100 K		
		RD24	0.08	RFG25	5.0	RFL12	3,600
RU14	0.32	RD25	0.08	REG26	100 K		
		RD26	0.08	RG27	25.0		
		RD27	0.08	REG28	100 K		
		RD28	0.08	RRG29	15.0	RRL14	7,200
RU16	0.32	RD29	0.08	REG30	100 K		
		RD30	0.08	RG31	25.0		
		RD31	0.08	REG32	100 K		
		RD32	0.08	RFG33	5.0	RFL16	3,600

Table 1 (cont'd)

Ungrounded Wire		Neutral Wire		Earth Ground		Load Resistance	
Symbol	Ohms	Symbol	Ohms	Symbol	Ohms	Symbol	Ohms
				RS	0.5		
RU18	0.32	RD33	0.08				
				REG34	100 K		
		RD34	0.08				
				RG35	25.0		
		RD35	0.08				
				REG36	100 K		
		RD36	0.08				
				RRG37	15.0	RRL18	7,200
RU20	0.32	RD37	0.08				
				REG38	100 K		
		RD38	0.08				
				RG39	25.0		
		RD39	0.08				
				REG40	100 K		
		RD40	0.08				
				RFG41	5.0	RFL20	3,600
RU22	0.32	RD41	0.08				
				REG42	100 K		
		RD42	0.08				
				RG43	25.0		
		RD43	0.08				
				REG44	100 K		
		RD44	0.08				
				RRG45	15.0	RRL22	7,200
RU24	0.32	RD45	0.08				
				REG46	100 K		
		RD46	0.08				
				RG47	25.0		
		RD47	0.08				
				REG48	100 K		
		RD48	0.08				
				RFG49	5.0	RFL24	3,600
RU26	0.32	RD49	0.08				
				REG50	100 K		
		RD50	0.08				
				RG51	25.0		
		RD51	0.08				
				REG52	100 K		
		RD52	0.08				
				RRG53	15.0	RRL26	7,200
RU28	0.32	RD53	0.08				
				REG54	100 K		
		RD54	0.08				
				RG55	25.0		
		RD55	0.08				
				REG56	100 K		
		RD56	0.08				
				RFG57	5.0	RFL28	3,600
		RD57	0.08				

1. 4,267 meters (14,000 feet) 7,200 volts multi-grounded single-phase distribution system fed fourteen load loops evenly spaced about 304.8 m (1,000 feet) apart. Half of the loads were assumed to be residential and half of the loads were assumed to be farms. Each residential load (RRL) was followed by a farm load (RFL). Ground electrodes were positioned at each farm load (RFG), at each residential load (RRG), and between transformers including the substation, node 1 (RG). Between the substation and the first grounding electrode there was one additional grounding electrode (RG). In one test condition, extra ground electrodes (REG) were added uniformly along the primary neutral line to simulate the effect of increasing ground rod number.
2. Along the primary neutral conductor line, from the substation to the last ground rod, 57 equally spaced nodes were selected. The node numbers were shown in Figure 1.
3. Primary conductors employed were number 2 AWG, ACSR. The ungrounded conductor (phase line) resistance (RU) between every two loads was 0.32 ohm (304.8 m of 2 ACSR) ohm. The neutral conductor resistance (RD) between every two adjacent nodes analyzed was 0.08 ohm (76.2 m of ACSR).
4. The substation (node 1) ground mat resistance (RS) was 0.5 ohm; each residential load neutral grounding electrode resistance (RRG) was 15 ohm; and each farm load grounding resistance (RFG) was 5 ohm. The additional neutral grounding electrode resistances (RG) were 25 ohm. It was assumed that the all

grounding electrodes were connected to the "true earth" whose resistance was zero.

5. At each residential transformer, the load resistance (RRL) was set at 7,200 ohm to produce a 1 ampere primary load. At each farm transformer, the load resistance (RFL) was set at 3,600 ohm to give a 2 ampere primary load. No secondary systems were connected to the transformer nodes to model the no load effects on all the secondary sides of the distribution transformers.

In the initial phase of modeling, the distribution line system was supplied by a DC voltage source equivalent to an actual AC source; and the resistance load was equivalent to the transformer load. The neutral-to-earth voltage values shown were equivalent to rms values. The negative DC values represented phase reversals in the AC network model.

With the DC base model, the eight cases were designed to reach the research objectives in the simulation of the effects of some different operational conditions on the neutral-to-earth voltage along the power distribution line on farm through the changing of corresponding electric parameters. In seven of eight cases, secondary system loads were omitted to model the no load condition; one secondary system was connected only in the last case to facilitate the study of the secondary-to-earth fault effect on the neutral-to-earth voltage.

In the field, the effects of these operational conditions are usually superimposed making the source identification of neutral-to-earth voltage difficult. However, the clear and thorough understanding of these effects need the individual contribution of each operational condition to be studied separately. Only one parameter at a time in each of these nine cases was changed, and all other parameters remained the same as in the original network.

4.2 Simulation of Abnormal Conditions along the Distribution Line

The single-phase distribution line base model as shown in Figure 1 was used for comparison with each of the abnormal line conditions studied. The deviation of the neutral-to-earth voltage of the test case as compared with the base model was considered as significant criteria for evaluation rather than the actual magnitude of the voltage *per se*.

4.2.1 Neutral Conductor Resistance Change

The simulated resistances of the primary neutral conductor RD32 and RD33 (located on the two sides of the farm transformer RFL16, between the two nodes 32 and 33 and nodes 33 and 34 in Figure 2, 0.08 ohm normal) were changed to the following values: 0.08, 0.50, 1.0, 5.0, 20.0 and 100K (open circuit condition) ohms. This was to model the the effect of a high resistance in the primary neutral conductor.

The effect of neutral conductor resistance change on the neutral-to-earth voltage under heavy load condition was studied by increasing the farm transformer load RFL16 (2A normal) for each value

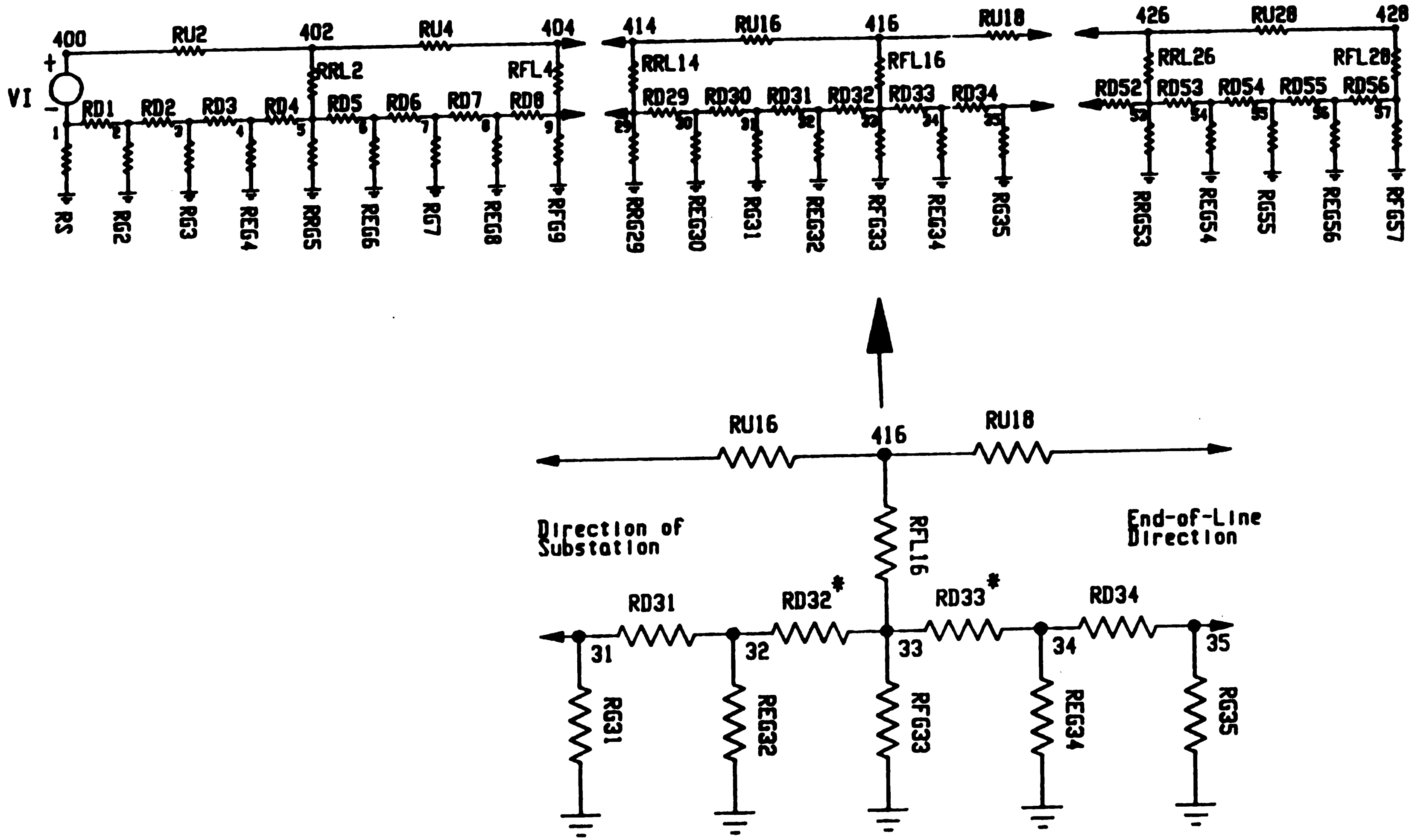


Figure 2. DC circuit model for single-phase electrical distribution system with abnormal neutral conductor resistance simulated

of the resistance RD32 and RD33. The simulated transformer loads were 2A (normal), 3A, 5A, and 10A. This was accomplished by altering the simulated load resistance RFL16 in sequence: 3,600, 2,400, 1,440, and 720 ohms in Figure 2.

4.2.2 High Resistance Connection of Neutral to Transformer Primary

Normally the primary neutral line makes a good connection with the transformer and grounding electrode with a contact resistance RC in Figure 3 near zero. There are cases in the field where the primary winding is properly connected to the grounding electrode at the transformer pole, but there is a high resistance connection to the primary neutral. The effect of the bad neutral connection with transformer winding and grounding electrode on the neutral-to-earth voltage was studied by increasing the contact resistance RC from 0 ohm respectively to 0.5 ohm, 1 ohm, 5 ohms and 100 kohms at a location near the middle of the distribution line (node 33).

4.2.3 Primary Phase-to-Neutral Fault (or Heavy Load)

The effect of primary unground phase conductor to neutral fault size on the neutral-to-earth voltage was studied by inserting a load resistor in the middle of the distribution line. This was accomplished by introducing a resistor RF1 from the ungrounded phase conductor node 416 to the corresponding neutral node 33 in Figure 4. RF1 was set at

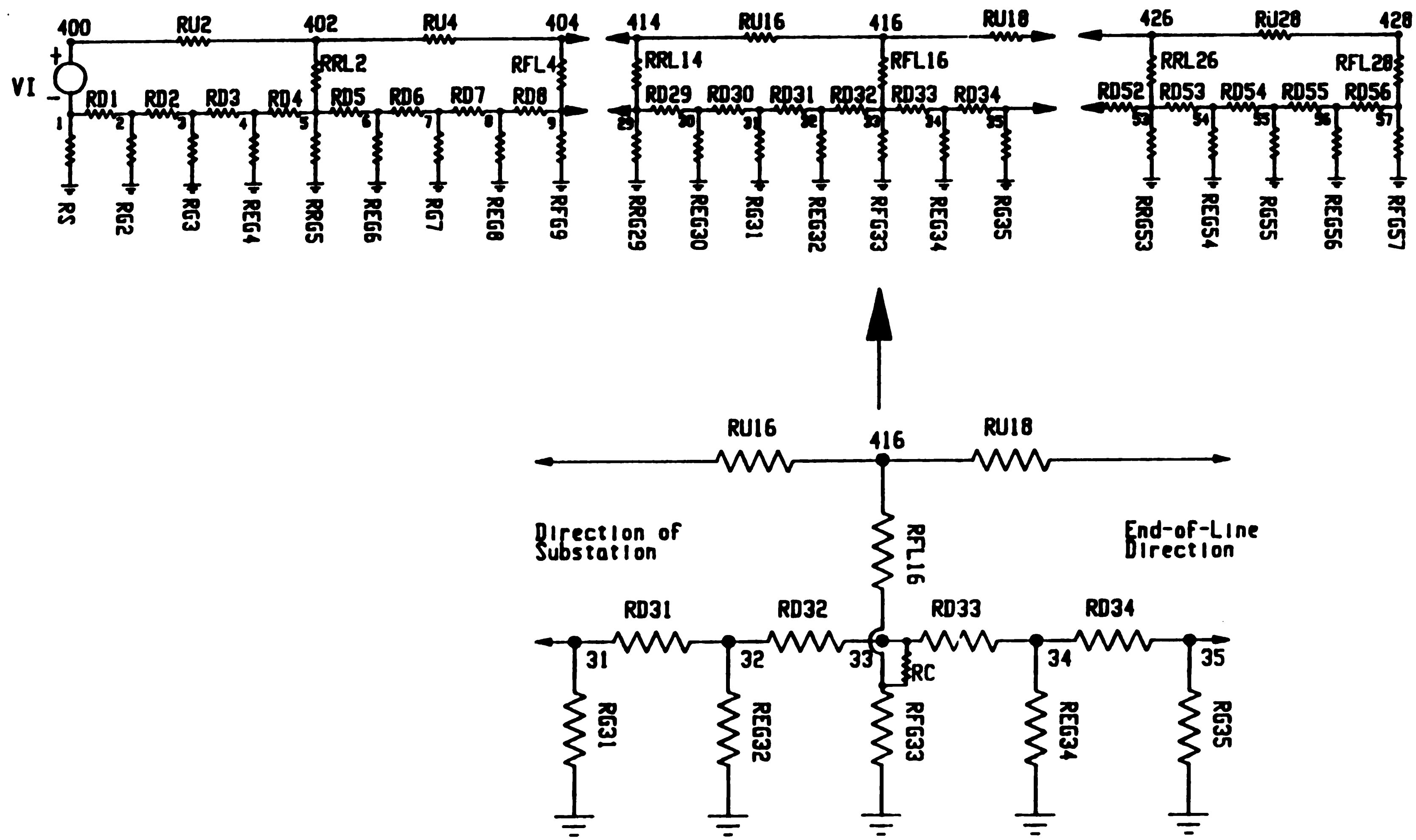


Figure 3. DC circuit model for single-phase electrical distribution system in simulation of bad neutral connection with transformer and ground rod

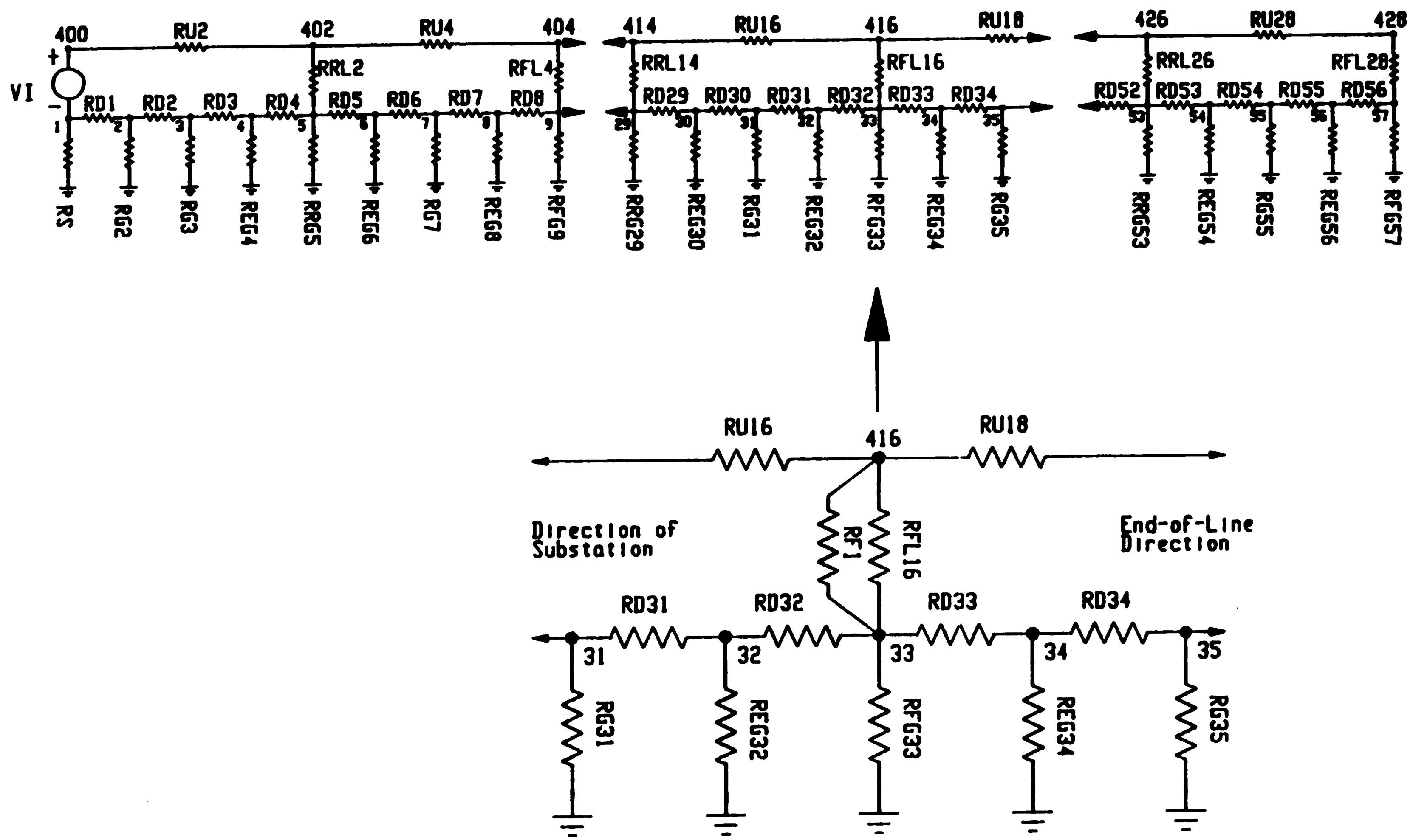


Figure 4. DC circuit model for single-phase electrical distribution system with primary phase-to-neutral fault simulated

the values of 7,200, 1,440, 720 and 360 ohms to model the fault levels of 1 A, 5 A, 10 A and 20 A respectively. A phase to neutral fault had the same effect as increasing the load on the line at the location of the fault.

The effect of this fault's location on the neutral-to-earth voltage was studied by moving the resistor RF1 above from node 416-33 to node 426-53, which was the farthest residential transformer location from the substation.

4.2.4 Primary Phase-to-Earth Fault

First, the effect of the primary ungrounded-phase-conductor-to- earth fault size on the neutral-to-earth voltage was studied by simulating a fault in the middle of the distribution line. This was accomplished by introducing a resistor RF2 from the ungrounded phase conductor node 416 to earth in Figure 5. RF2 was set at the values of 7,200, 1,440, 720 and 360 ohms to model the fault levels of 1A, 5A, 10A and 20A respectively.

The effect of this fault's location on the neutral-to-earth voltage was studied by moving the resistor RF2 above from node 416 to node 404 and to node 428 respectively. Node 404 was the farm transformer location nearest the substation and node 428 was the farm transformer location farthest from the substation. At this time, RF2 was only set at 360 ohms to model a 20 A fault, the most serious fault situation.

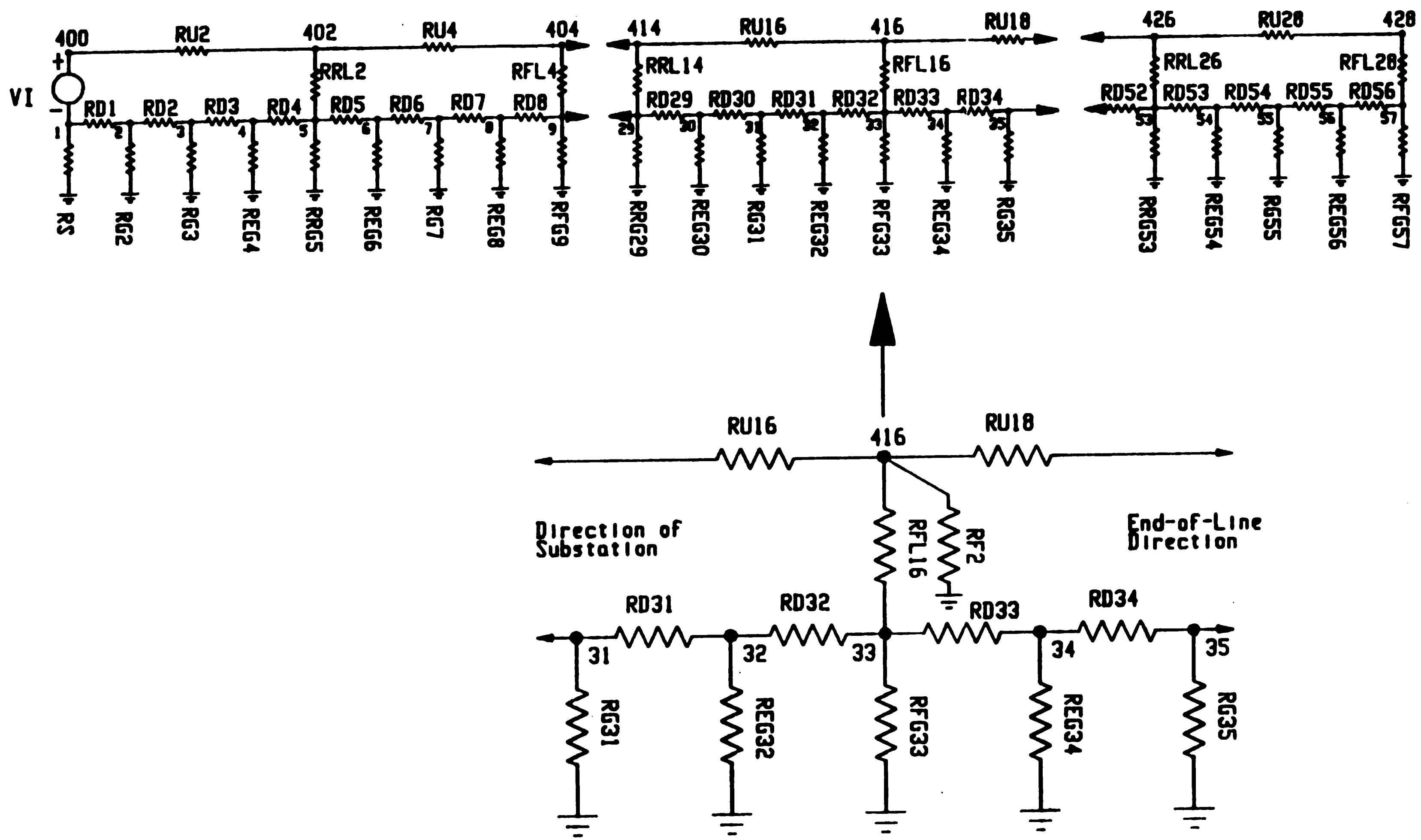


Figure 5. DC circuit model for single-phase electrical distribution system with primary phase-to-earth fault simulated

4.2.5 Substation Grounding Resistance Change

The normal grounding resistance for the substation in this model is 0.5 ohm. The substation grounding resistance change effect on the neutral-to-earth voltage was studied by increasing substation grounding resistance RS from 0.5 ohm respectively to 1 ohm, 5 ohms, 10 ohms, 20 ohms and 40 ohms at the substation, node 1 in Figure 1. This was to model the effect of a poor grounding connection at the substation on neutral-to-earth voltage.

4.2.6 Neutral-to-Earth Resistance Reduction

The normal grounding resistance in the model for each residential transformer is 15 ohm and for each farm transformer is 5 ohm. The neutral-to-earth resistance reduction effect on neutral-to-earth voltage was studied by reducing the grounding resistance RFG33 from 5 ohm to 3 ohm and then to 1 ohm. Grounding electrode RFG33 was at the middle of the distribution neutral line (node 33) which was the fourth farm transformer location from the substation shown in Figure 1. This exercise was to model how well a low resistance-to-earth electrode could lower a neutral-to-earth voltage at a farm.

In the base case, the normal grounding resistance for each residential transformer was 15 ohm, and for each farm transformer was 5 ohm. There was one grounding electrode at 25 ohm between each transformer. The effect of lowering the grounding electrode resistance all along the distribution line was studied by changing the extra grounding electrode resistance, REG, from 100 kohm to 25 ohm. This resulted in a simulation with a grounding electrode of not more than 25 ohms at every pole along the distribution line. The distribution line model is shown in Figure 1 and the base case values of grounding electrode resistance are listed in Table 1.

4.2.7 Primary Operating Voltage Level Change

In the base case, the primary operating voltage level was 7.2 kV. The effect of the change of primary operating voltage level on the neutral-to-earth voltage was studied by simulating the other primary operating voltage levels of 2.4 kV, 4.8 kV and 26.4 kV, respectively. The secondary load currents for all these cases were maintained the same as in the base simulation of 30 amperes for residential transformer secondaries and 60 amperes for farm transformer secondaries. The power consumed on the circuit remained the same as the base case. The resistances RRL and RFL were changed to maintain the desired secondary current. Values of primary voltage, VI, load resistances RFL and RRL, and primary current are listed in Table 2.

4.2.8 Secondary Earth Fault

The secondary circuit simulation (Figure 6) was a 120/240 volt, single-phase, three wires grounded system with a balanced load. The grounding resistances of the primary and the secondary were paralleled, with the resultant resistance remained at 5 ohms. The no load condition was still assumed. The secondary earth fault effect on the neutral-to-earth voltage was studied by introducing the 2.5, 5.0 and 10 A secondary ground faults through the resistor RF3 set at 48, 24 and 12 ohms from the ungrounded conductor of the secondary circuit to earth. The faults of in-phase (only SW3 and SW4 closed in Figure 6) and 180° out-of-phase (only SW3 and SW5 closed in Figure 6) on the secondary side were respectively attached to: (1) node 9 which was the farm transformer location nearest the substation; (2) node 33 which was the fourth farm transformer located at the middle of the primary distribution line; and (3) node 57 which was the farm transformer location farthest from the substation.

4.3 Operation of the AC Model

In verifying the effectiveness of the DC model, an AC model with the 150/75 kVA, 7,200/120/120 V distribution transformer model and the 60 Hz, 7,200 V (rms) sinusoidal voltage source as well as the transmission line inductance effect was developed. Figure 7 shows the AC network model. In this AC model, the 60 Hz, 7,200 V (rms) sinusoidal voltage source replaced the 7,200 DC source; the 150/75 kVA, 7,200/120/120 V distribution transformer model replaced each simulated load resistance; and simulated inductance was inserted along each segment of ungrounded and neutral conductor (X_L = R on each segment) in the DC base model of Figure 1. On the secondary side of each residential transformer, a 4 ohm resistor was connected to draw a 30A load. On the secondary of each farm transformer, a 2 ohm resistor was connected to create a 60A load.

In the AC model with the line inductance established above in Figure 7, along the entire distribution system, the primary neutrals and secondary neutrals in each of the fourteen residential and farm transformers were designed into two different connection styles -- bonded and separated. The "bonded" meant that the secondary neutral was connected with the primary neutral ground system. "Separated" meant that each of primary neutrals and secondary neutrals had their own ground system.

Beside the normal, no fault and balanced operational condition, 10 A secondary ground faults were introduced through a 12 ohm resistor placed between the ungrounded conductor of the secondary circuit and earth. The faults (in-phase and 180 ° out-of-phase) on the secondary side were attached to node 33 (similar to what had been done to the DC model in 4.1.10.)

Table 2. Primary Current and Load Resistance, RRL and RFL, for Different Primary Voltage Simulations.

Distribution Voltage	Residential Load Pri. A	Residential Load Sec. A	Residential Load RRL	Farm Load Pri. A	Farm Load Sec. A	RFL
2.4kV	3.0	30	800	6.0	60	400
4.8kV	1.5	30	3,200	3.0	60	1,600
7.2kV	1.0	30	7,200	2.0	60	3,600
26.4kV	0.27	30	96,800	0.54	60	48,400

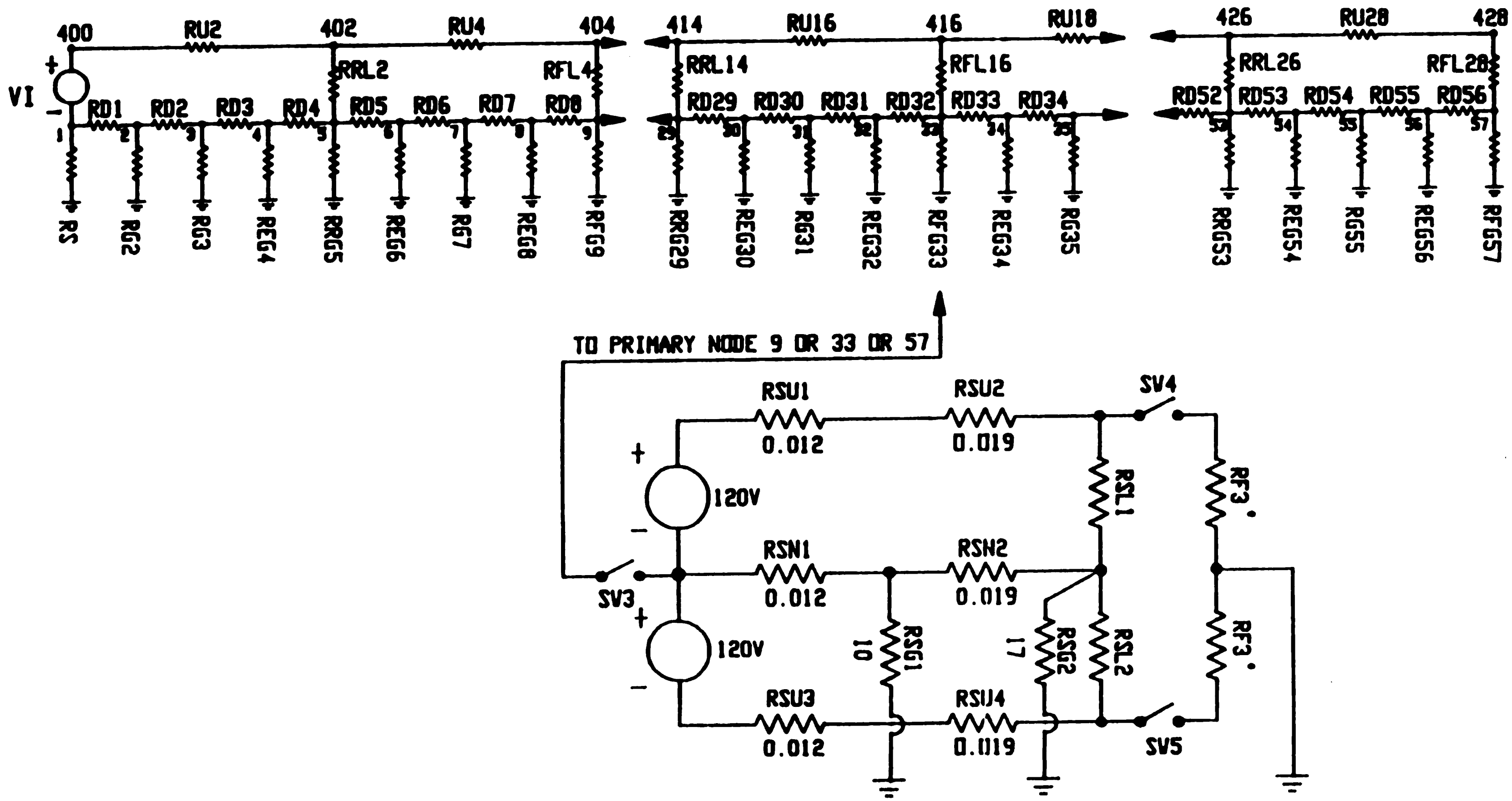


Figure 6. DC circuit model for single-phase electrical distribution system with secondary earth fault simulated

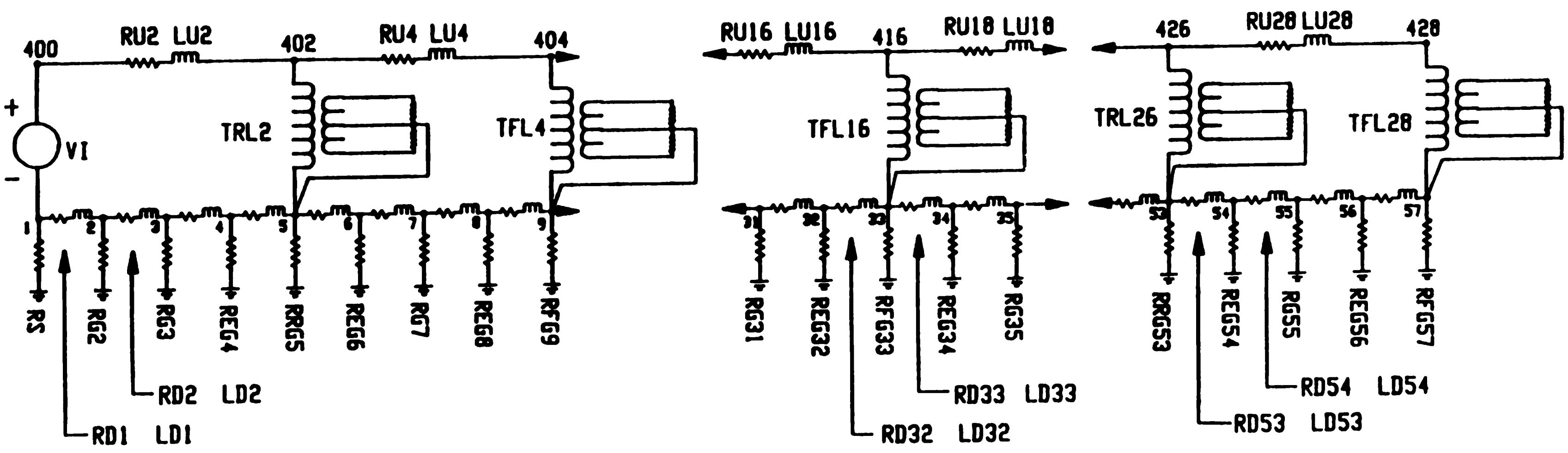


Figure 7. AC circuit model for single-phase electrical distribution system (input voltage 7,200 V)

V. RESULT and DISCUSSION

The computer simulation results of the eight DC cases and the AC models were analyzed to determine the level of the neutral-to-earth voltage produced under various operational conditions.

Although the neutral-to-earth voltage profiles were presented as if continuous, only the discrete voltage values at each of the 57 node locations were meaningful.

5.1 The DC Model Analysis

The effects of the different operational conditions on the neutral-to-earth voltage were studied primarily through the DC model. The effectiveness of the DC model was verified using an AC model of the same network.

As mentioned in section 4.1, for the DC cases, the negative values shown on the voltage profile diagrams signify phase reversals in the AC model. Some DC voltage profiles were analyzed with the negative signs changed to positive signs to represent the magnitudes of the rms voltage values which would be found in the AC model or on an actual distribution line. Some voltage profiles became confusing when the DC

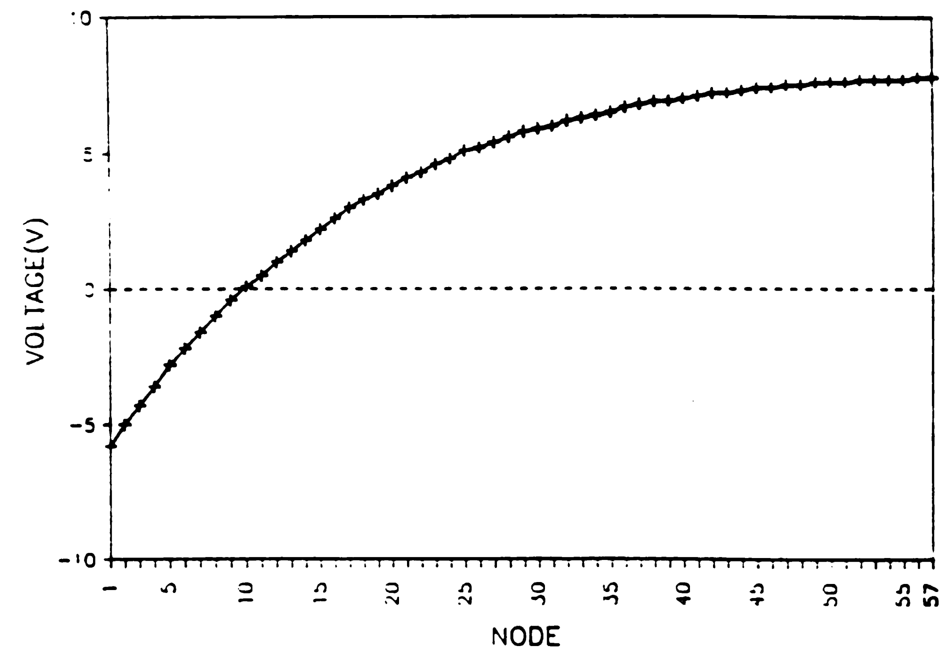


Figure 8. Profile of the neutral-to-earth voltage along the primary distribution line from substation (node 1) to 57th node for the base model

simulated neutral-to-earth voltages were all converted to positive values; in these cases, both positive and negative DC voltage values were shown.

5.1.1 Normal Operational Condition

The profile of the neutral-to-earth voltage along the distribution line for the base model is shown in Figure 8. The profile shows that the magnitude of the neutral-to-earth voltage at the substation (5.8 V) was slightly lower than at the end of the primary neutral line (7.8 V). Note that the magnitude of the neutral-to-earth voltage decreased as the distance away from the substation increased, reaching zero and experiencing a 180 degree phase angle change near node 10. Then the neutral-to-earth voltage increased as the distance from the substation became greater, leveling off toward the end of the neutral line.

Along the multi-grounded neutral power distribution systems which are commonly used in rural areas of the United States, some level of neutral-to-earth voltage is always present; it is an inherent phenomenon. Kehrle (1984), Gustafson (1985) and Surbrook et al. (1986) also obtained theoretical profiles of neutral-to-earth voltage similar to Figure 8.

5.1.2 Neutral Conductor Resistance Change

Figures 9 through 13 present the neutral-to-earth voltage simulation curves resulting from changing the neutral conductor resistance RD33 between nodes 33 and 34 (Figure 2) in different load conditions.

Figure 9 shows the the primary neutral-to-earth voltage profile with the variable neutral conductor resistance RD33 in the normal load condition (2A load in the primary side of the farm transformer RFL16). Note in the base case, when normal neutral resistance RD33 was 0.08 ohm, the voltage drop across this segment was only 0.1 V. (6.3 V neutral-to-earth voltage at node 33, 6.4 V at node 34). When RD33 was increased to 0.5 ohm to simulate an abnormal resistance in the neutral, 0.5 V voltage drop occurred between nodes 33 and 34. The neutral-to-earth voltage decreased by 0.2 V at node 33 toward the substation side, while it increased by 0.3 V at node 34 toward the end of the line. When neutral resistance RD33 was increased to 20 ohm, there was a 3.1 V voltage drop between node 33 and node 34. The neutral-to-earth voltage decreased by 1.2 V at node 33 and it increased by 1.8 V at node 34 as compared with the normal RD33 (0.08 ohm) condition. As the abnormal resistance RD33 was increased, the voltage drop across this segment also increased. The neutral-to-earth voltage became lower at nodes toward the substation from the location of the abnormal neutral resistance, and higher at nodes toward the end of the line. Note that the effect on neutral-to-earth voltage of an abnormal

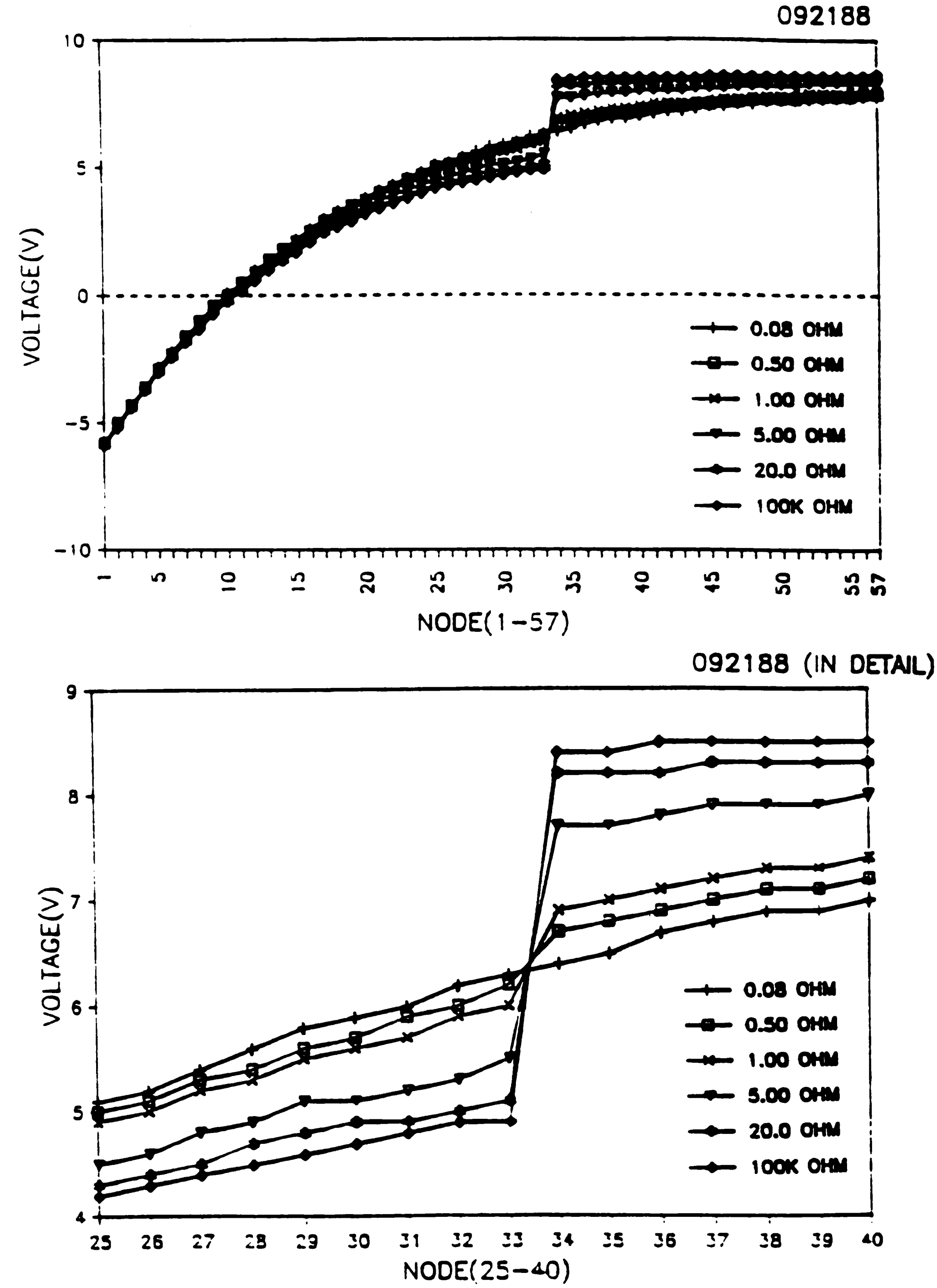


Figure 9. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with variable neutral conductor resistance RD33 between node 33 and node 34 and a customer load of 2A at node 33

neutral conductor resistance diminished as the distance from the neutral resistance RD33 increased. In the extreme case, when RD33 increased to 100 kohm (open circuit simulated), the voltage drop across this segment reached 3.5 V. The neutral-to-earth voltage decreased by 1.5 V at node 33 and increased by 2.1 V at node 34. However, the neutral-to-earth voltage was only changed 0.1 V at the substation and 0.9 V at the end of the line, as compared with the normal RD33 (0.08 ohm) situation (base case).

When a 3A load located at node 33 was chosen to repeat the simulation, the neutral-to-earth voltage profile of the 3A load simulation was similar to that of the 2A load simulation, but the voltage drop across the line segment RD33 was smaller than that of the 2A load simulation. The voltage drop between nodes 33 and 34 was 2.4 V in the open circuit condition of this segment, 69% of the 3.5 V voltage drop of the 2A load simulation in open circuit condition. See Figure 10.

When a 5A customer load was chosen at node 33 to repeat the simulation, no matter how the neutral resistance RD33 was changed, all neutral-to-earth voltage profiles were nearly identical. This result is shown in Figure 11. All these identical neutral-to-earth voltage profiles were higher than those in the base case with the largest difference 2.5 V at node 34 and the smallest difference 0.2 V at node 9 (near profile phase reversal node).

When a 10A load was chosen at node 33 to repeat the simulation, the profile of neutral-to-earth voltage increased on the substation side of neutral conductor resistance RD33 as compared with the 5A customer load. This is shown in Figure 12. As the abnormal RD33 was increased, the voltage drop across this segment also increased significantly again. But, unlike cases of the 2A and 3A load simulation, this time the neutral-to-earth voltages were higher at nodes toward the substation side and lower at nodes toward the end of the line. However, similarly, the effect on both sides was diminished rapidly away from the high resistance segments. In the extreme case, when RD33 was increased to 100 kohm (open circuit simulated), the voltage drop across this segment reached 4.9 V. But this time the voltage increased by 2.0 V at node 33 and decreased by 2.9 V at node 34. The voltages only changed 0.1 V at the substation and 1.2 V at the end of the line, as compared with the normal RD33 (0.08 ohm) situation.

The profile changing trend in the variable load cases when an abnormal resistance in series with the primary neutral conductor RD33 was in the extreme open circuit situation (RD33=100 kohms) is shown in Figure 13. As the load at node 33 increased, the neutral-to-earth voltages became higher on the substation side of node 33; and the profiles were identical from node 34 to the end of the line. The changes of the neutral-to-earth voltage decreased as the distance increased along the direction from node 33 to the substation in all load cases. In those cases of the loads less than 5A, the neutral-to-earth voltages from node 33 to the substation were lower than those from node 34 to the end; and the difference between them became smaller as the load became heavier. In those cases of the loads more than the 5A, the neutral-to-earth voltages from node 33 to the substation were higher

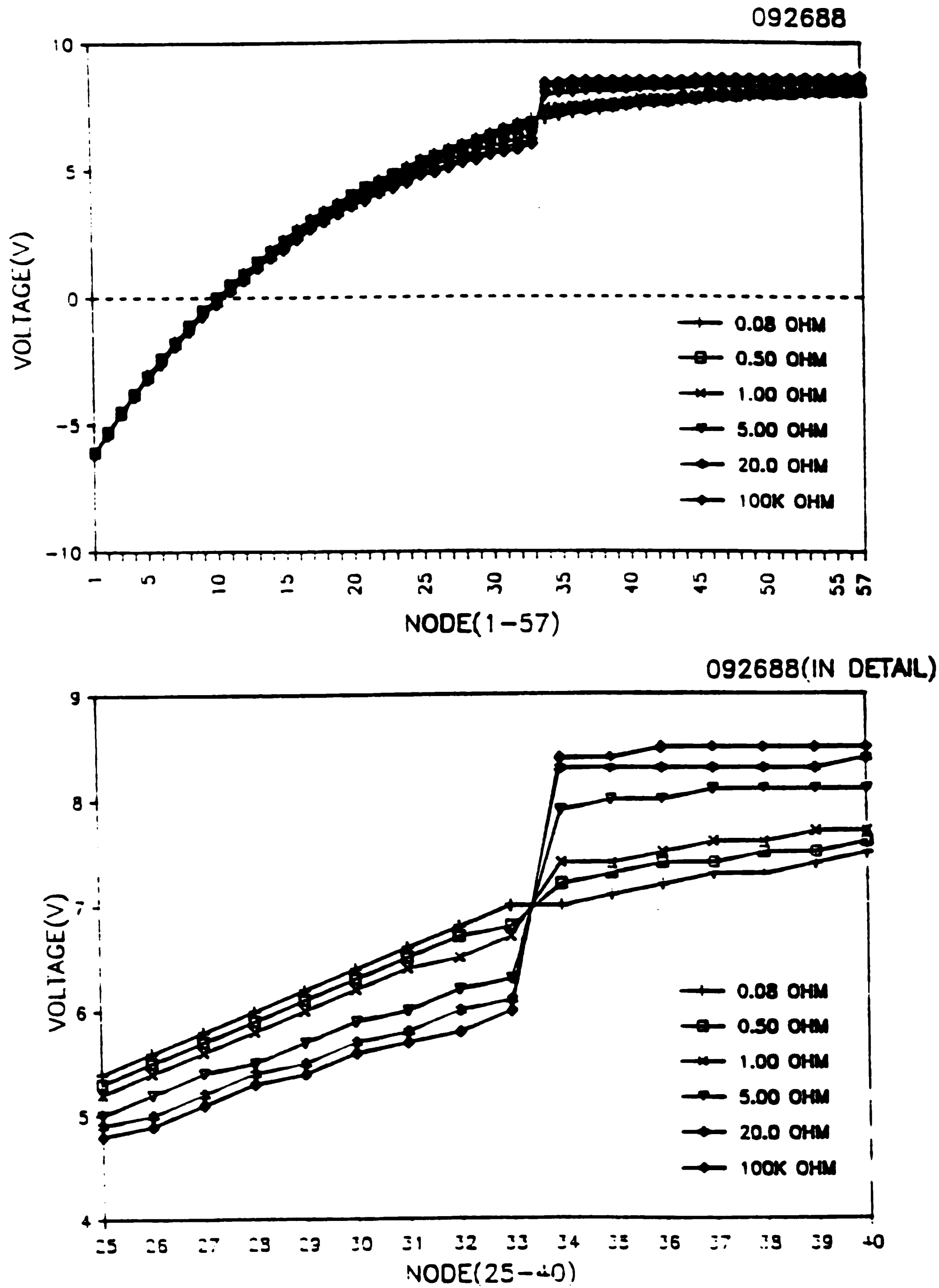


Figure 10. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with variable neutral conductor resistance RD33 between node 33 and node 34 and a customer load of 3A at node 33

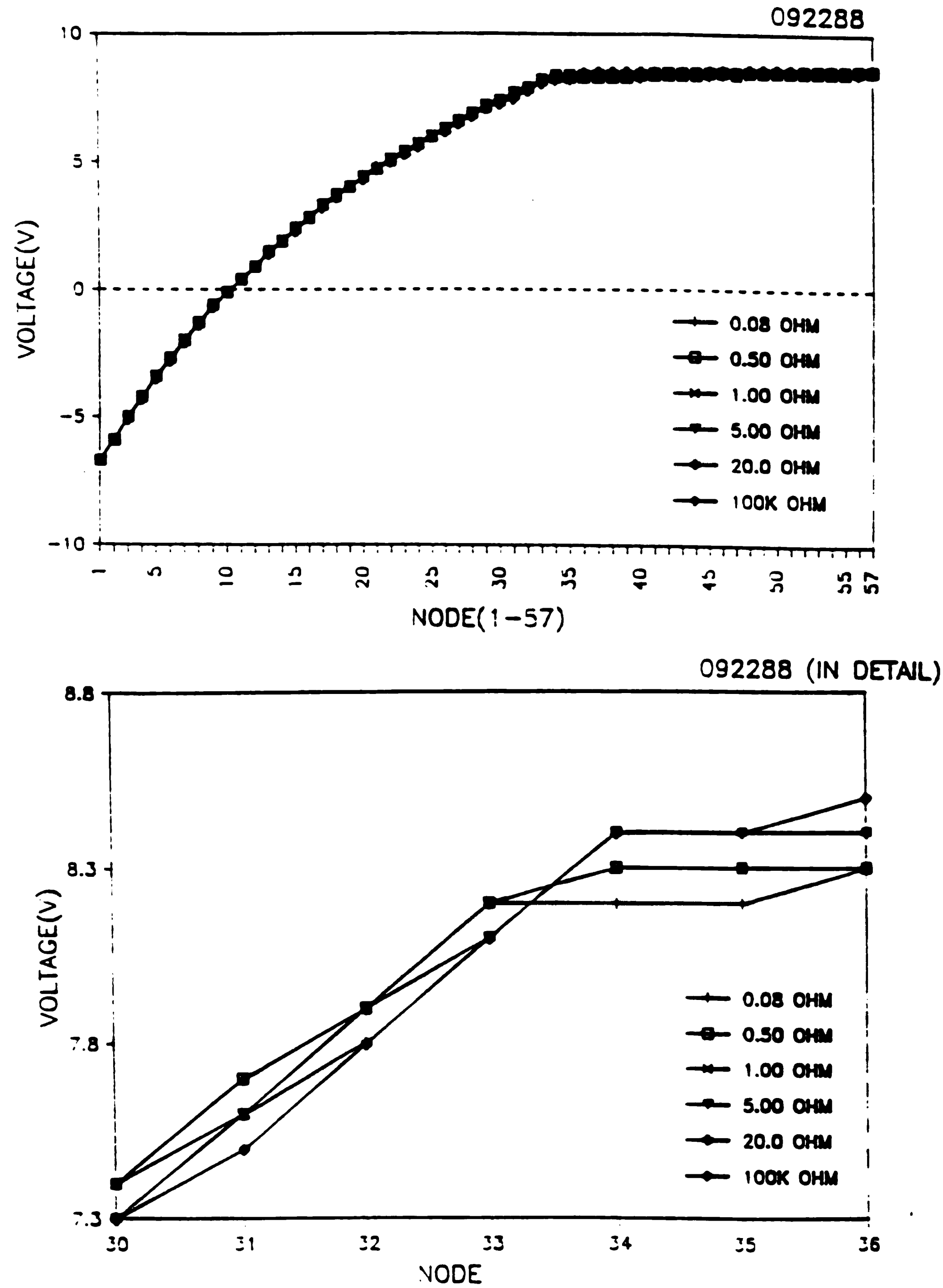


Figure 11. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with variable neutral conductor resistance RD33 between node 33 and node 34 and a customer load of 5A at node 33

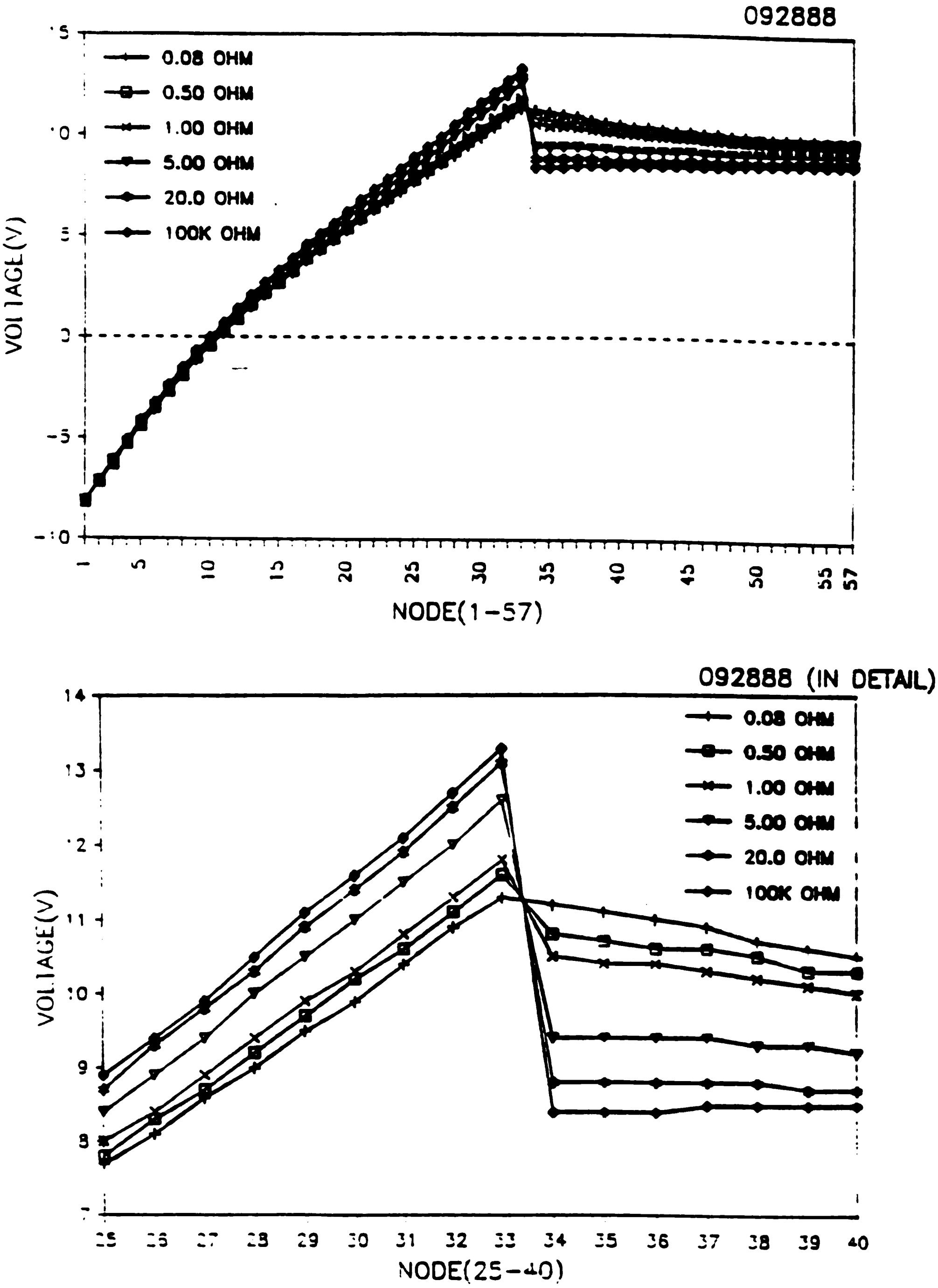


Figure 12. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with variable neutral conductor resistance RD33 between node 33 and 34 (10A Load)

than those from node 34 to the end of the line; and the difference between them became larger as the load became heavier.

The theoretical calculation and practical field measurement indicate that primary neutral-to-earth voltage is highly associated with the current in the local primary neutral conductor -- higher neutral current results in higher neutral-to-earth voltage locally and lower neutral current results in lower neutral-to-earth voltage locally (this will be discussed in detail in section 5.1.5 and 5.1.9). In Figure 13, since there was an open circuit between node 33 and node 34 in the circuit system, and the resistance on the substation side of node 33 was much lower than the ground rod resistance, most load current took the pathway in the neutral conductor from node 33 toward the substation side. In the heavy load condition, this raised the electric potential on the substation side. The heavier the load, the higher the potential raised.

Simulation of the neutral-to-earth voltage along single-phase primary distribution lines reported by Kehrle (1984), Gustafson (1985) did not examine the effect of level of primary load located immediately on the substation side of an abnormal resistance in the neutral conductor. As can be seen from Figure 13, it is possible to have a higher neutral-to-earth voltage on the substation side of an abnormal neutral resistance than on the side toward the end of the line.

Figures 14 through 16 present the neutral-to-earth voltage simulation curves resulting from changing the neutral resistance RD32 between nodes 32 and 33 in different load conditions (see Figure 2 for circuit model).

Figure 14 shows the the primary neutral-to-earth voltage profile with the variable neutral conductor resistance RD32 in the normal load condition (2A load). The voltage change trends were similar to those in the same load condition of the RD33 change shown in Figure 9. When RD32 was 100 kohm (open circuit simulated), the voltage drop across the segment of node 32 and node 33 reached 5.4 V. This value was 86% of that at node 33 in the base case, a decrease by 2.9 V at node 32 and an increase by 2.5 V at node 33. However, the neutral-to-earth voltage was only changed 0.2 V at the substation and 1.0 V at the end of the line, as compared with the normal RD32 (0.08 ohm) situation (base case).

Figure 15 shows the the primary neutral-to-earth voltage profile with the variable neutral conductor resistance RD32 and a 5 A load at simulated transformer, RFL16. The voltage change trends were different from those in the same load condition of the RD33 change (in that case all the voltage profile were identical) but similar to those with the 2 A load condition of the RD32 change. The voltage changed more dramatically. When the line segment RD32 was 100 kohm (open circuit simulated), the voltage drop across the segment of node 32 and node 33 reached 9.6 V. This value was 1.52 times of that at node 33 in the base case with a value of 6.3 V.

The neutral-to-earth voltage profile changing end in the variable load (RFL16) cases with an abnormal resistance in series with the

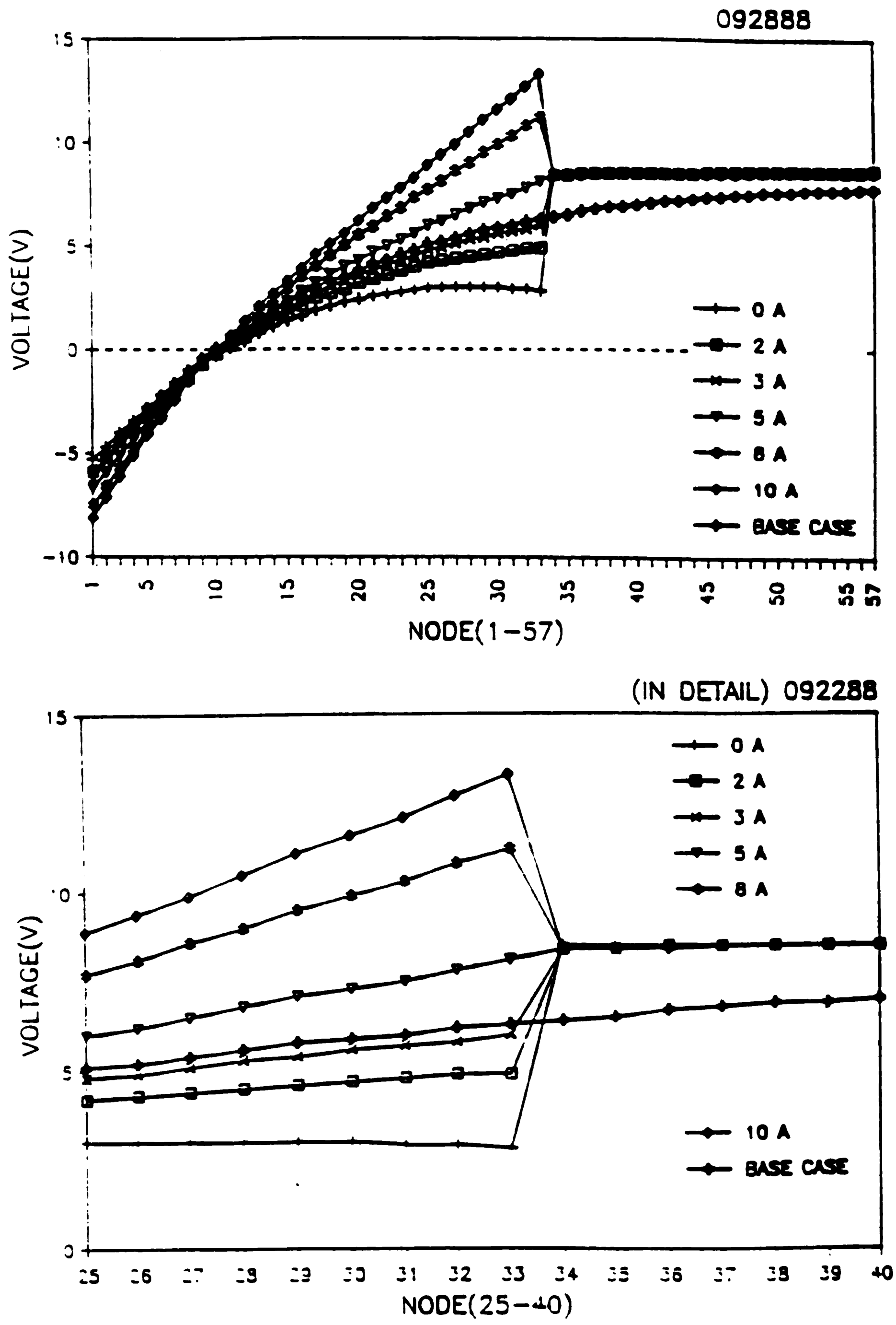
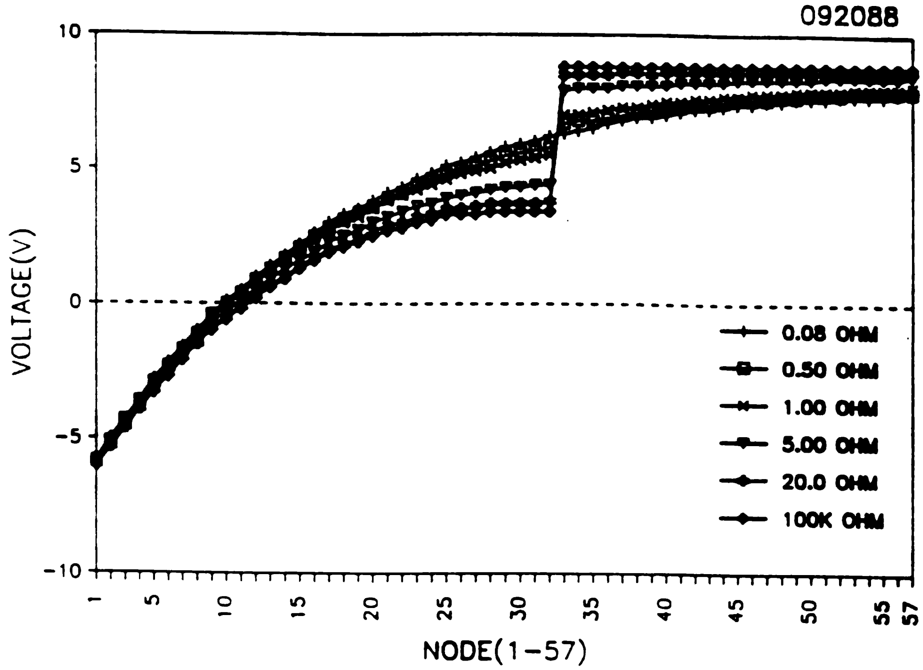


Figure 13. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with load condition changed in the open circuit (between node 33 and 34) situation.



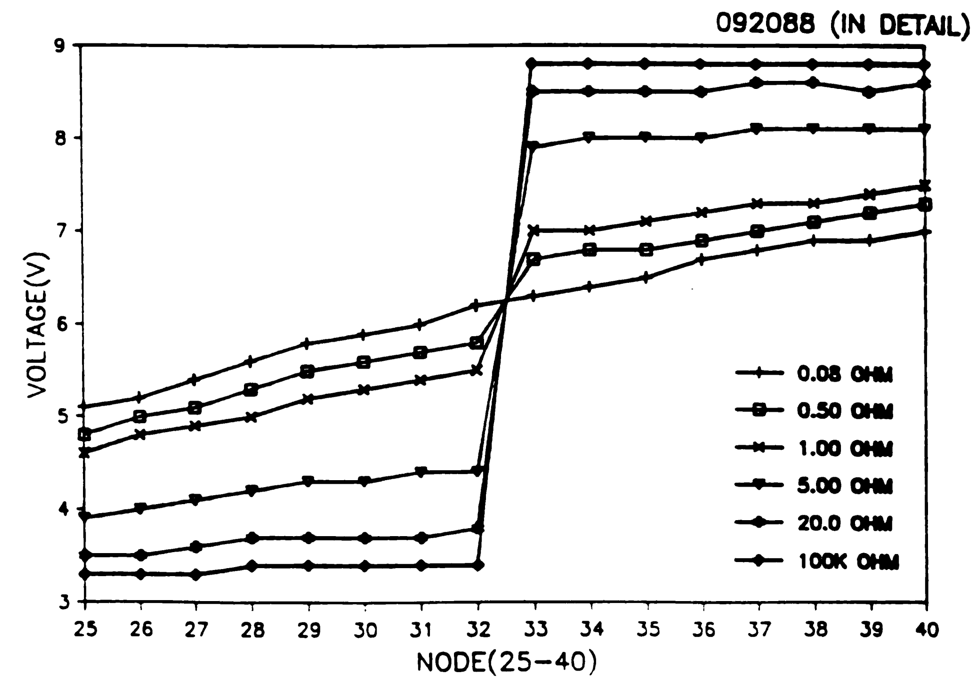
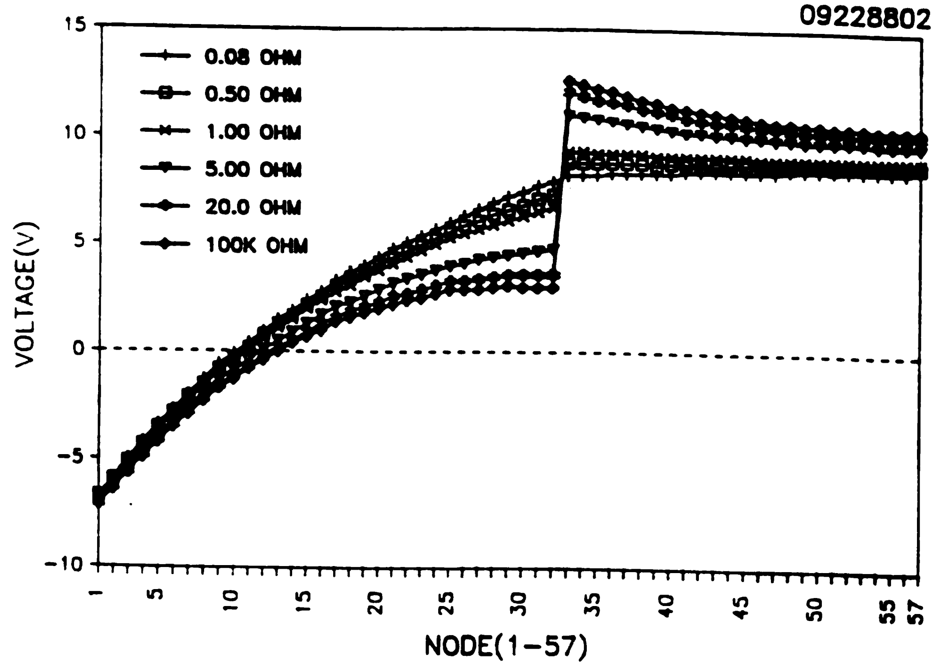


Figure 14. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with variable neutral conductor resistance RD32 between node 32 and 33 (2A Load)

primary neutral conductor RD32 in the extreme open circuit situation is shown in Figure 16. As the load became heavier, the neutral-to-earth voltages became higher from node 33 to the line end (node 57); and the profiles were not significantly different from node 32 to the substation node 1). The changes of the neutral-to-earth voltage decreased as the distance increased along the direction from node 33 to the end of the line (node 57) in all load cases when RD32 was 100 kohm.

Figure 16 also can be explained by the level of neutral current on the local line segment. In Figure 16, there was an open circuit between node 32 and node 33 in the circuit system, and the resistance on the end side of the line near node 33 was much lower than the ground rod resistance. Most of the load current took the pathway in the neutral conductor from node 33 toward the end of the line. In the heavy load condition, this raised the neutral-to-earth voltage on the direction toward the end of the line. The heavier the load, the higher the neutral-to-earth voltage raised.

From Figure 9 through Figure 16, it can be seen that the primary neutral-to-earth voltage changes sharply at the high resistance segment along the primary neutral line, resulting in the neutral-to-earth voltage improvement at some distance along the distribution line and worsening elsewhere along the distribution line. Generally speaking, the higher the resistance of the segment, the larger the changing effect. But the effect is both localized and load-dependent. This indicates that along the primary neutral line, the substantial changes in the neutral-to-earth voltage may occur in the immediate vicinity of the bad connection, but



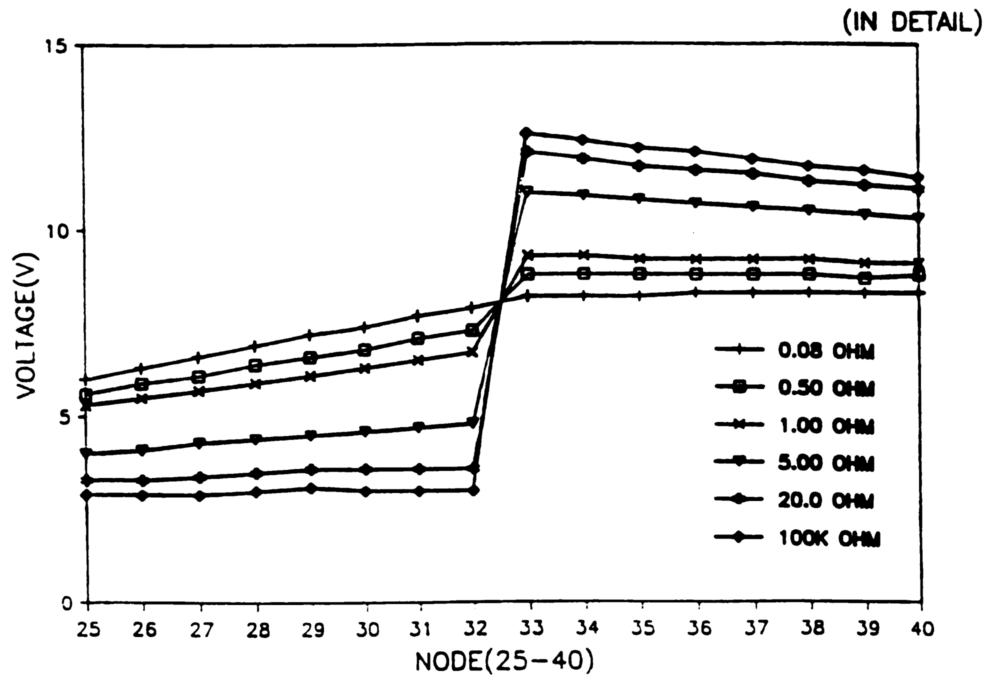


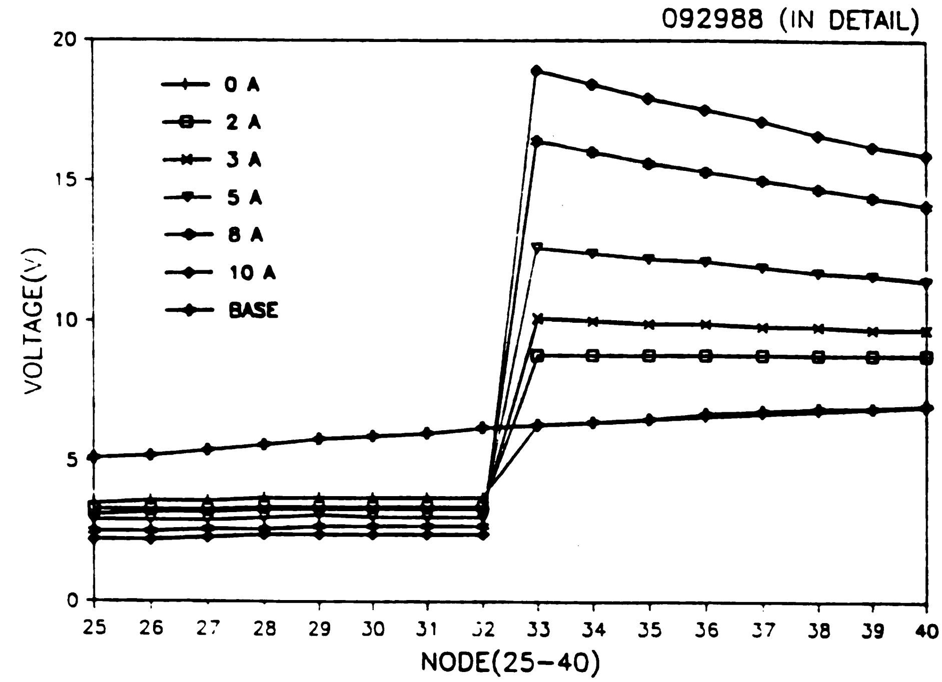
Figure 15. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with variable neutral conductor resistance RD32 between node 32 and 33 (5A Load)

the effect will be damped rapidly along the line toward both directions. However, when the segment resistance is beyond some threshold, say, 20 ohm, the changing effect approaches a maximum for given load conditions.

Stetson et. al (1984), Kehrle (1984), Gustafson (1985) and Surbrook et al. (1986) found the profile split phenomenon in neutral-to-earth voltage caused by a high resistance at some location along the primary neutral conductor in a normal load condition similar to Figure 9 and Figure 14. But the effect of high primary neutral resistance associated with a heavy load condition near the abnormal neutral resistance on neutral-to-earth voltage has not been documented prior to this thesis.

5.1.3 High Resistance Connection of Neutral to Transformer Primary

Figure 17 presents the neutral-to-earth voltage simulation curves resulting from changing neutral contact resistance RC with transformer-to-ground rod at node 33 (circuit connection in Figure 3). In this scenario, the neutral terminal of the transformer primary winding is solidly connected to ground rod RFG33, but it experiences a high resistance (RC) connection to the primary neutral at node 33. This condition has been experienced in the field where the neutral-to-earth voltages along a distribution line were normal except for a high neutral-to-earth voltage at the customer transformer location of the high resistance connection.



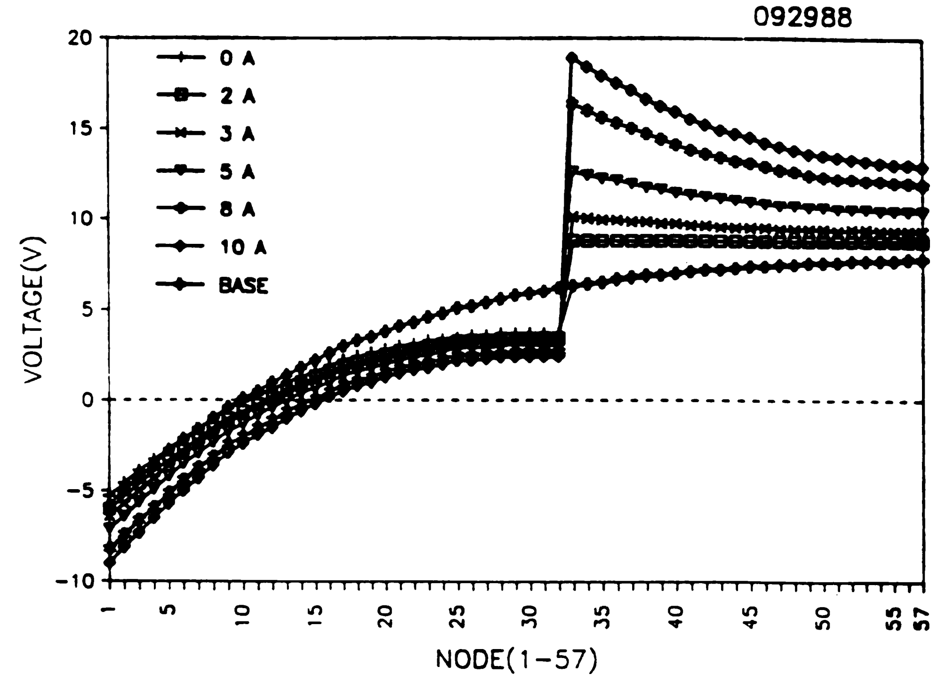


Figure 16. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with load condition changed in the open circuit (between node 32 and 33) situation.

Compared with base case, when contact resistance RC was increased from 0 ohm (base case) to 0.5 ohm, 1 ohm, 5 ohm and 100 kohm, at the poor connection node, neutral-to-earth voltage increased sharply as the contact resistance increased. Note in the base case, when the RC was zero, the value of neutral-to-earth voltage at node was 6.3 V. When the value of RC was increased to 0.5 ohm, the voltage increased by 0.3 V. When the value of RC was increased another 0.5 ohm (total RC = 1 ohm), the voltage again increased by 0.3 V. When the value of RC was increased to 5 ohms, the voltage increased to 8.0 V (2.7 V higher than base case), but the increase was only at the transformer location of bad connection. In the extreme case, when the value of RC was increased to 100 kohm (open circuit simulated), the voltage reached 9.9 V, creating an acute local increase of neutral-to-earth voltage. This was due to all local primary load current (2 A) flowing through the pathway of ground rod RFG33 (product of 2 A and 5 ohms was 10 V).

No significant neutral-to-earth voltage changes occurred elsewhere along the whole line system away from the bad connection. This means that to locate a bad connection of this type, the measurements must be at the customer transformer location.

5.1.4 Primary Phase-to-Neutral Fault (or Heavy Load)

Figure 18 presents the neutral-to-earth voltage simulation curves resulting from different currents through a simulated fault or additional heavy load between primary ungrounded conductor node 416 and neutral node 33 (circuit connection in Figure 4). Faults in equipment on a primary distribution line have been reported to have resulted in a lowering of the neutral-to-earth voltage in a local area when the fault situation was corrected. Previous research did not explain how this phenomenon could occur. Analysis of possible primary fault scenarios revealed that a fault usually as an ungrounded phase conductor to grounded equipment (neutral) fault. The behavior of a phase to neutral fault is identical to placing a phase to neutral load at the location of the fault. Vegetation making intermittent simultaneous contact with the ungrounded conductor and the neutral will cause an intermittent increase in the neutral-to-earth voltage as shown in Figure 18.

Compared with the base case, when fault or additional load current was increased from 0 A (base case) respectively to 1.0 A, 5.0 A, 10 A and 20 A, the neutral-to-earth voltage also increased accordingly in most segments along the distribution line. Note the most significant increases of the neutral-to-earth voltage occurred at node 33 where the fault took place. At this node, in the base case, when the fault current was zero, the value of the neutral-to-earth voltage was 6.3 V. When the fault was increased to 1.0 A, the voltage increased by 0.7 V, to 7 V. When the fault was increased to 5.0 A, the voltage increased by another 2.5 V, to 9.5 V. When the fault was increased to 10 A, the voltage again increased another 3.1 V, to 12.6 V. When the fault was increased to 20 A, the voltage reached 18.7 V (increased by 2.0 times from the base case

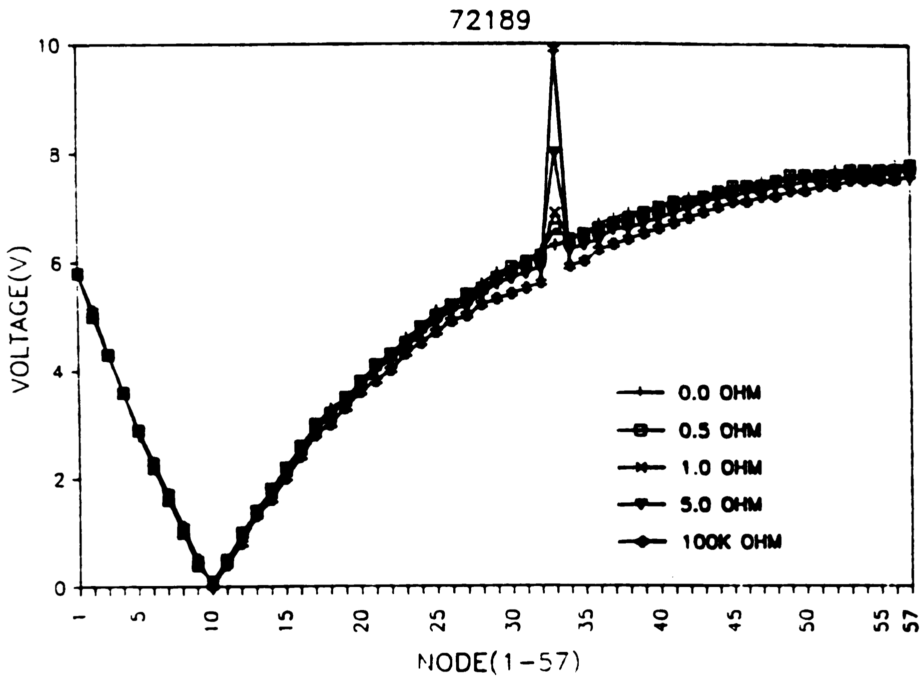


Figure 17. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with variable bad neutral connection resistance RC with transformer and ground rod at node 33

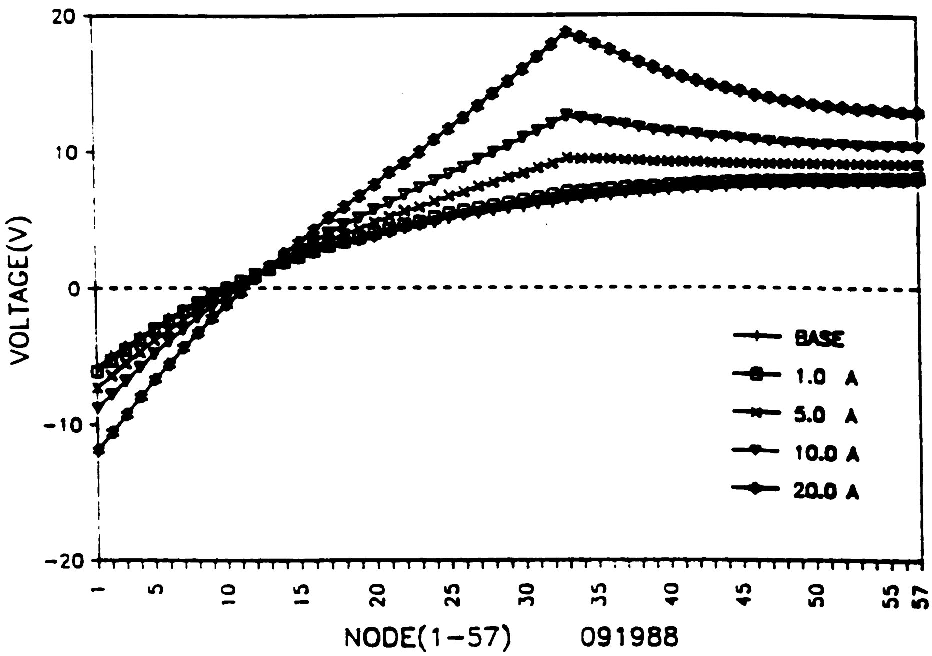
of 6.3 V). The neutral-to-earth voltage increased almost linearly with the fault current at a rate of 0.6-0.7 V/A near the fault node.

Toward the end of the line node 57, the neutral-to-earth voltage increase was less significant. Even so, when the fault was 20 A, the voltage at node 57 increased to 12.9 V, 165% of the base case value of 7.8 V.

Toward the direction of the substation, the neutral-to-earth voltage increases first diminished, approaching the values close to those of base case near node 13. From node 13 to the substation node 1, as the distance increased, the voltages also increased slightly. Near the substation, when the fault was 20 A, the voltage increased to 11.9 V, 2.05 times of the base case value of 5.8 V.

Figure 19 presents the neutral-to-earth voltage simulation curves resulting from changing current through fault simulation bypass from primary unground conductor node 426 to neutral node 53 near the end of the line.

Compared with the base case, when fault current was increased from 0 A (base case) respectively to 1.0 A, 5.0 A, 10 A and 20 A, the neutral-to-earth voltage also increased accordingly in most segments along the distribution line. Note the most significant increase of the neutral-to-earth voltage occurred at node 53 where the fault took place. This voltage increase was similar to that of the fault at node 33 except that the significant voltage increase occurred at the different location. At node 53, in the base case, when the fault current was zero, the value of the neutral-to-earth voltage was 7.8 V. When the fault was increased



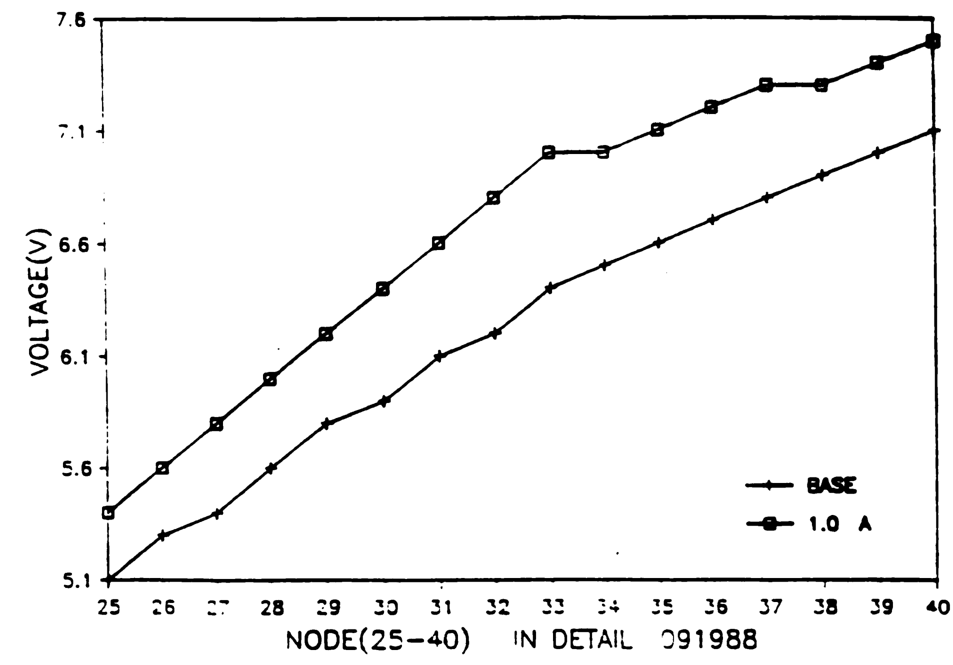


Figure 18. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with variable unground phase conductor to neutral fault at node 416-33

to 1.0 A, the voltage increased by 0.9 V, to 8.7 V. When the fault was increased to 5.0 A, the voltage increased by another 3.8 V, to 12.5 V. When the fault was increased to 10 A, the voltage again increased one more 4.8 V, to 17.3 V. When the fault was increased to 20 A, the voltage reached 26.8 V (increased by 2.5 times from base case 7.7 V). The neutral-to-earth voltage increased almost linearly with the fault current at rate 0.9-0.96 V/A near the fault node 53.

Toward the direction of the substation, the neutral-to-earth voltage increases first diminished, approaching the values close to those of the base case near node 19. From node 19 to the substation node 1, as the distance increased, the voltages also increased slightly. Near the substation, when the fault was 20 A, the voltage increased to 12.5 V, 2.2 times of the base case value 5.8 V.

From Figure 18 and Figure 19, it can be seen that when a primary phase-to-neutral fault occurs somewhere in the distribution line, the neutral-to-earth voltages increased in most segments along the distribution line. These voltage changes are fault-size and fault-location dependent. The voltages increased as the fault currents increased. The most significant voltage increase occurs near the fault location. This is due to the large neutral current injection from local fault current. The same conditions would be created by placing a large load at a specific location along the distribution line.

5.1.5 Primary Phase-to-Earth Fault

Figure 20 presents the neutral-to-earth voltage simulation curves resulting from fault current through a resistance between the primary ungrounded conductor at node 416 and the earth (circuit connection in Figure 5). A similar condition has been reported in the literature, but it is repeated here as a comparison with the data produced with the primary ungrounded phase conductor to neutral fault condition.

Compared with base case, when fault current was increased from 0 A (base case) respectively to 1.0 A, 5.0 A, 10 A and 20 A, the neutral-to-earth voltages increased accordingly in some segments near the substation and decreased some distance away from the substation toward the end of the line. This is shown in Figure 20. Note the most significant changes of the neutral-to-earth voltage occurred near node 1 where the substation was located. Near the substation, in the base case, when fault current was zero, the value of neutral-to-earth voltage was 5.8 V. When the fault was increased to 1.0 A, the voltage also increased by 0.3 V, to 6.1 V. When the fault was increased to 5.0 A, the voltage increased by another 1.5 V, to 7.6 V. When the fault was increased to 10 A, the voltage increased 1.8 V, to a level of 9.4 V. When the fault was increased to 20 A, the voltage reached 13.1 V (increased by 1.26 times from base case 5.8 V). Similar to the primary-to-neutral fault situation discussed in section 5.1.4, the neutral-to-earth voltage increased almost linearly with the fault current, but this time at a rate of 0.3-0.37 V/A near the substation node 1.

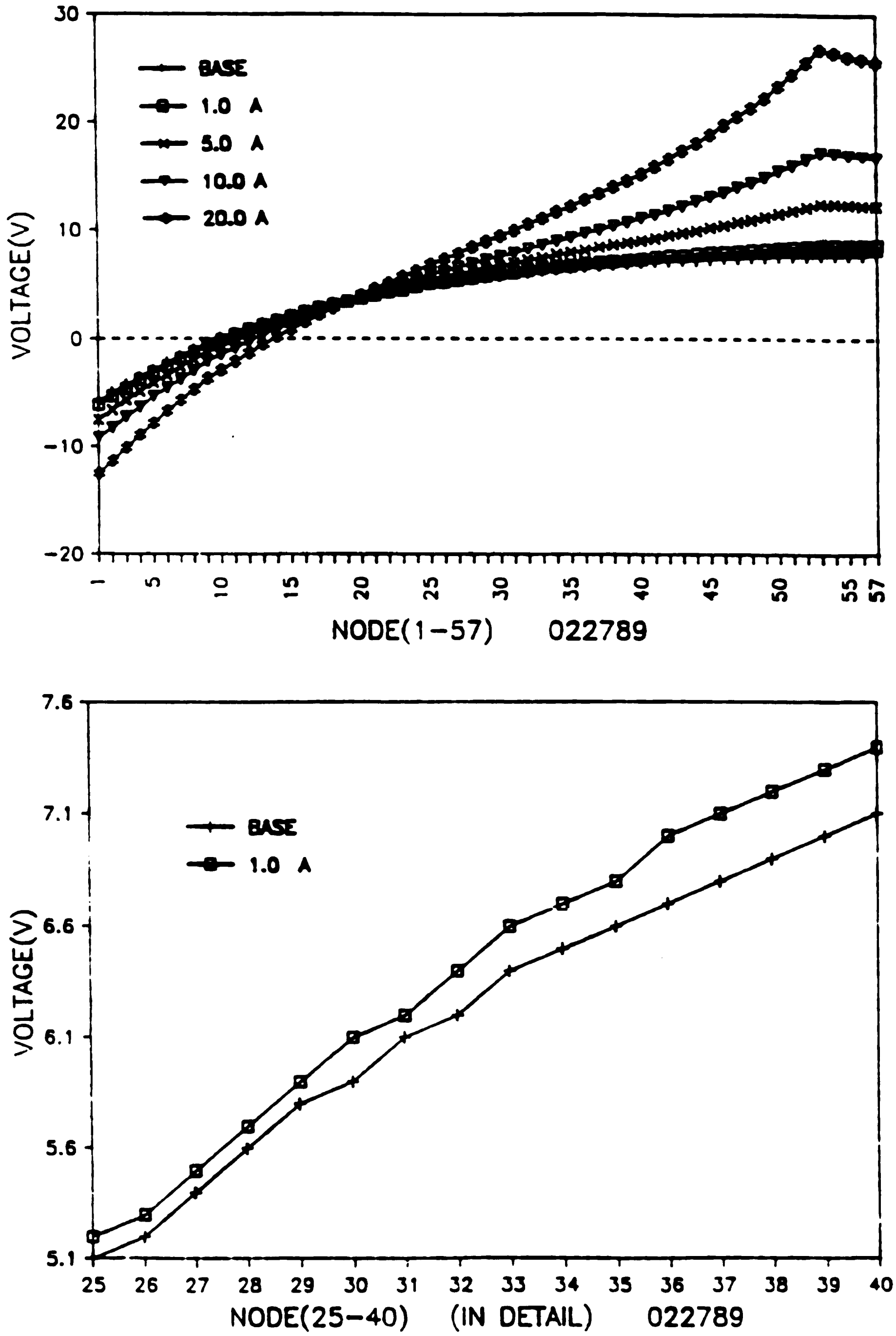


Figure 19. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with variable unground phase conductor to neutral fault at node 426-53

This effect of the change of the neutral-to-earth voltage diminished rapidly as the distance increased from substation node 1 toward the end (node 57) of the line. In a 20 A fault, at the middle (node 33) of the line, the voltage was 5.1 V, 81% of base case value 6.3 V; at the end node 57, the voltage was 7.3 V, only 93.6% of the base case value of 7.8 V. It is important to note that a primary ungrounded conductor to earth fault resulted in a decrease in the neutral-to-earth voltage from middle to the end of the line.

Figure 21 presents the comparison of the neutral-to-earth voltage simulation curves resulting from a 20 A simulated fault from the primary ungrounded conductor to earth introduced at three locations -- node 404, node 416, and at node 428 (absolute values of the DC voltages were shown). It can be seen that the neutral-to-earth voltage profiles along the distribution line were identical for all three fault cases. An observed abnormally high neutral-to-earth voltage near the substation may be caused by a primary ungrounded conductor to earth fault at any point along the whole line system.

It is important to note from Figure 20 and 21 that the neutral-to-earth voltage decreased from node 15 to the end of the line when a primary ungrounded conductor to earth fault occurred at any location along the line. Even when the primary fault to earth occurred near the end of the line (node 428) the neutral-to-earth voltage was decreased even at the fault node as compared to the base case without a fault condition.

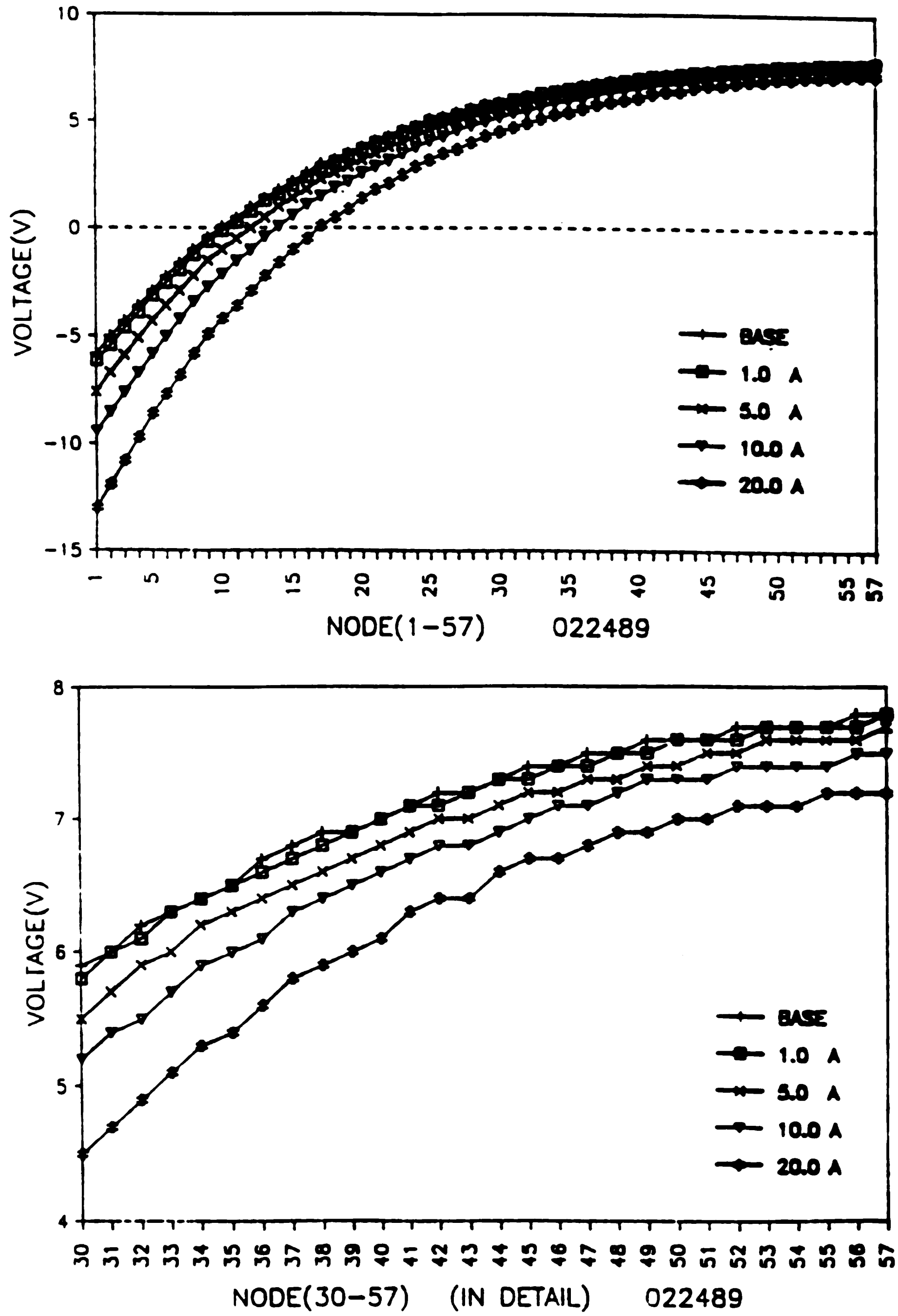


Figure 20. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with an ungrounded phase conductor to earth fault at node 416 compared with the normal line

Figures 22 through 26 present the electric current distribution situation of the entire system resulting from a 20 A fault current from primary ungrounded conductor to earth introduced at node 416 near the middle of the line.

From Figure 22 it can be seen that compared with the base case, there was an increase in the current flow on the primary neutral in the fault case due to fault current returning to the neutral by way of the distribution line grounds. This current increase was associated with the local neutral-to-earth voltage increase, significant along the line near substation node 1 and less and less significant in the direction away from the substation. In this fault case, near the substation, the current on the primary neutral was 14.3 A, 154% of the base case value 9.3 A; near the end node 57, the neutral current was 0.5 A, only 125% of the base case value 0.4 A.

In this simulation of an ungrounded primary conductor to earth, the grounding electrode current consisted of the load current flowing between the neutral and the earth and the fault current flowing between the earth and the neutral. Near the substation, the load current flowing through the grounding electrodes and the fault current were in phase. Therefore, the two currents added to cause the increase in neutral-to-earth voltage near the substation observed in Figures 20 and 21. From node 11 to the end of the line, the load current and the fault current flowing through the grounding electrodes was 180 degrees out of phase thus subtracting. From node 15 to the end of the line, the net grounding electrode current was smaller for the primary ungrounded

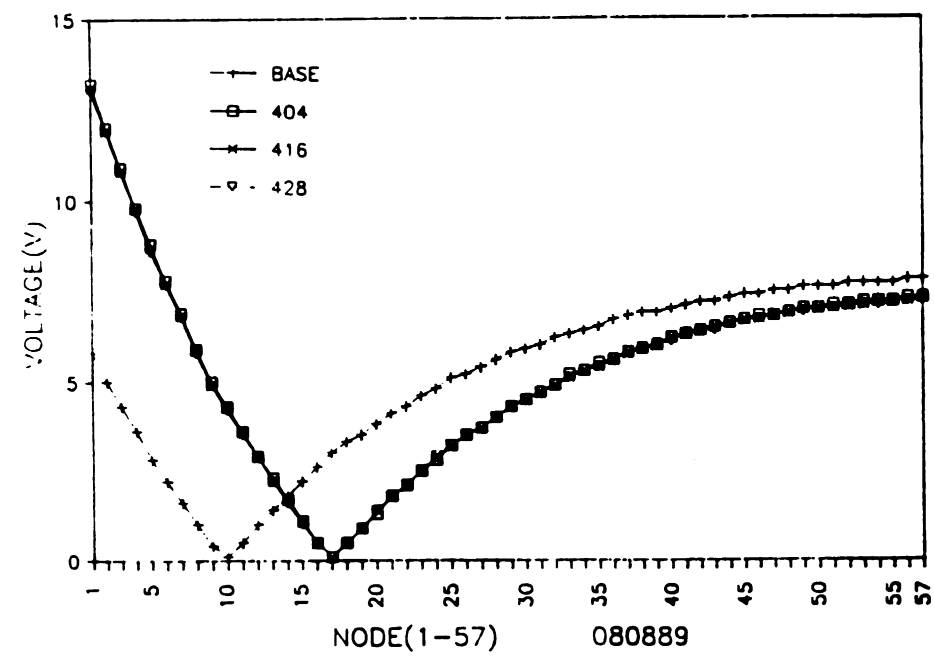


Figure 21. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with 20 A phase conductor to earth fault at node 404, 416, or 428 compared with normal line

conductor to earth fault case than for the normal case without a fault. This resulted in a lower neutral-to-earth voltage for the fault case than for the normal case. The case of a phase to earth fault located at node 428 at the end of the line is illustrated in Figure 23.

The highest level of phase to earth fault current simulated was 20 amperes. Comparison of Figures 24 and 25 reveals the amount of fault current returning to the substation by way of the substation grounding electrode. Subtraction of node 1 current of Figure 24 from node 1 current of Figure 25 reveals that the fault component of the substation grounding electrode current is approximately 15 amperes. Figure 24 shows the grounding electrode currents along the line for the normal load case. Figure 25 shows the grounding electrode currents along the line with normal load plus a 20 ampere phase to earth fault at node 416. Node 1 on both figures is the current of the substation grounding electrode.

Note that for nodes 2 through 9 in Figure 25 as compared to Figure 24, fault current is detected returning to the primary neutral. For other nodes towards the end of the line, the grounding electrode currents is actually reduced, but the change is difficult to detect. The reduction of normal line current due to fault current returning to the neutral conductor can be seen at nodes 17, 21 and 25 of Figure 25 compared with Figure 24.

It is also important to note from Figures 20, 22, and 25 that it is not possible to determine that a primary phase to earth fault is actually present (node 416) by observing a neutral-to-earth voltage or neutral

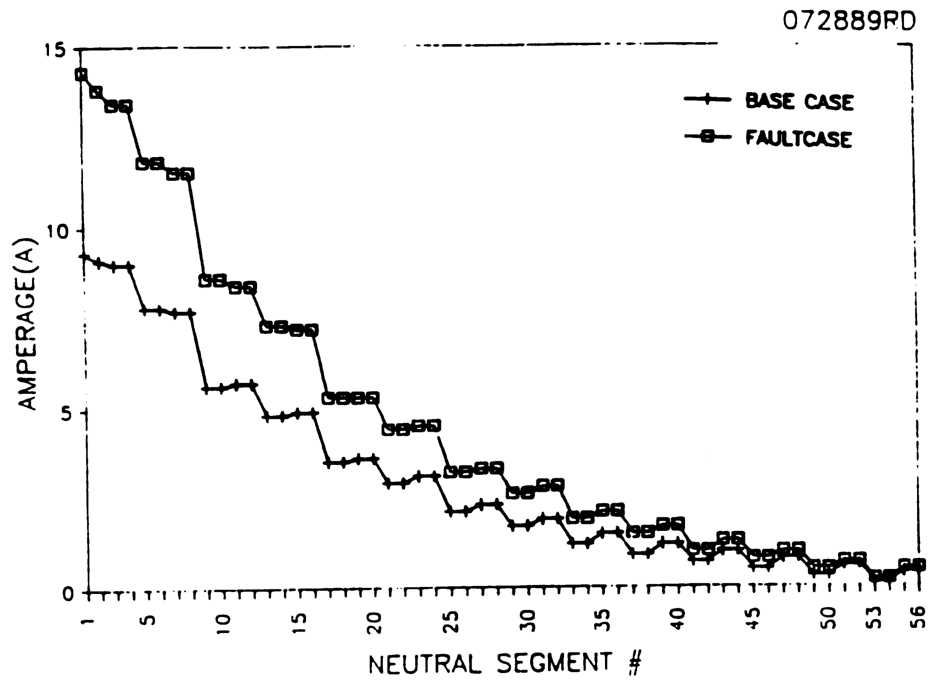


Figure 22. The primary neutral conductor current for each line segment from the substation to the end of the line for normal load compared with normal load plus a 20 A fault at node 416

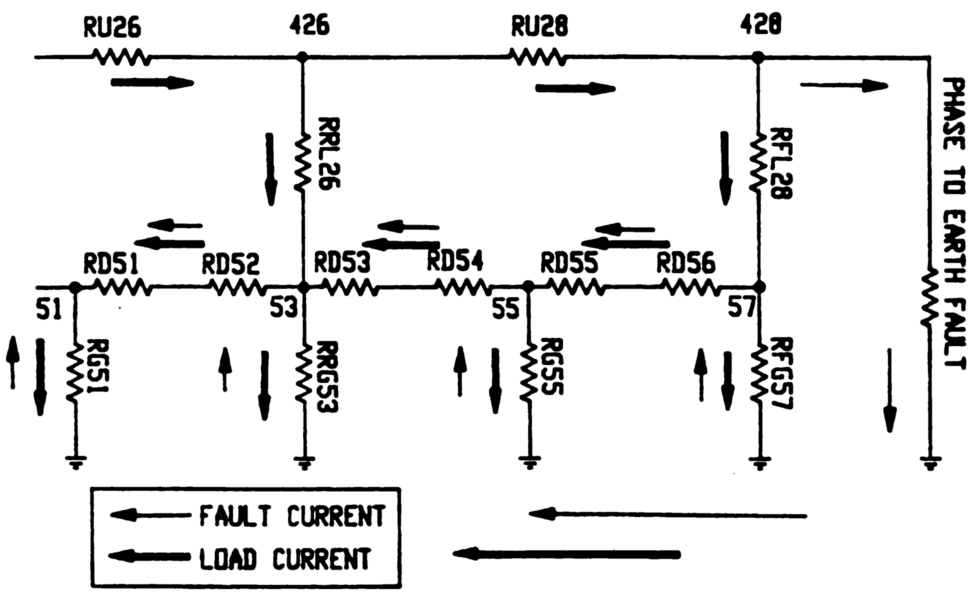


Figure 23. Phase relationship of normal neutral load current and primary to earth fault current at the end of the line

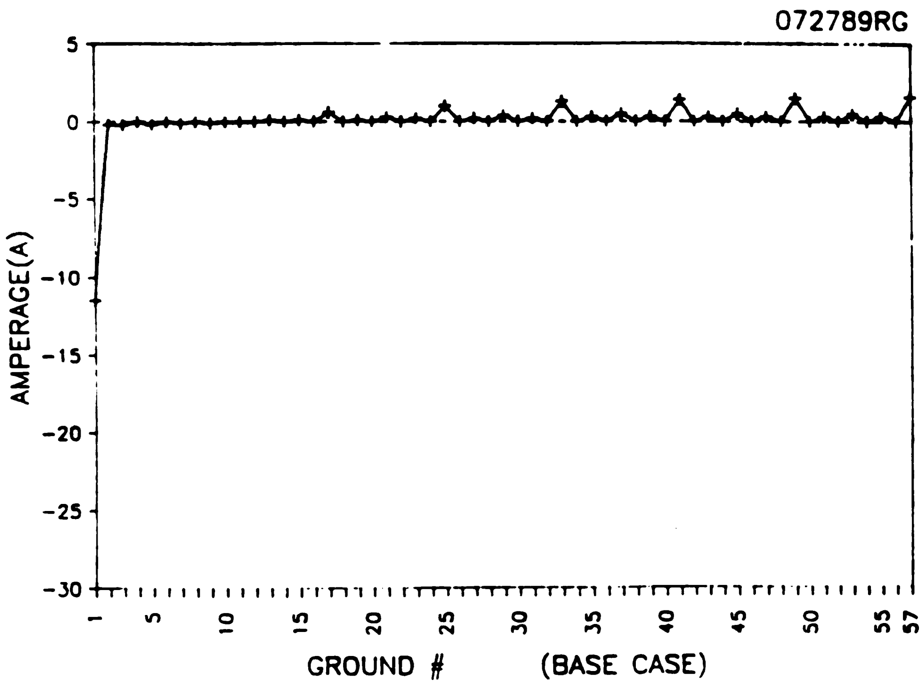


Figure 24. The normal operating distribution line grounding electrode currents from the substation to the end of the line

current abnormally in the area of the fault. The presence of the fault can be seen by the step reduction in primary ungrounded conductor current at the location of the phase to earth fault as shown in Figure 26.

Figure 27 represents the current in each segment of the primary neutral conductor for the normal load case and for the normal load plus a 20 ampere primary to earth fault at node 404, 416, and 428. The top curve of Figure 27 is the same regardless of the location of the primary to earth fault. Note that at the end of the line, the current flow on the neutral conductor is only slightly changed by a primary to earth fault at the end of the line or at any other location along the line. The step changes in the neutral current of Figures 22 and 27 are due to the transformer currents and current flowing between the neutral and the earth at each grounding electrode. The neutral current level change at the grounding electrode located between transformers is different at the end of the line as compared with the change near the substation. Neutral line current flows into the earth at the end of the line while it returns from the earth onto the neutral conductor near the substation.

Figure 28 shows the current supplied by the substation transformers and the current of the load transformers along the line for the normal line case and for the case with a primary to earth fault at node 404, 416, or at 428. The 20 amperes primary ungrounded conductor to earth fault increases the substation transformer current output, but it does not have an effect upon the current of the load transformers. The changes in neutral current shown in Figures 22 and 27 for the primary fault to earth case as compared to the normal load

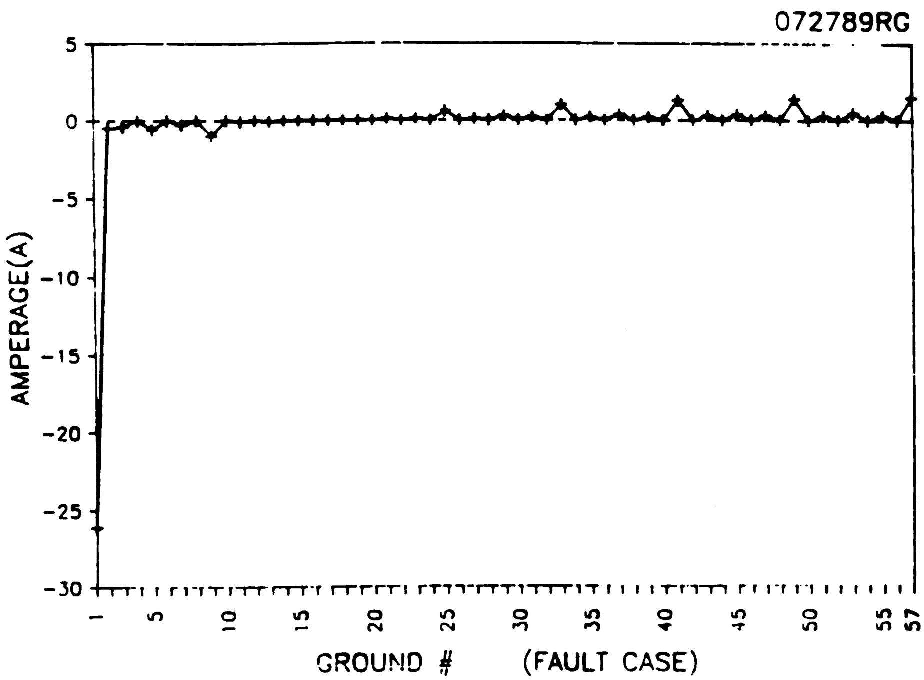


Figure 25. Grounding electrode currents from the substation to the end of the line with a 20 A phase to earth fault at node 416 plus normal line loading

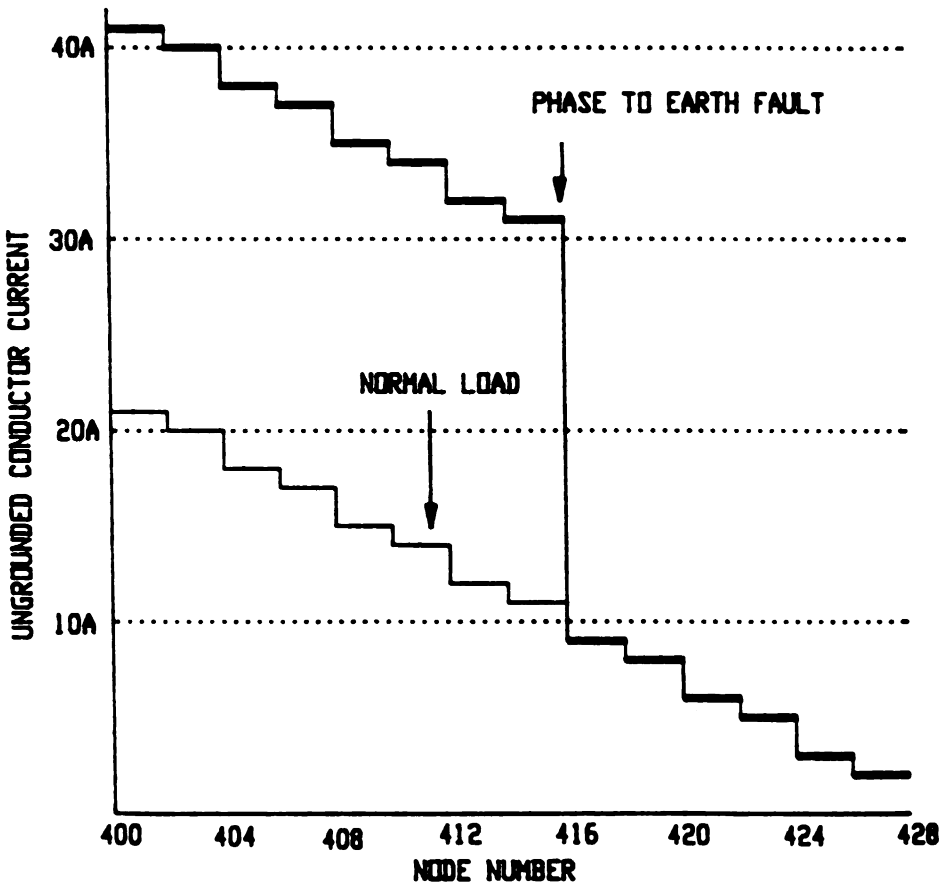


Figure 26. Primary ungrounded phase conductor current comparison from the substation to the end of the line for normal line load vs. normal line load plus a 20 A phase to earth fault at node 416

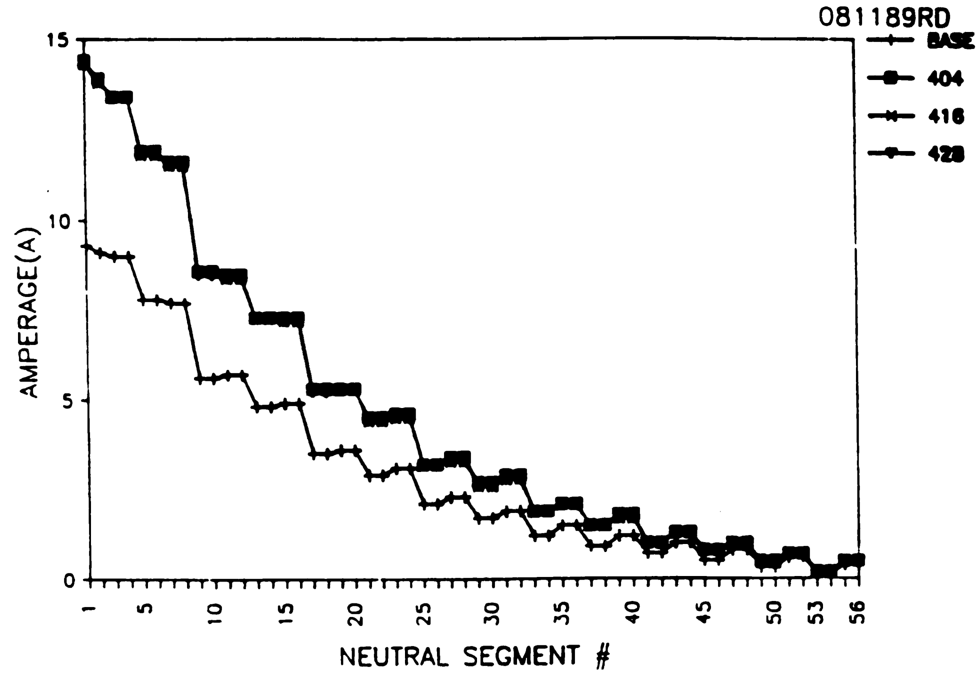


Figure 27. The primary neutral conductor current for each line segment from the substation to the end of the line for normal load compared with normal load plus a 20 A fault at node 404, 416, or 428

case are due to current flow between the earth and the neutral conductor through the grounding electrodes.

Figure 29 shows the current flow on the primary ungrounded conductor for the normal load case as compared to the case where there was a 20 amperes primary to earth fault at node 404, 416, or at 428. Note that the primary ungrounded conductor current level is increased by 20 amperes as compared to the normal load case up to the point where the primary to earth fault is located.

From Figure 20 and Figure 21, it can been seen that when primary phase-to-earth fault occurs somewhere in the distribution line, the neutral-to-earth voltages increase in some segments near the substation and decrease some distance away from substation toward the end of the line. These voltage changes are fault-size dependent and fault-location independent. The voltage changes increase as the fault currents increase. The most significant changes of the neutral-to-earth voltage occur near the substation. The neutral-to-earth voltage profiles at the three fault locations (the middle and the both ends of the line) are identical. Similar result was reported by Kehrle (1984), but the reasons for the results were not explained.

5.1.6 Substation Grounding Resistance Change

Figure 30 presents the neutral-to-earth voltage simulation curves resulting from changing the substation grounding resistance. Such a change can occur due to corrosion, water-table fluctuation or nearby

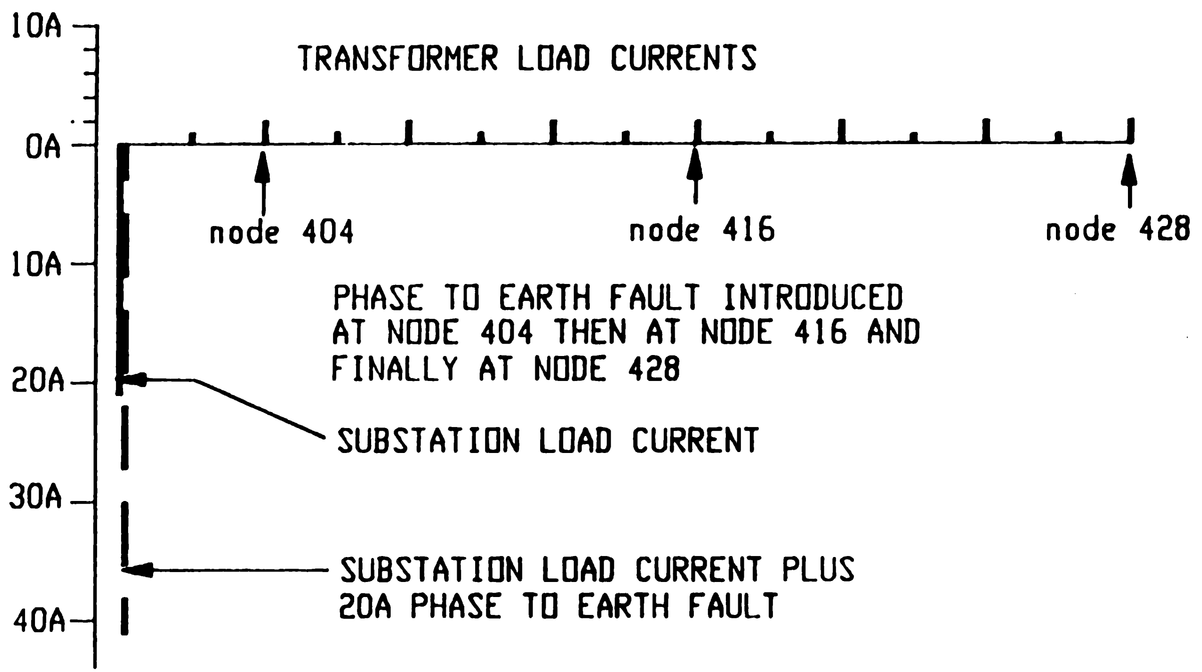


Figure 28. Substation and transformer current comparison for the normal load case and for phase to earth fault at node 404, then at node 416, and finally at node 428

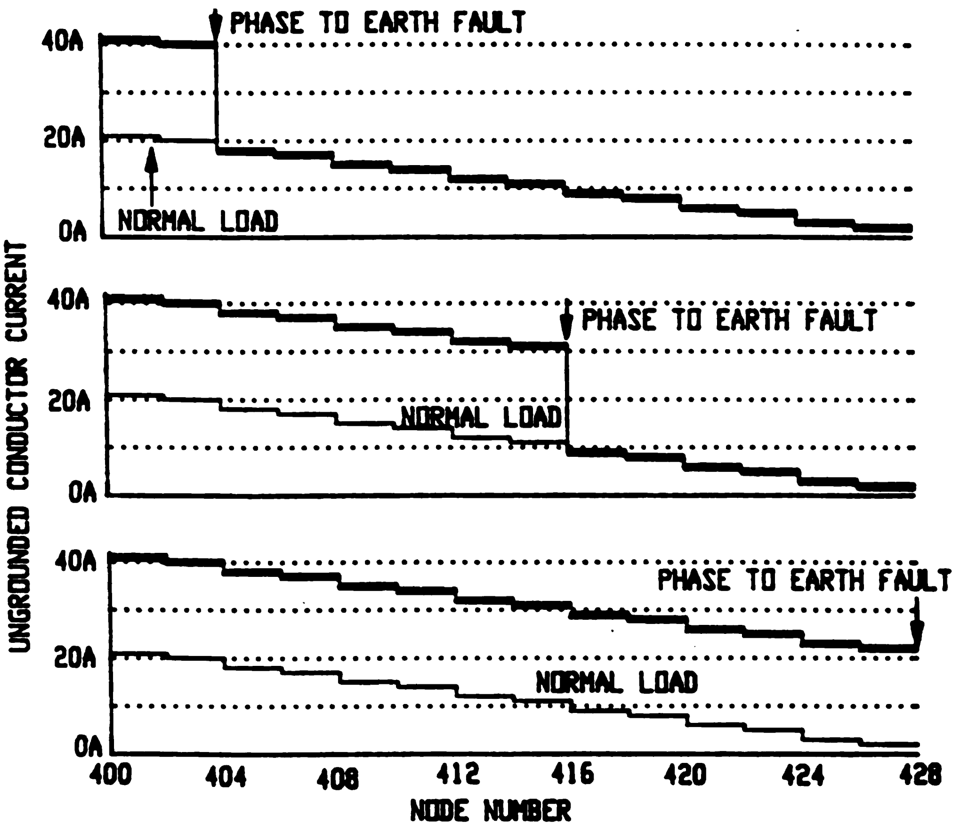


Figure 29. Primary ungrounded phase conductor current comparison from the substation to the end of the line for normal line load vs. normal line load plus a 20 A phase to earth fault at node 404, 416, and 428

earthwork construction. Low substation resistance to earth may be difficult to achieve due to soil conditions.

Compared with base case, when substation resistance was increased from 0.5 ohm (base case) respectively to 1.0, 5.0, 10, 20 and 40 ohms, the neutral-to-earth voltages increased accordingly in some segments near the substation and decreased some distance away from the substation toward the end of the line. Note the most significant changes of the neutral-to-earth voltage occurred near node 1 where the substation was located. At the substation, in the base case, when the substation resistance was 0.5 ohm, the value of neutral-to-earth voltage was 5.8 V. When the substation resistance was increased to 1.0 ohm, the voltage also increased by 3.4 V, to 9.2 V. When the substation resistance was increased to 5.0 ohms, the voltage increased by another 8.3 V, to 17.5 V. When the substation resistance was increased to 10 ohms, the voltage increased another 2.3 V, to 19.8 V. When the substation resistance was increased to 20 ohms, the voltage was only increased by 1.3 V, to 21.1 V. When the substation resistance was increased to 40 ohms, the voltage was only increased another 0.7 V, to 21.8 V. Generally, the voltage change was increased near the substation as the substation resistance was increased; the effect was significant in the resistance range from 20 -- 40 ohms.

This effect on the neutral-to-earth voltage diminished rapidly as the distance increased from the substation (node 1) toward the end (node 57) of the line. With 40 ohms substation resistance, at substation node 1, the neutral-to-earth voltage was 21.8 V, 3.76 times of base case value of 5.8 V; at the middle node 33, the voltage was 3.8 V, 60% of the base case value of 6.3 V; at the end node 57, the voltage was 6.7 V, only 86% of the base case value of 7.8 V.

A high value of substation resistance results in a reduced amount of neutral load current flowing to earth on the grounding electrodes from the middle to the end of the line. A lowered substation grounding mat resistance results in a lowered neutral-to-earth voltage.

From Figure 30, it can be seen that when the substation grounding resistance is increased, the neutral-to-earth voltages increased in some segments near the substation and decreased some distance away from substation toward the end of the line. These voltage changes are related to the distance from and the resistance-value of the substation. The neutral-to-earth voltages are increased significantly near the substation and changed less and less significantly as the distance is away from the substation. Similar results were reported by Kehrle (1984) and Gustafson (1985) in their simulation.

From Figure 20 and Figure 30, it may be found that the neutral-to-earth voltage changing trends of this case and the primary-to-earth fault case mentioned in 5.1.5 were very similar, except the voltage changing rates were different. In the case of 5.1.5, the voltage change rate was quite uniform, almost linear at the rate of 0.3-0.37 V/A near the substation node 1. In the substation-resistance case, the voltage change rate was not uniform at all, much higher at the lower resistance levels and much lower at the higher resistance levels. The explanations given for the phenomenon are as follows:

In the case mentioned in 5.1.5, when the ground fault current increased, most of the current returned to the substation through the grounding resistance (0.5 ohm), which was much lower than those in other places. This can cause a voltage increase at the substation proportionally with the fault current increase. In this substation resistance case, the substation resistance increase can also cause an increase in the voltage. But this voltage change across the high substation ground resistance is constrained by the current that the system can provide.

5.1.7 Neutral-to-Earth Resistance Reduction

Figure 31 presents the neutral-to-earth voltage simulation curves resulting from reducing neutral-to-earth grounding electrode resistance RFG33 at the middle of the distribution neutral line.

Compared with the base case, when the grounding electrode resistance RFG33 was reduced from 5 ohm to 3 ohm and then to 1 ohm at node 33, at node 33 and nearby along the distribution line, the neutral-to-earth voltage decreased as the grounding resistance was reduced. However, this reduction of neutral-to-earth voltage was localized. The most significant neutral-to-earth voltage reduction occurred at node 33 itself. At node 33, in the base case, when RFG33 was 5 ohms, the value of neutral-to-earth voltage was 6.3 V. When the RFG33 was decreased to 3 ohms, the voltage also decreased by 0.5 V, to 5.8 V. When RFG33 was decreased to 1 ohm, the voltage decreased by

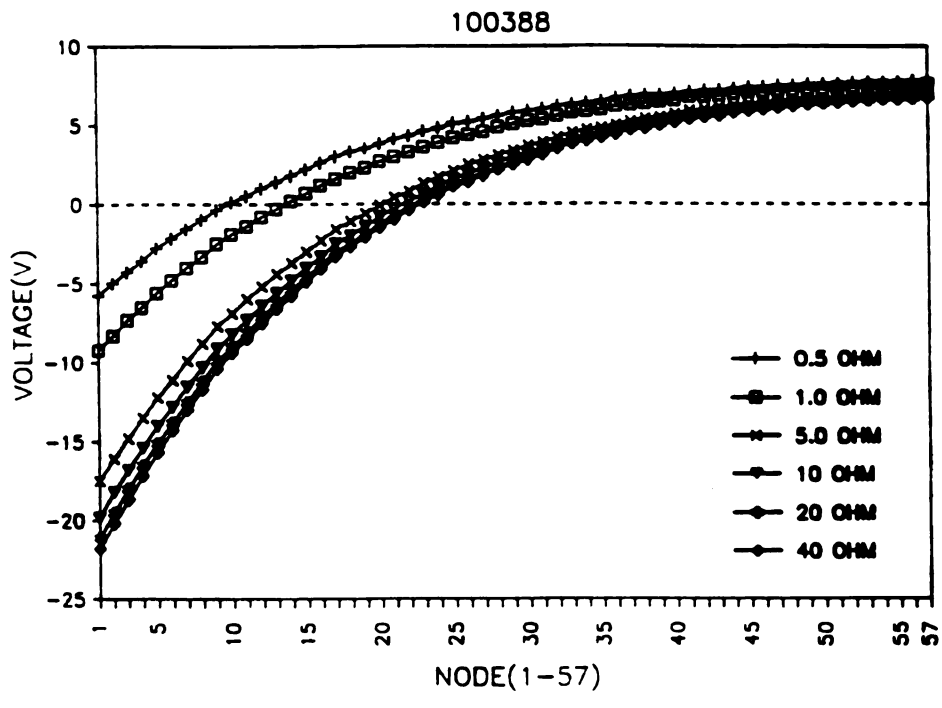


Figure 30. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with basecase vs. variable substation resistance RS

another 1.7 V, to 4.1 V. The neutral-to-earth voltage decreased more dramatically at this node when RFG33 was reduced from 3 ohms to 1 ohm than from 5 ohms to 3 ohms.

This voltage reduction effect was less and less significant as the distance increased from node 33 toward both the substation and the end of the distribution line. When RFG33 was 1 ohm, at node 33, the voltage was 4.1 V, 65% of the base case value of 6.3 V; at the end node 57, the voltage was 6.9 V, 88% of the base case value of 7.8 V; however, at the substation node 1, a very small neutral-to-earth voltage change was experienced with the voltage at 6.0 V, slightly changing in the contrary directions to those of nodes 33 and 57, 103.4% of the base case value 5.8 V.

From Figure 31, it can be seen that when the neutral-to-earth resistance is decreased somewhere in the middle location of the distribution line, the neutral-to-earth voltages also decrease accordingly in most segments along the distribution line. This voltage reduction effect is localized. The most significant voltage reduction occurs at the location where the grounding resistance is reduced. The voltage reduction is less and less significant as the distance increases from that location in either direction. Similar results were also reported by Kehrle (1984) and Surbrook et al., (1988) in their simulation.

Prothero et al. (1988) also reported from their field measurement data that their tests showed a net resistance of less than 0.5 ohm for the primary neutral network. The measured resistance of farm ground systems ranged from 2.0 to 5.0 ohms per farm. The connection of these low resistance farm grounds to the primary neutral network was found to have a larger influence over primary neutral-to-earth voltage levels than the additional ground electrodes or counterpoise. This is consistent with the theoretical analysis in this research.

Figure 32 presents the neutral-to-earth voltage simulation curves resulting from improving neutral-to-earth grounding by adding an extra grounding electrode of 25 ohms at every node on the neutral conductor where the resistance was previously set at 100 kohms. See Figure 1 and Table 1. For this simulation, there is a grounding electrode of not more than 25 ohms at each pole along the distribution line.

Compared with the base case, when the grounding electrode number was doubled, the neutral-to-earth voltage was lowered at most nodes (from node 11 to node 57) along the distribution line. This voltage reduction effect was significant from the end to the middle location of the distribution line. At the end (node 57), the value of neutral-to-earth voltage decreased by 1.9 V, to 5.8 V, 74.4% of the base case value 7.8 V; at the middle node 33, voltage was 4.7 V, 75% of the base case value 6.3 V; however, at the substation node 1, very small neutral-to-earth voltage change was experienced with the voltage 5.9 V, slightly changing in the contrary direction to those of nodes 33 and 57, 101.7% of the base case value 5.8 V. Note the "zero point" of the neutral-to-earth voltage was slightly shifted from node 10 in base case to node 11 in this case.

From Figure 32, it can be seen that when the grounding electrode number was doubled uniformly along the neutral line, the

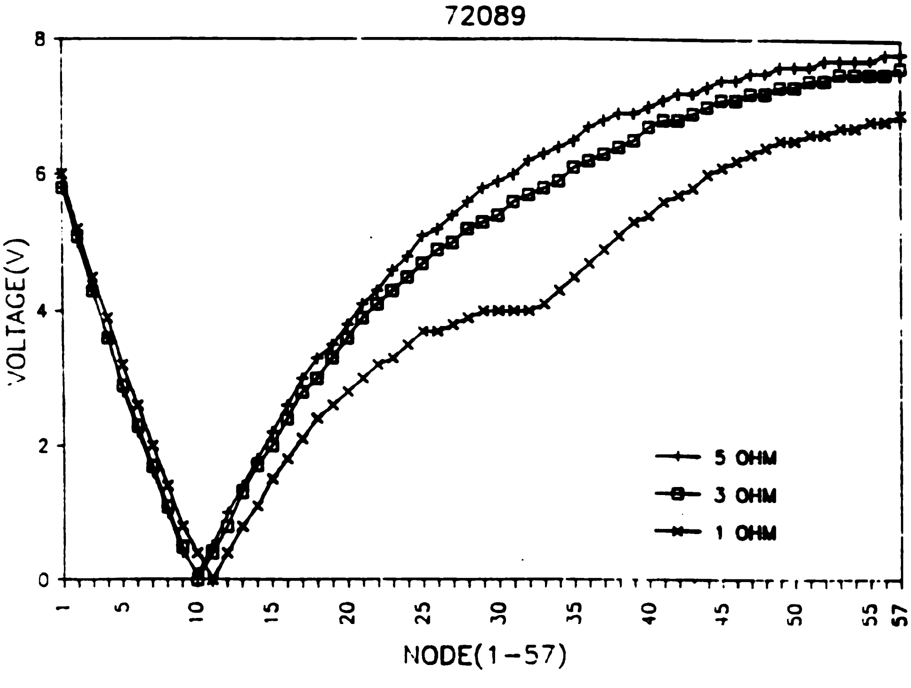


Figure 31. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with base case vs. ground resistance RFG33 change at node 33

neutral-to-earth voltage was lowered in most of the transformer nodes along the distribution line. This voltage change was insignificant near the substation.

Reduction of the grounding electrode resistance at node 33 in the middle of the line decreased the local neutral-to-earth voltage. Addition of extra grounding electrodes was equivalent to increasing the parallel resistance number and decreasing the actual overall resultant ground resistance.

Prothero et al. (1988) also reported from their field measurement that the addition of numerous supplemental grounding electrodes, to the extent that every distribution pole was grounded, had only a slight effect on reducing primary neutral-to-earth voltage.

Although increasing the number of grounding electrodes can decrease the neutral-to-earth voltage to some extent, a large number of ground rods will be costly and the effect may not be as good as expected. For this simulation, doubling the number of grounding electrodes along the primary line only resulted in approximately a 25 percent reduction in neutral-to-earth voltage at the end of the line.

5.1.8 Primary Operating Voltage Level Change

Figure 33 presents the neutral-to-earth voltage simulation curves resulted from changing the primary operating voltage levels. The base case simulation assumes a primary ungrounded conductor operating at 7.2 kV.

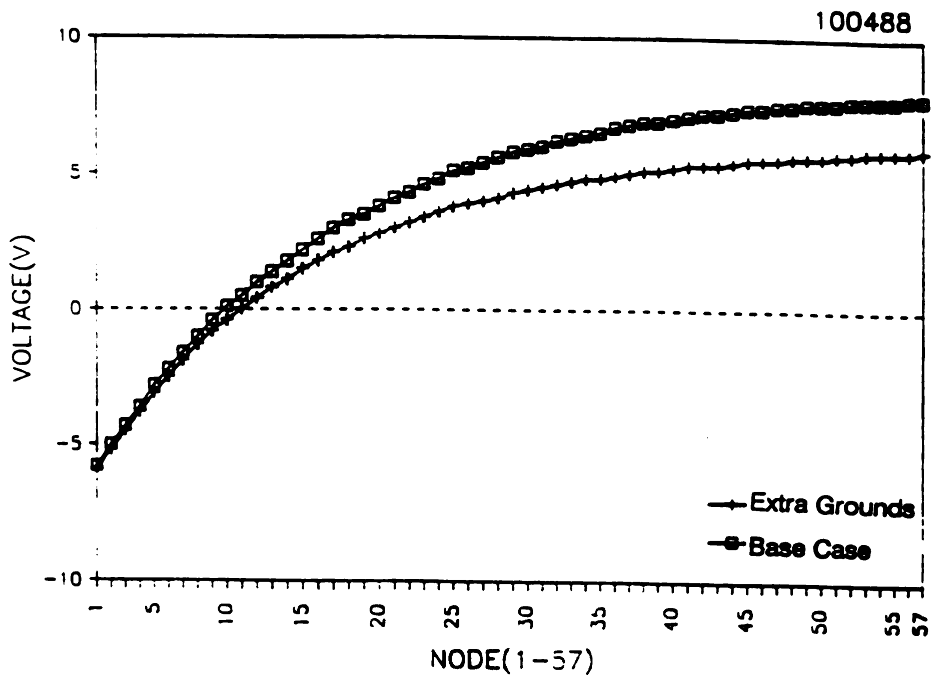


Figure 32. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with base case vs. ground rod number increasing along the entire system

When the primary operating voltage levels were increased from 2.4 kV respectively to 4.8 kV, 7.2 kV and 26.4 kV with power unchanged, the neutral-to-earth voltages in all these four distribution systems decreased correspondingly along the distribution line. These voltage profiles had the similar shapes and the same positions with the different proportion scales. All four voltage profiles approached convergence near node 10.

The neutral-to-earth voltages of all four systems decreased as the distance away from the substation increased, reaching zero and changing 180 degree in phase angle between node 9 and node 10. Then the voltage increased as the distance toward the end of the line increased until reached the maximum value at node 57. The neutral-to-earth voltage profile changed sharply at first, then leveled off toward the end of the neutral line. At node 10, the neutral-to-earth voltages corresponding to the systems of 2.4 kV, 4.8 kV, 7.2 kV and 26.4 kV were 0.4 V, 0.1 V, 0.1 V and 0 V, respectively. At the substation node 1, the neutral-to-earth voltages corresponding to the systems of 2.4 kV, 4.8 kV, 7.2 kV and 26.4 kV were 16.4 V, 8.6 V, 5.8 V and 1.6 V, respectively. At the end (node 57), the neutral-to-earth voltages corresponding to the systems of 2.4 kV, 4.8 kV, 7.2 kV and 26.4 kV were 22 V, 12 V, 7.8 V and 2.1 V, respectively.

Generally, the higher the operating voltage, the lower the neutral-to-earth voltage. This is due to the constant power situation: the higher the operating voltage, the lower the current on transformer primary side. The lower transformer primary current leads to lower current injection to the neutral line and parallel ground path.

This neutral-to-earth voltage change effect due to the primary operating voltage change was much more significant in the operating voltage level range from 2.4 -- 4.8 kV than the range from 7.2 -- 26.4 kV. The neutral-to-earth voltage decreased 20% per kV on the average in the operating voltage level range from 2.4 -- 4.8 kV and only 3.8% per kV on the average in the range 7.2 -- 26.4 kV. This implies that striving for high operating voltage levels may not reduce the neutral-to-earth voltage as much as expected.

5.1.9 Secondary Earth Fault

Figures 34 through 39 present the neutral-to-earth voltage simulation curves resulting from normal line loading plus a ground fault on the secondary side of one of the transformers. The simulation network used in this case is shown in Figure 6.

When the out-of-phase secondary ground faults of 2.5, 5.0 and 10 amperes were introduced at the transformer between nodes 416 and 33, at the middle of the distribution line, from Figure 34, compared with the base case, some changes in the neutral-to-earth voltage were observed. The most significant voltage changes occurred near node 33 where the faulted secondary network was attached. At node 33, the voltage increased significantly as the fault current increased. In the base case, when the fault current was zero, the value of neutral-to-earth voltage

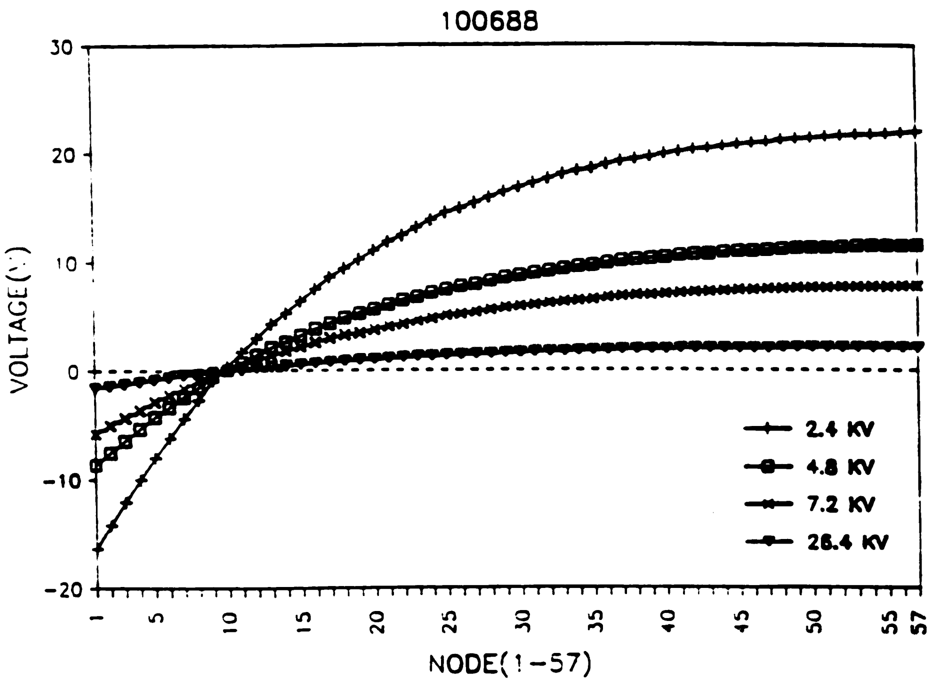


Figure 33. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with base case 7.2 kV operating voltage vs. 2.4, 4.8 and 26.4 kV operating voltages

was 6.3 V. When the fault current was increased to 2.5 A, the voltage increased by 1.6 V, to 7.9 V. When the fault current was increased to 5.0 A, the voltage increased by another 1.6 V, to 9.5 V. When the fault current increased to 10 A, the voltage increased an additional 2.9 V, to 12.4 V, 197% of the base case value 6.3 V.

This voltage change effect was less and less significant as the distance increased from node 33 toward both the substation and the end along the distribution line. When the fault was 10 A, at node 33, the voltage was 12.4 V, 197% of the base case value 6.3 V; at the end node 57, the voltage was 10.3 V, 132% of the base case value 7.8 V; however, at the substation node 1, very small neutral-to-earth voltage change was experienced with the voltage 5.2 V, slightly changing in the contrary directions to those of nodes 1 and 57, 90% of the base case value 5.8 V.

When the in-phase secondary ground faults of 2.5, 5.0 and 10 amperes were introduced at the transformer between node 416 -- 33, at the middle of the distribution line, from Figure 35, compared with the base case it can be seen that neutral-to-earth voltage changed in a similar way to the in-phase secondary ground fault situation except the voltage changes were in the contrary direction. Note in Figure 35 that a 10 ampere secondary in-phase ground fault is subtractive with the primary load produced neutral-to-earth voltage resulting in a net neutral-to-earth voltage value near zero at node 33.

When the out-of-phase secondary ground faults of 2.5, 5.0 and 10 amperes were introduced at the transformer between node 404 -- 9, the first farm transformer location along the distribution line, from Figure

36, compared with the base case it also can be seen that there were changes in the neutral-to-earth voltage. The significant voltage changes occurred near node 9 where the faulted secondary network was attached. At node 9, the voltage was increased significantly as the fault current increased. In the base case, when the fault current was zero, the value of neutral-to-earth voltage was 0.4 V. When the fault current was increased to 2.5 A, the voltage also increased by 0.6 V, to 1.0 V. When the fault current was increased to 5.0 A, the voltage increased by another 1.3 V, to 2.3 V. When the fault current was increased to 10 A, the voltage increased an additional 2.6 V, reaching 4.9 V, 12 times of the base case value 0.4 V.

This voltage change effect was less significant as the distance increased from node 9 in either direction of the distribution line. When the fault was 10 A, at node 9, the voltage was 4.9 V, 12 times of the base case value 0.4 V; at the end node 57, the voltage was 8.4 V, 107.6% of the base case value 7.8 V; however, at the substation node 1, the voltage was 3.6 V, changing in the contrary directions to those of nodes 33 and 57, 62% of the base case value 5.8 V.

When the in-phase secondary ground faults of 2.5, 5.0 and 10 amperes were introduced at the transformer between node 404 -- 9, the the first farm transformer location of the distribution line, from Figure 37, compared with the base case it could be seen that the neutral-to-earth voltage changed in a similar way to the in-phase ground fault situation except the voltage changes went to the contrary direction.

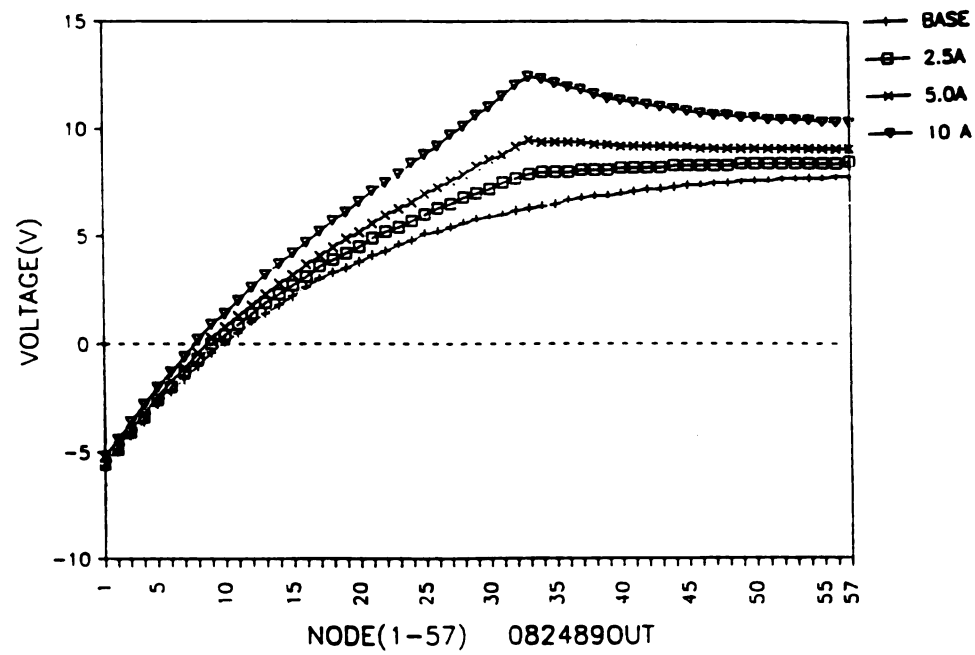


Figure 34. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with base case vs. variable secondary ground fault attached to node 33 (out-of-phase)

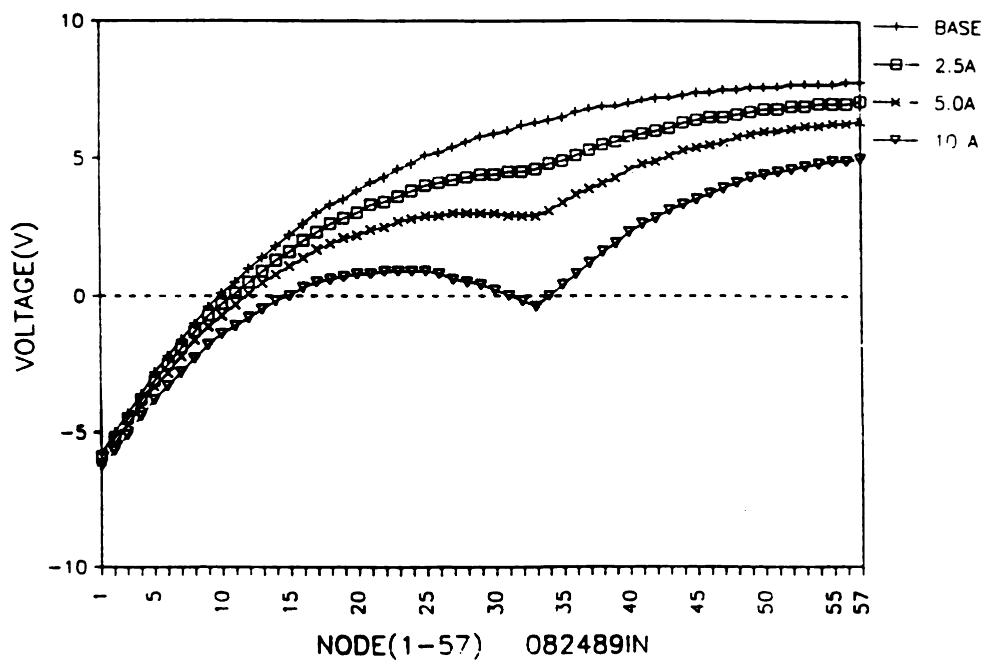


Figure 35. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with base case vs. variable secondary ground fault attached to node 33 (in-phase)

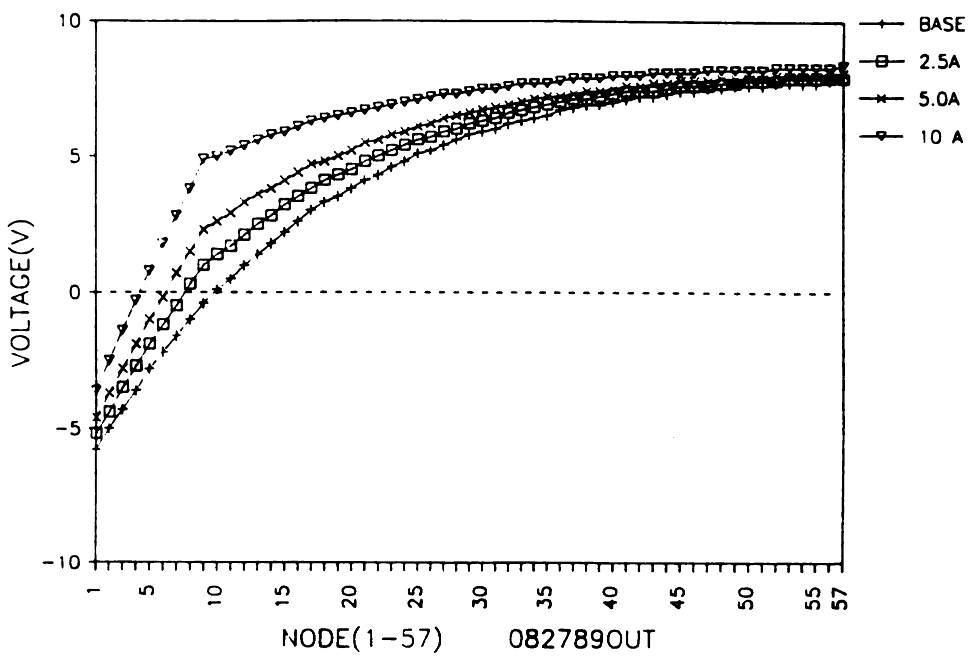


Figure 36. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with base case vs. variable secondary ground fault attached to node 9 (out-of-phase)

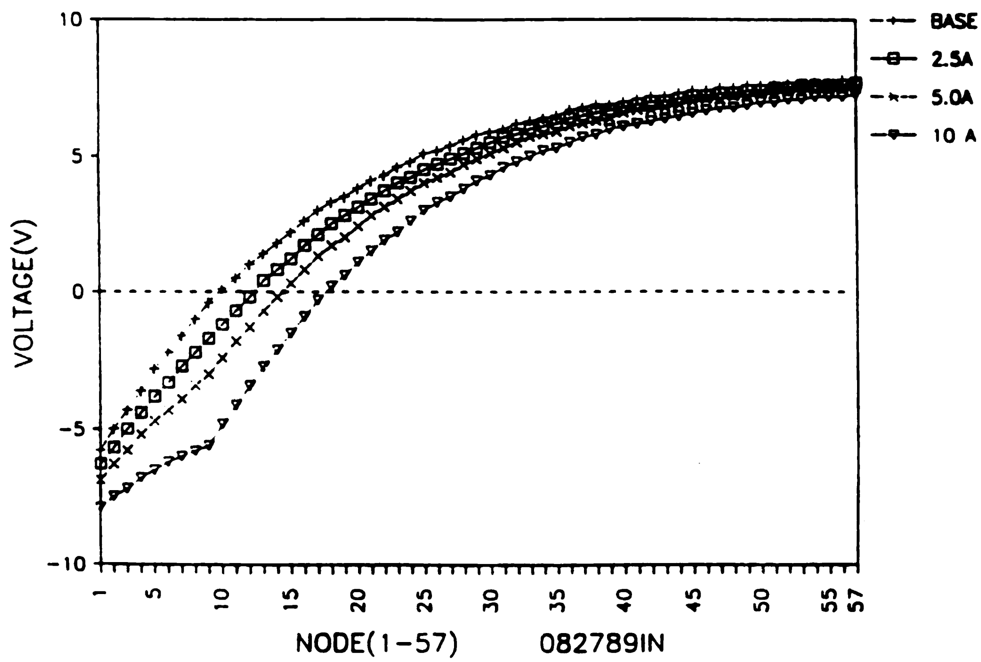


Figure 37. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with base case vs. variable secondary ground fault attached to node 9 (in-phase)

With an out-of-phase secondary ground fault at node 33 in the middle of the line, most customers experienced an increase in neutral-to-earth voltage as shown in Figure 34. When there was an in-phase secondary ground fault at node 33 in the middle of the line, most customers experienced a decrease in the neutral-to-earth voltage (Figure 35). But this was not true when the secondary ground fault was at a location near the substation. Examination of Figures 36 and 37 shows that some customers experience a lowering of the neutral-to-earth voltage while others experience an increase whether the secondary ground fault was in-phase or out-of-phase with the primary load produced neutral-to-earth voltage.

When the out-of-phase secondary ground faults of 2.5, 5.0 and 10 amperes were introduced at the transformer between node 428 -- 57, the last farm transformer location of the distribution line, from Figure 38, compared with the base case it still can be seen that there was some changes in the neutral-to-earth voltage. The most significant voltage changes occurred near the end node 57 where the faulted secondary network was attached. At node 57, the voltage was increased significantly as the fault current increased. In the base case, when the fault current was zero, the value of the neutral-to-earth voltage was 7.8 V. When the fault current was increased to 2.5 A, the voltage also increased by 2.7 V, to 10.5 V. When the fault current was increased to 5.0 A, the voltage increased by another 2.5 V, to 13.0 V. When the fault current was increased to 10 A, the voltage increased by an additional 4.7 V, reaching 17.7 V, 2.3 times of the base case value 7.8 V.

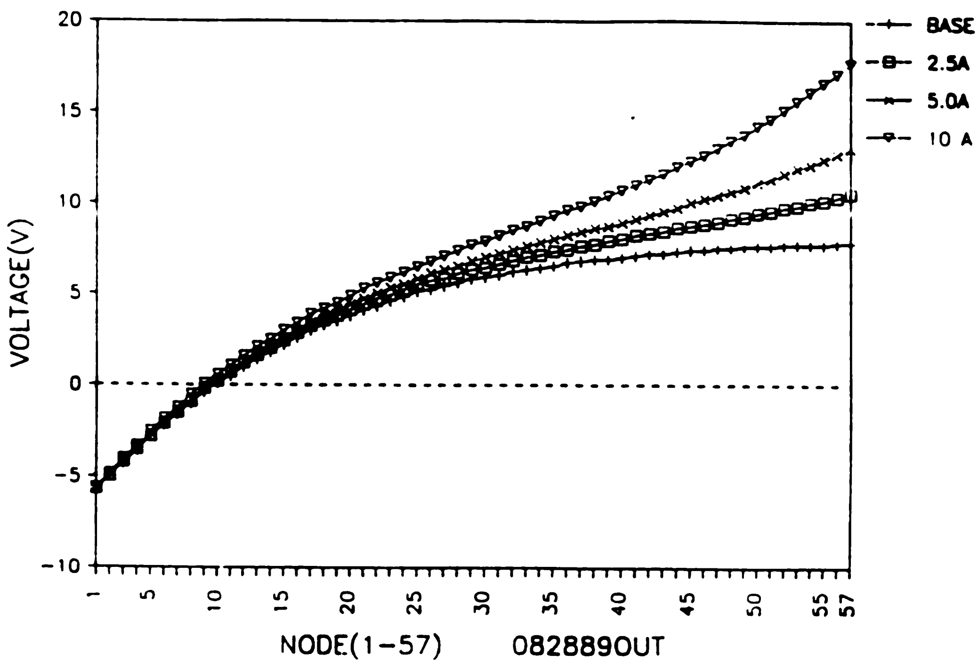


Figure 38. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with base case vs. variable secondary ground fault attached to node 57 (out-of-phase)

This voltage change effect was less significant as the distance increased from the end node 57 toward the substation node 1 along the distribution line. When the fault was 10 A, at the end node 57, the voltage was 17.7 V, 2.3 times of the base case value 7.8 V; at node 33, the voltage was 8.7 V, 112% of the base case value 7.8 V; however, at the substation node 1, very small neutral-to-earth voltage change was experienced with the voltage 5.6 V, slightly changing in the contrary directions to those of nodes 33 and 57, 96.6% of the base case value 5.8 V.

When the in-phase secondary ground faults of 2.5, 5.0 and 10 amperes were introduced at the last farm transformer location node 428 -- 57, from Figure 39, compared with the base case it could be seen that the neutral-to-earth voltage changed in a similar way to the in-phase ground fault situation except the voltage changes went to the contrary direction. The net effect of the in-phase secondary ground fault was to reduce the neutral-to-earth voltage.

From Figure 34 through Figure 39, it can be seen that for a ground fault on the secondary side of a transformer, the neutral-to-earth voltages along the distribution line were changed to some extent. Generally, this kind of change is fault-size, fault-phase and fault-location dependent. The heavier the fault currents, the more significantly the neutral-to-earth voltages change. The voltages change in contrary directions when the in-phase or out-of-phase fault occurs. Much more significant changes in neutral-to-earth voltage occur at and near node at which the faulted secondary circuit is attached. The farther the distance along the line away from the fault node, the less significant the neutral-to-earth voltages change. A similar result was also reported by Kehrle (1984) in her simulation.

The change in level of neutral-to-earth voltage due to a secondary ground fault is greater at the end of the line than at the middle of the line as can been seen from Figures 36 through 39. Near the substation the amount of change was less, but whether a particular location would experience a net increase or decrease in neutral-to-earth voltage was difficult to predict. At the end of the line as was the case at the middle of the line, an out-of-phase secondary ground fault caused an increase in neutral-to-earth voltage for all customers. For the in-phase secondary ground fault, customers experienced a reduction of neutral-to-earth voltage unless the amount of reduction was great enough to result in a phase angle change in the neutral-to-earth voltage. In this latter situation, it is possible for the net rms value of the voltage to actually become higher.

It is important to note that a secondary ground fault can be additive or subtractive to the primary line load produced neutral-to-earth voltage. The elimination of a secondary ground fault at one location resulting in a lowering of neutral-to-earth voltage at that location may indeed cause a significant increase in the neutral-to-earth voltage at other locations. When a secondary ground fault is discovered, it is recommended that voltage measurements be taken along the distribution line in the area after the elimination of the

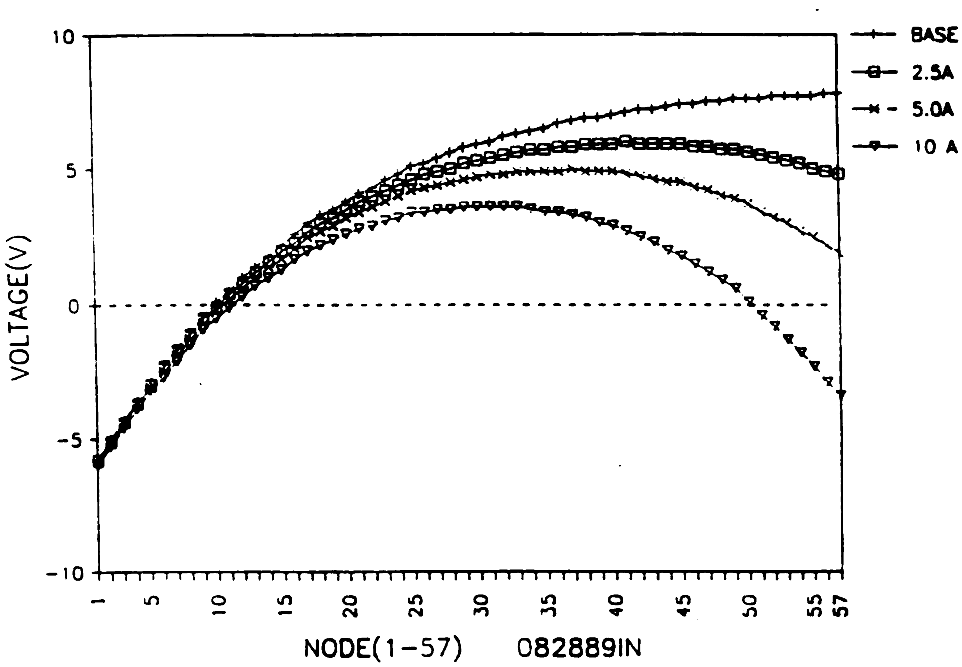


Figure 39. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with base case vs. variable secondary ground fault attached to node 57 (in-phase)

secondary ground fault to determine if any customers have experienced an increase in neutral-to-earth voltage.

The out-of-phase and in-phase secondary ground fault condition at the end of the distribution line is illustrated in Figures 40 and 41. Figure 40 shows the end of the distribution line with the simulated secondary electrical system attached. The net grounding electrode resistance to earth of the three grounding electrodes (25, 17, and 10 ohm) is 5 ohms which is the same as used in all simulations at node 57. The out-of-phase fault condition with respect to the primary line is defined by observing the phase relationship of the phase angle of the fault current of the secondary ground fault circuit with respect to the primary current, in Figure 40 compared with Figure 23. It is important to note that the fault current and the normal line load current flowing through the grounding electrodes is in-phase thus resulting in a net increase in grounding electrode current at the end of the line. Figure 38 shows the increase in neutral-to-earth voltage at the end of the line as a result of the increase in grounding electrode current.

Figure 41 shows the end of the distribution line with simulated secondary network attached at node 57. In this case the secondary ground fault is in-phase with respect to the primary line. Note that the phase relationship of the secondary ground fault current of Figure 41 is in the same phase of the primary ground fault current of Figure 23. Note also in Figure 41 that the normal line load produced grounding electrode current is out-of-phase with the secondary ground fault current flowing on the grounding electrodes. There will be a net reduction of the grounding electrode current at the end of the line when there is an in-phase secondary ground fault. This can be seen by the reduction of grounding electrode current in the in-phase secondary ground fault condition as shown in Figure 42. The secondary ground faults of 2.5, 5.0, and 10 amperes were located at the last farm transformer on the line which was at nodes 428 -- 57. The neutral-to-earth voltage will be reduced as shown in Figure 39.

Figure 42 shows the reduction of the grounding electrode current of the grounding electrodes near the end of the line when there is a secondary in-phase ground fault at the end of the line. Note that at node 57 grounding electrode, a 10 A secondary ground fault causes enough current flow on the grounding electrode to result in a change in phase of the current. This accounts for the change in phase of the voltage near the end of the line in Figure 39.

Compared with the base case, from Figure 43, it can be seen that the primary neutral currents did change to a large extent. The neutral current change trend was very similar to that of the neutral-to-earth voltage of the corresponding case (compared with Figure 39). The most significant neutral currents increase (in reverse direction of that in the portion of the line near the substation along the neutral line mainly due to secondary fault current returning from earth) occurred near the end node 57 where the fault secondary network was attached and maximum neutral-to-earth voltage change occurred. At node 57, the neutral current was increased significantly as the fault current increased. In the base case, when the fault current was zero, the value of the neutral

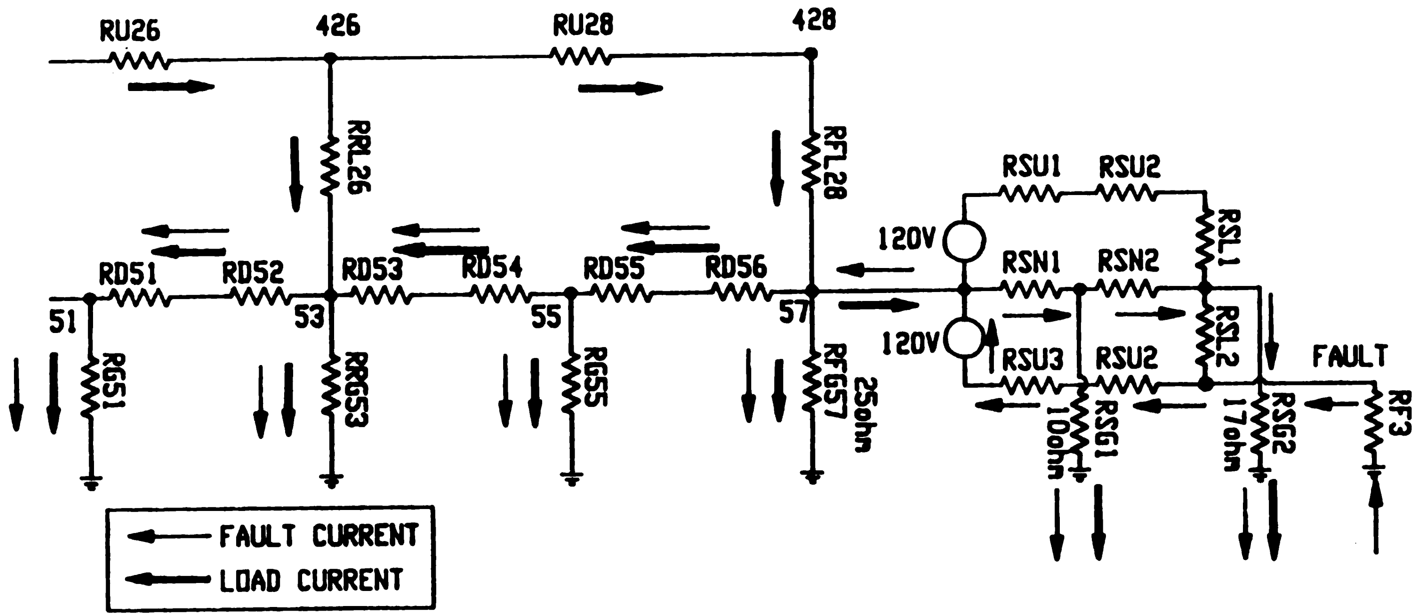


Figure 40. Neutral conductor and grounding electrode current with secondary out-of-phase ground fault attached at node 57 at the end of the distribution line

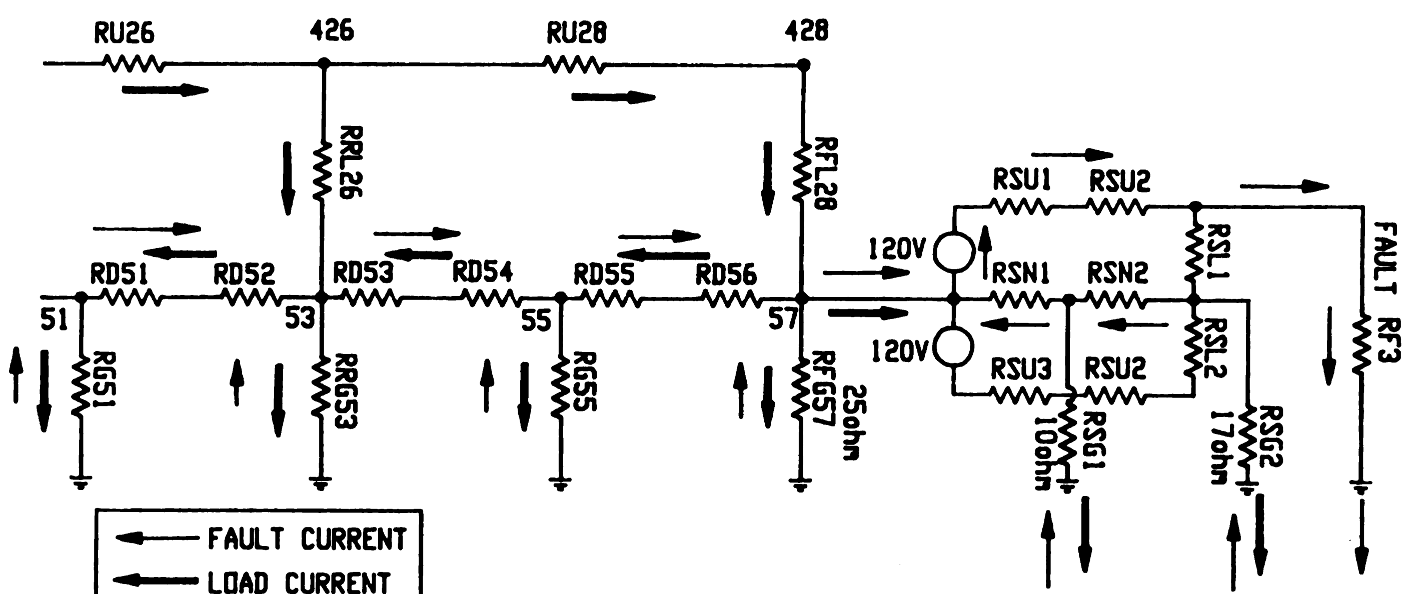


Figure 41. Neutral conductor and grounding electrode current with secondary in-phase ground fault attached at node 57 at the end of the distribution line

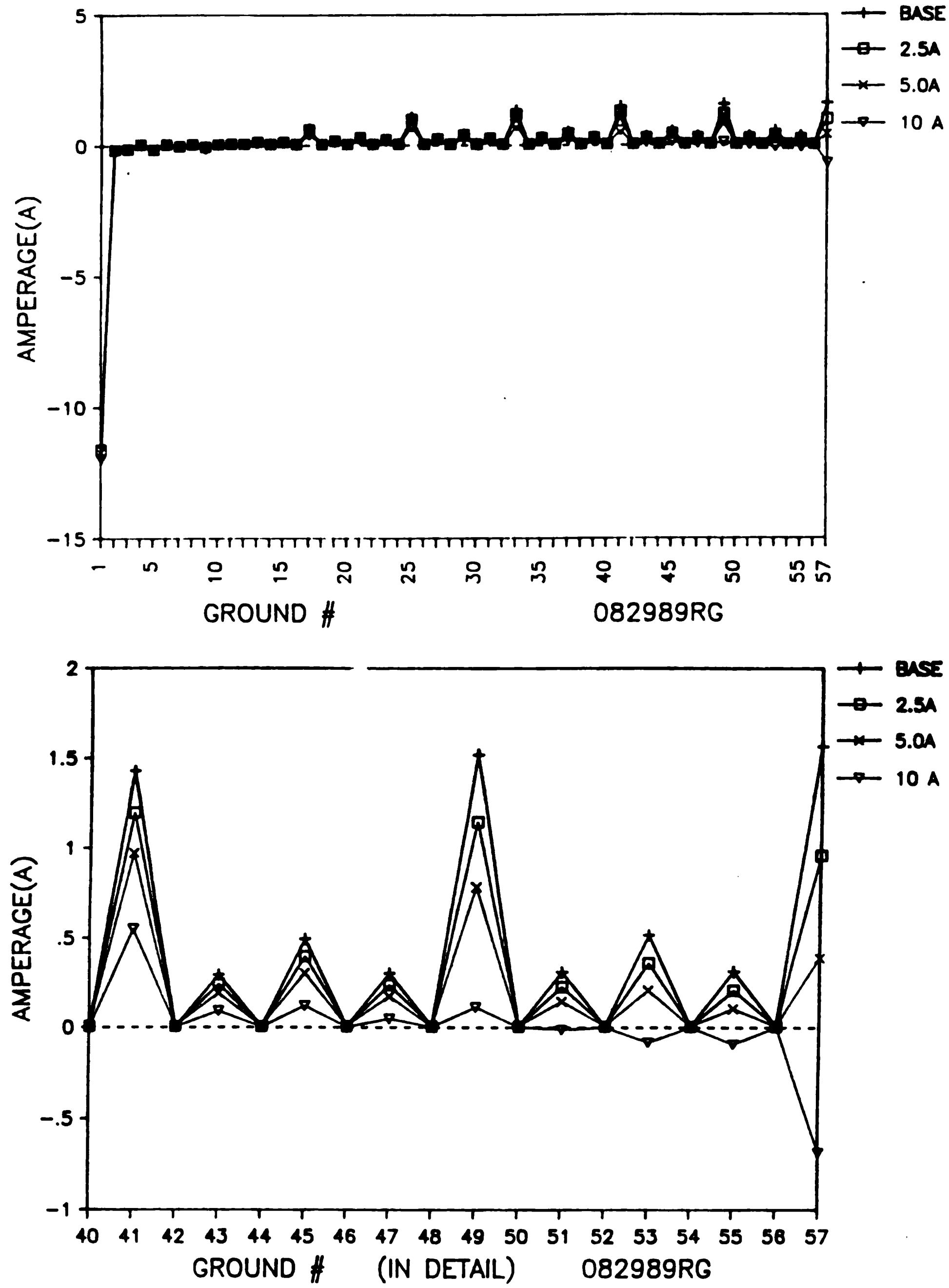


Figure 42. The ground rod current situation comparison in the distribution system from substation to end with base case vs. 2.5, 5 and 10 A secondary in-phase ground fault attached to node 57

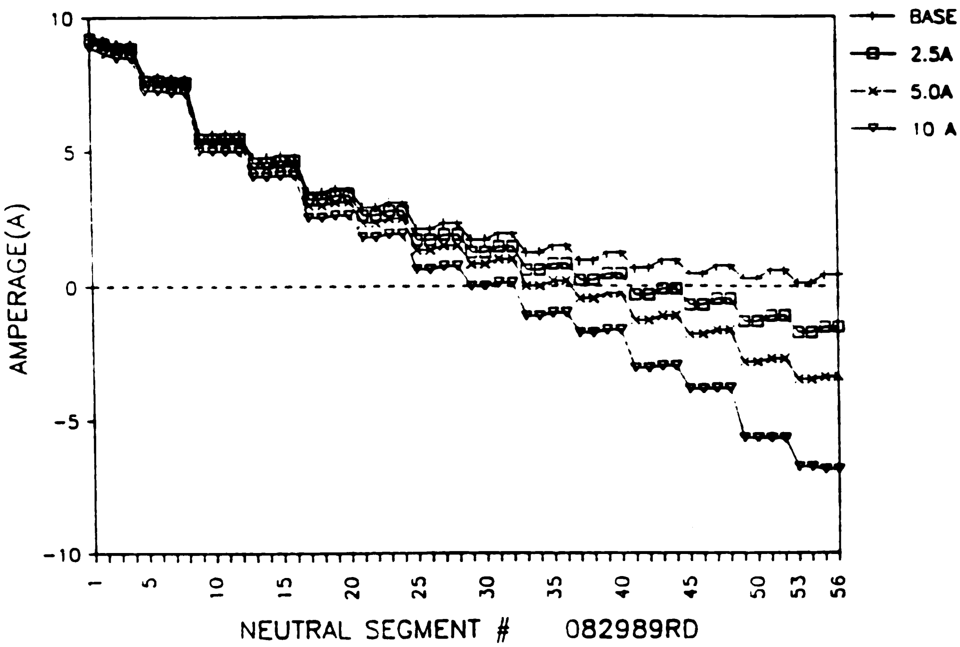


Figure 43. The neutral conductor current situation comparison in the distribution system from substation to end with base case vs. 2.5, 5 and 10 A secondary in-phase ground fault attached to node 57

current was 0.42 A. When the fault current was increased to 2.5 A, the neutral current also increased by 1.95 A inversely, to -1.53 A. When the fault current was increased to 5.0 A, the neutral current increased by another 1.87 A inversely, to -3.40 A. When the fault current was increased to 10 A, the neutral current increased by one more 3.49 A inversely, reaching -6.89 A, 17.3 times of the base case value 0.42 A.

The previous analysis of secondary ground faults assumes a 0 degree or a 180 degree phase deference between the current flowing in the neutral, grounding electrodes and earth as a result of normal line loading and secondary ground fault current. This will only occur if the power factor of the primary distribution line and of the secondary ground fault circuit are unity. This analysis shows the maximum changes possible as a result of a secondary ground fault. If the primary neutral grounding electrode current and the secondary fault current flowing on the grounding electrode are at some phase angle difference other than 0 degrees or 180 degrees, the resultant current flowing in the grounding electrode will be at some magnitude less than the maximum shown here and more than the minimum values. It would, therefore, be expected that less extreme results would occur for a secondary ground fault on an actual operating single-phase distribution line.

5.2 Operation of the AC Model

So far, only the results and analyses for the DC model have been presented. A question, of course, should be asked: How effective is the

DC model? Figures 44 through 48 show some comparisons between the DC based model and its relevant AC based model.

Figure 44 shows the neutral-to-earth voltage magnitude profiles of the two AC models (with and without transmission line inductance) compared with the 7,200 DC base model profile. To make the DC model profile more comparable with that of the AC model, the minus signs of the voltage values near the substation in the DC profile were taken away in Figure 44. Although the curve position of the AC model was slightly higher than that of DC model, the shapes of these two profiles were identical. The profile of the AC model with the line inductance effect did not experience the "zero voltage value" point like the DC model did, the reason being that the neutral return currents from the earth could not cancel each other out completely when the AC model transmission line series inductance effect was taken into account. This implies that the DC model can indicate some changing trends of the neutral-to-earth voltage magnitude.

Figure 45 and Figure 46 show the comparison between the AC model neutral-to-earth voltage phase angle profiles with and without the transmission line inductance effect. Note that the profile with the line inductance effect was smoother than that without line inductance effect.

Figure 47 and Figure 48 show the comparison between voltage regulation along the ungrounded distribution lines of the DC model and the AC model with the transmission line inductance effect. There is

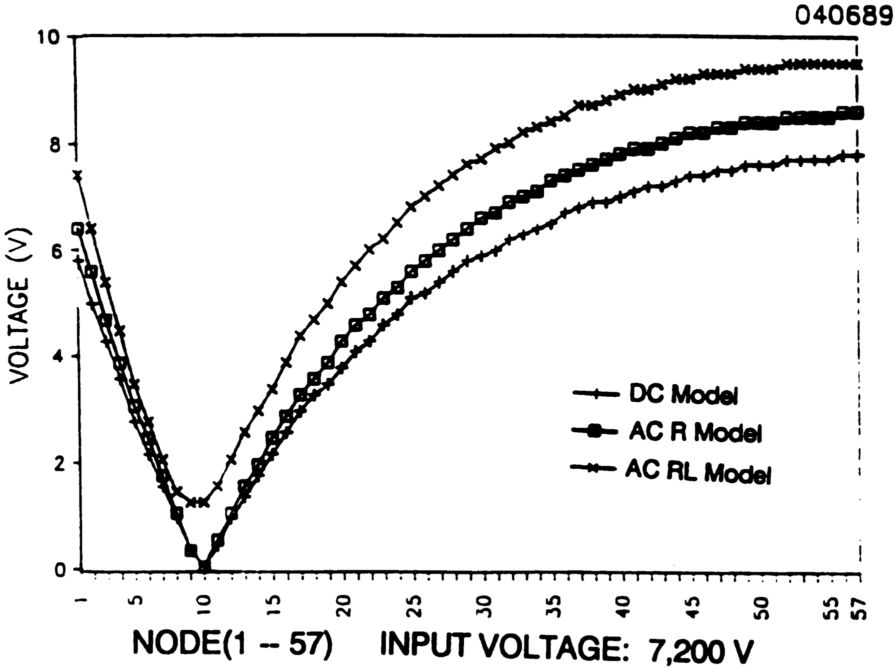


Figure 44. Neutral-to-earth voltage profile along a simulated distribution line with the DC model on the bottom, AC model with pure resistance line in the middle and AC model with resistance and induction line elements on top 57

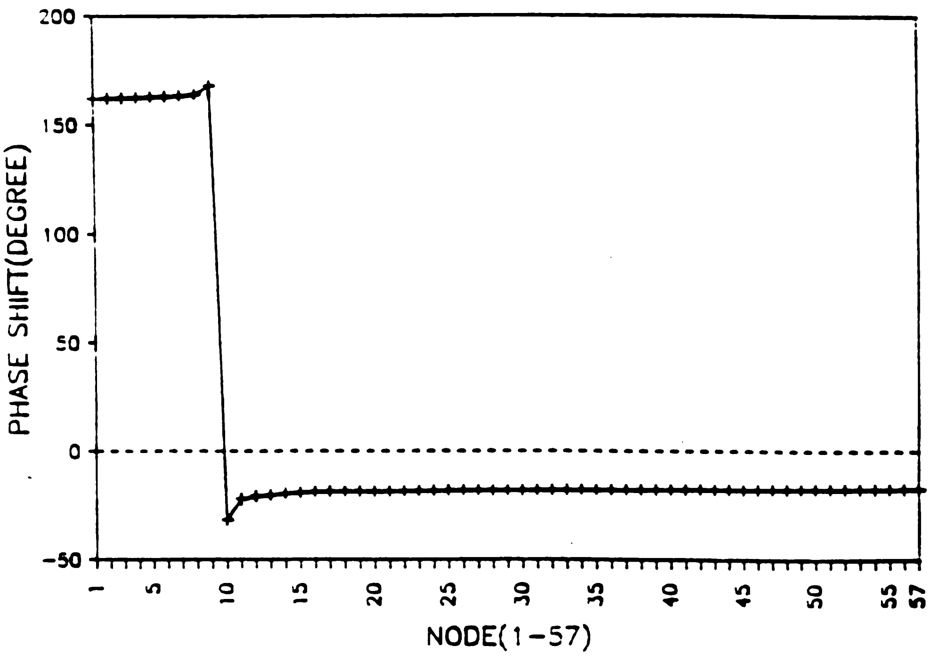


Figure 45. The AC model phase angle profile of the neutral-to-earth voltage along the primary distribution line from substationto 57th node (without line inductance effect)

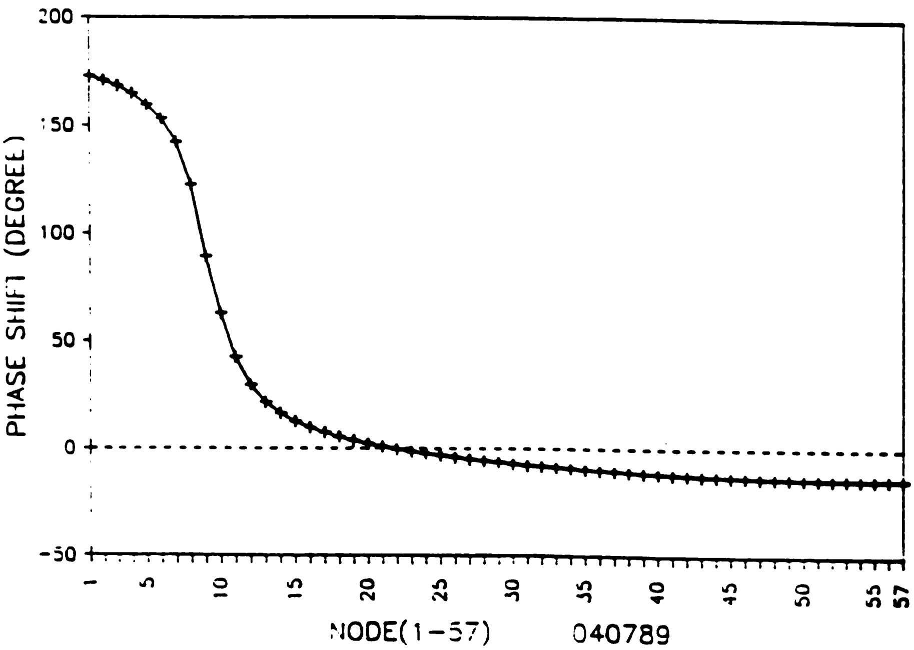


Figure 46. The AC model phase angle profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node (with line inductance effect)

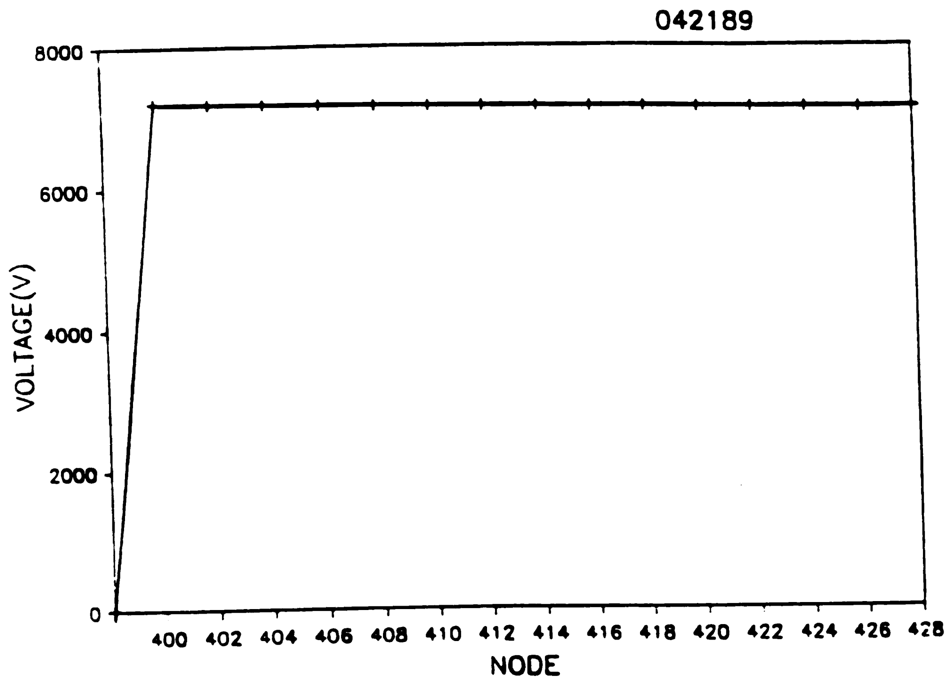


Figure 47. Voltage regulation along the distribution system for the AC model with the line inductance effect

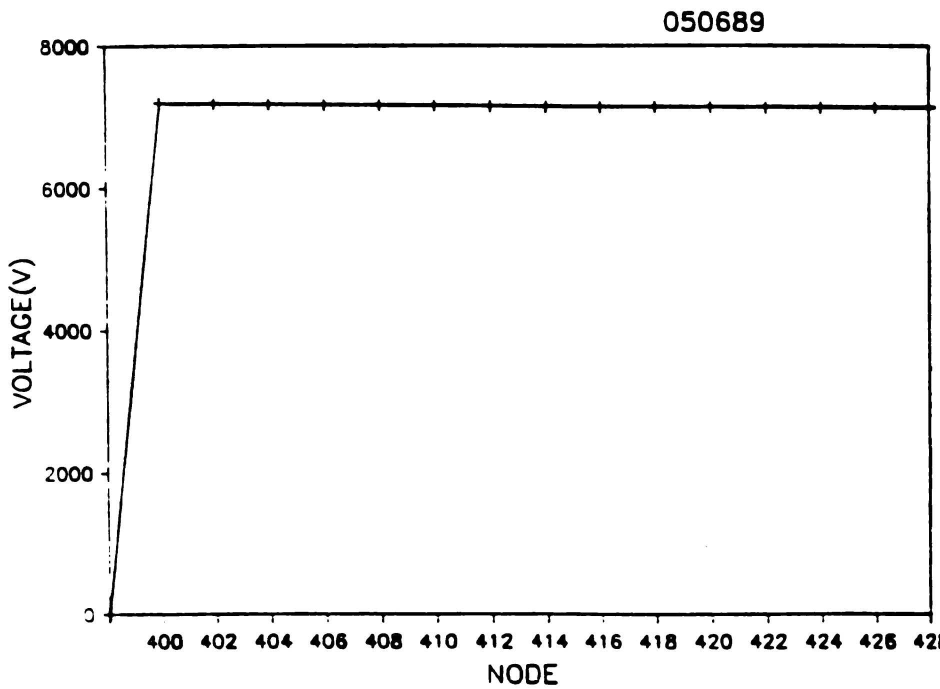


Figure 48. Voltage regulation along the distribution system for the DC base mode

little difference between these two regulation curves. The regulation for the DC model was 0.9% and for the AC model was 1.2%.

Figures 49 through 52 show the transformer bank operating conditions of the AC network model with the distribution line inductance effect. Figure 49 and Figure 50 show the magnitude of the primary current and secondary current of each transformer. For each residential transformer, primary current was 1.2 A and secondary current was almost 30 (29.6 -- 29.9) A. For each farm transformer, the primary current was 2.1 A; and secondary current was almost 60 (59.2 -- 59.7) A. The ratio of the primary current magnitude to that of secondary was not strictly 1/30 because the iron core excitation currents were neglected.

Figure 51 and Figure 52 show the primary current and secondary current phase angles of each transformer. It was assumed that the voltage source phase angle was zero degrees. For each residential transformer, the primary current phase angle was within the range -27.5 -- 27.3 degrees; and the secondary current phase angle was close to zero (-0.3 -- 0.1) degrees. For each farm transformer, the primary current phase angle was within -15.3 -- 15.1 degrees; and the secondary current phase angle was also close to zero (-0.4 -- 0.2) degree. Both the residential and farm transformer secondary current phase angles were close to zero degrees due to the pure resistance loads assumed.

Figures 53 through 55 present the neutral-to-earth voltage simulation curves resulted from the two different connection styles of primary and secondary neutrals of the distribution system. In one case

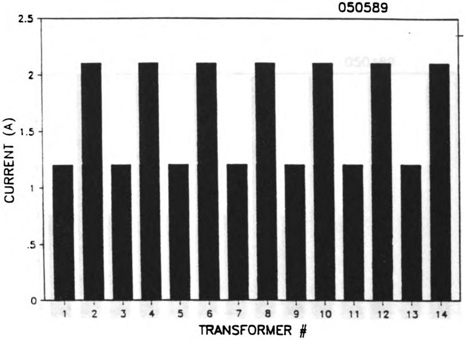


Figure 49. The transformer primary side current situation along the distribution system from substation to the end of the line in AC model with line inductance effect

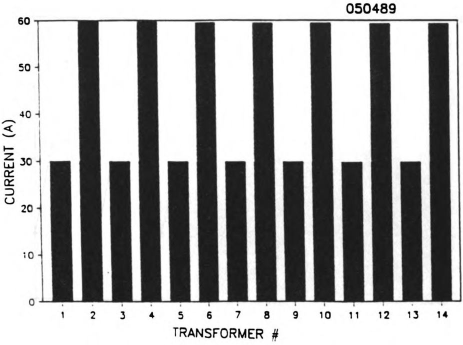


Figure 50. The transformer secondary side current situation along the distribution system from substation to the end of the line in AC model with line inductance effect

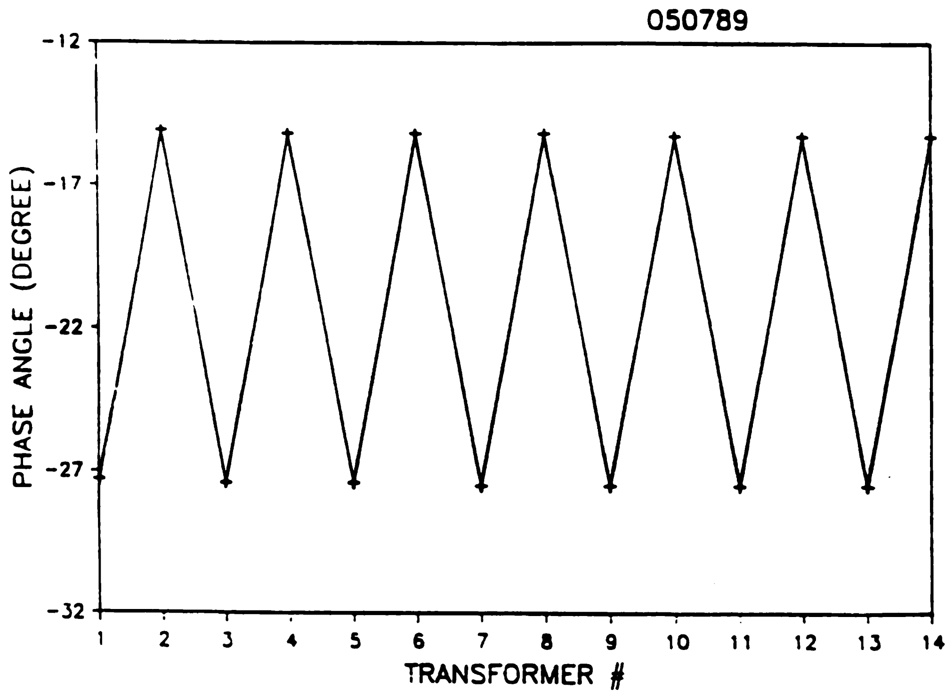


Figure 51. The transformer primary side voltage phase angles along the distribution system from substation to the end of the line in AC model with line inductance effect (take voltage phase angle at substation as zero reference)

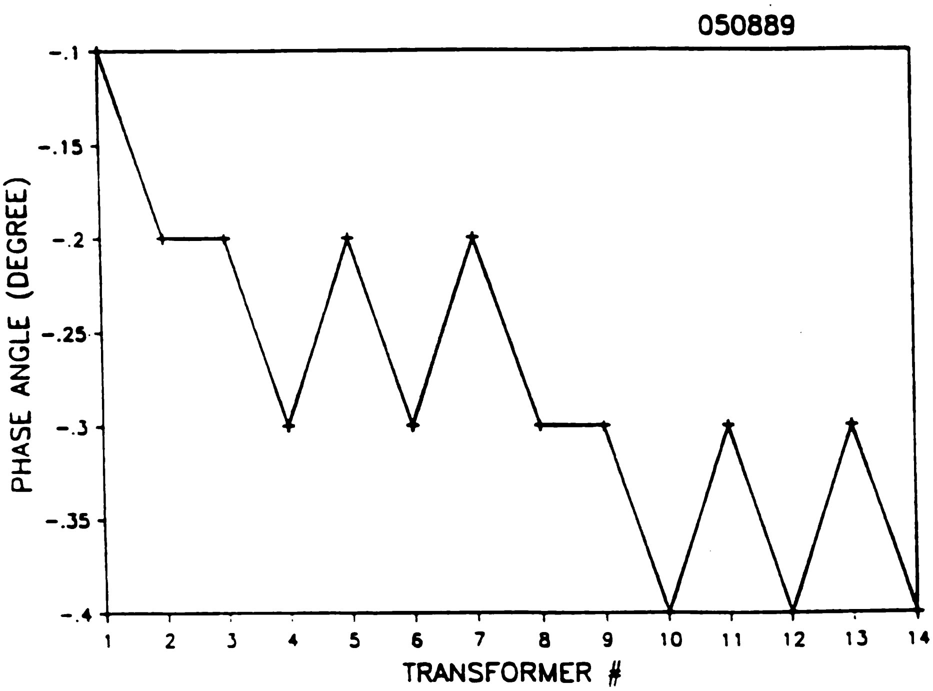


Figure 52. The transformer secondary side voltage phase angles along the distribution system from substation to the end of the line in AC model with line inductance effect (take voltage phase angle at substation as zero reference)

the primary and secondary neutrals were bonded together, and in the other case the neutrals were separated.

Figure 53 shows the the primary neutral-to-earth voltage profiles with primary and secondary neutrals bonded and separated in normal no fault condition. It can be seen that the voltage profiles of the two different neutral connection styles were identical.

Figure 54 shows the the primary neutral-to-earth voltage profiles with primary and secondary neutrals bonded and separated in 10 A secondary in-phase fault attached to node 33. It can be seen that the voltage profile of the separated neutral case was different from the voltage profile of the neutral bonded connection style. From node 11 (near the first farm transformer) toward the end of the line, the neutral-to-earth voltage decreased significantly. At node 18 (near the second farm transformer) the voltage with bonded neutrals was 1.9 V, 40% of the 4.7 V of the separated neutral connection case. At node 32 (near the fourth farm transformer in the middle of the line) the voltage with bonded neutrals was 3.4 V, 42% of the 8.0/8.1 V of the separated neutral connection case. At node 57 (near the seventh farm transformer at the end of the line) the voltage with bonded neutrals was 6.7 V, 70% of the 9.5/9.6 V of the separated neutral case. From the substation to node 10 the neutral-to-earth voltage was slightly increased by less than 1.1 V for the bonded neutral case as compared with the separated neutral case.

Figure 55 shows the primary neutral-to-earth voltage profiles with primary and secondary neutrals bonded and separated in 10 A

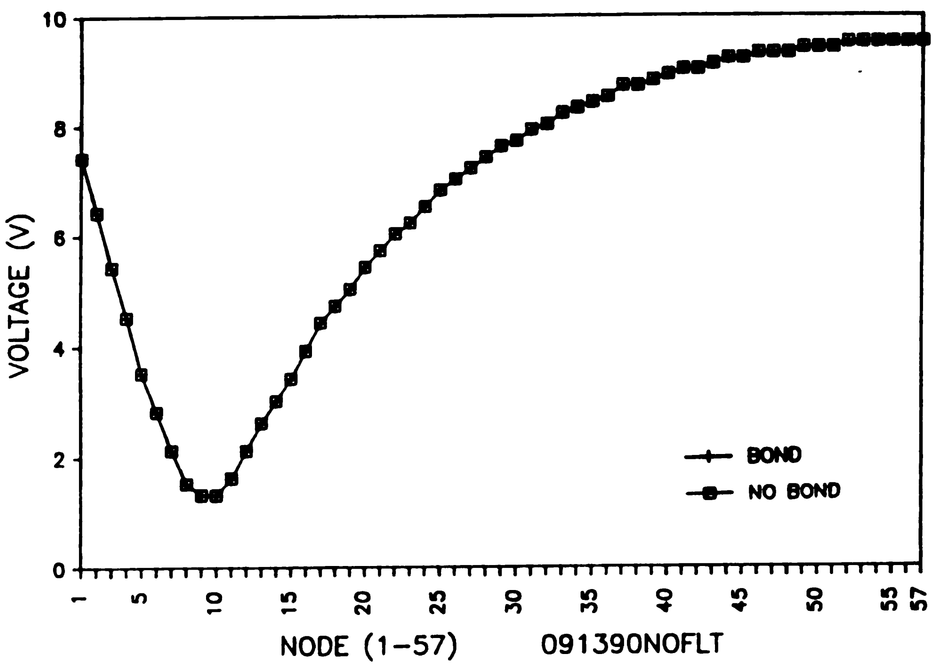


Figure 53. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with primary and secondary neutrals bonded and separated in no fault condition (AC model with line inductance effect)

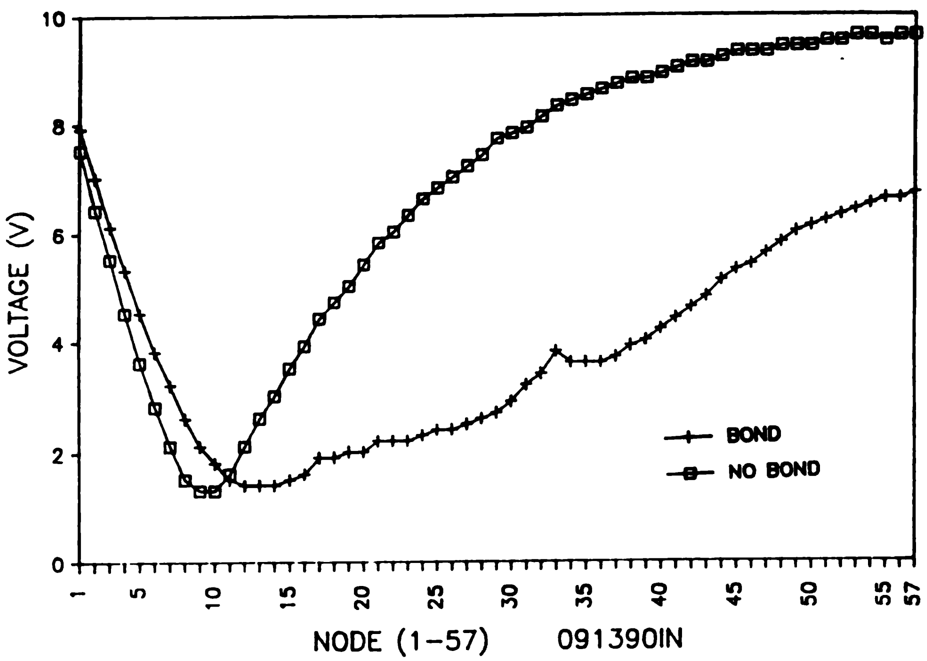


Figure 54. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with primary and secondary neutrals bonded and separated in 10 A secondary in-phase fault attached to node 33 (AC model with line inductance effect)

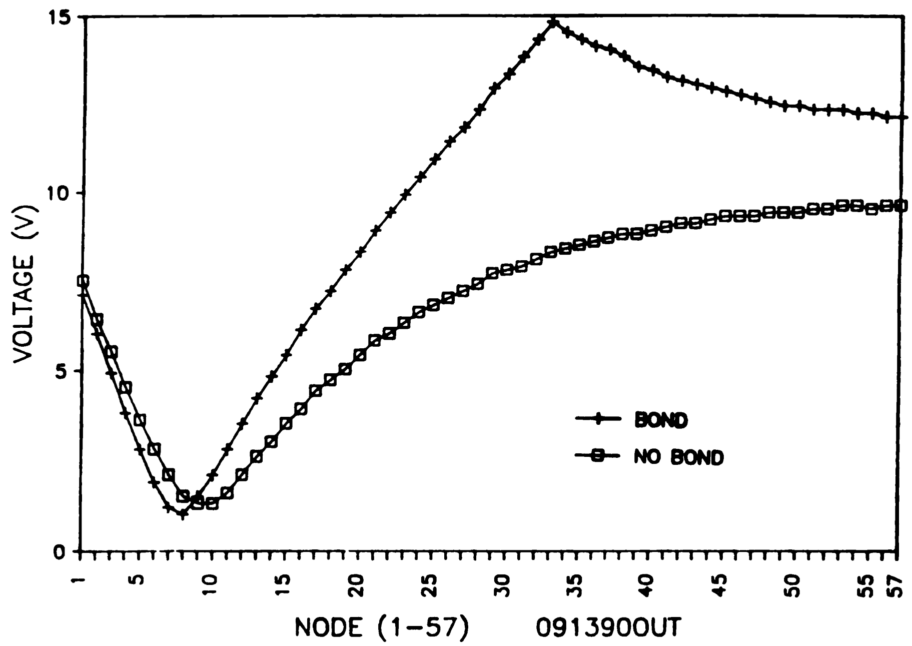


Figure 55. Profile of the neutral-to-earth voltage along the primary distribution line from substation to 57th node with primary and secondary neutrals bonded and separated in 10 A secondary out-of-phase fault attached to node 33 (AC model with line inductance effect)

secondary out-of-phase fault attached to node 33. It also can be seen that the voltage profile of the separated neutral connection and the voltage profile of the neutral bonded connection were significantly different. The voltage change trend of the latter was similar to the secondary ground fault DC simulation in the same operational condition mentioned in 5.1.9 in Figure 34. From node 9 (near the first farm transformer) toward the end of the line, the neutral-to-earth voltage increased significantly. The most significant voltage increase occurred at node 33 where the fault was attached. At this node (near the fourth farm transformer in the middle of the line) the voltage with bonded neutral was 14.8 V, 179% of the 8.3 V of the separated neutral connection case. At node 18 (near the second farm transformer) the voltage with bonded neutral was 7.2 V, 153% of the 4.7 V of that with neutral separated. At node 57 (near the seventh farm transformer at the end of the line) the voltage with the bonded neutral was 12.1 V, 127% of 9.6 V of that with neutral separated. From the substation to node 8, the neutral-to-earth voltage was slightly decreased by less than 1.0 V compared with the case with primary and secondary neutral separated.

Prothero et al. (1988) concluded from their field measurements that the common practice of solidly bonding primary and secondary neutrals was consistent with the goal of minimizing primary neutral-to-earth voltage on rural feeders. Figure 54 was consistent with this conclusion when the secondary side had a large current in-phase with primary side current. On the other hand, from Figure 55, theoretical analysis indicated when the secondary side had abnormally high fault current out-of-phase with the primary current, the local primary neutral-to-earth voltage could increase.

From Figure 53 through Figure 55 it also can be seen that removing the bond or separating the ground connection between the primary and secondary neutrals can prevent secondary faults from affecting the original primary neutral-to-earth voltage distribution system.

VI. CONCLUSIONS

A computer simulation was developed and used to study the neutral-to-earth voltage profile along a single-phase, radial distribution line with different normal and abnormal operating conditions. The conclusions drawn from this study are:

1. The DC circuit model developed in this research is sufficiently valid to predict the changing trends of the neutral-to-earth voltage profile along a single-phase primary distribution line.
2. Neutral-to-earth voltage caused by a high resistance segment in the neutral conductor of a primary distribution line will be greatest in the local area of the high resistance segment and will decrease in magnitude as the distance increases away from the high resistance segment, and the magnitude of this neutral-to-earth voltage is also dependent upon the level and location of loads with respect to the abnormal resistance in the neutral.
3. A high resistance connection between the transformer primary neutral terminal to down ground and the primary neutral conductor, in the middle of the distribution line, will result in an elevated level of neutral-to-earth voltage when load is drawn at

the transformer. No significant neutral-to-earth voltage changes occur elsewhere along the distribution line.

4. A phase-to-neutral fault on a primary distribution line is the same as placing a large load at that location on the line, and will result in a local increase in the neutral-to-earth voltage.
5. When a primary phase-to-earth fault occurs anywhere along the line, the neutral-to-earth voltages increase in line segments near the substation and decrease for line segments from the middle to the end of the line with the most significant changes near the substation.
6. A high substation resistance-to-earth for a single-phase radial distribution line will result in an increase in neutral-to-earth voltage along the line near the substation when load current is carried on the primary neutral.
7. Lowering the resistance-to-earth of the single-phase distribution line may not result in a significant lowering of the neutral-to-earth voltage of the line, and usually the lowering is most significant in the local area where the resistance-to-earth was reduced.
8. Increasing the primary distribution line operating voltage resulted in a decrease in primary line current and thus the neutral-to-earth voltage along the line. The reduction of neutral-to-earth voltage was less significant when the voltage increased above 7.2 kV than when the voltage was increase from a lower value up to 7.2 kV.

9. A secondary ground fault may cause a significant increase or decrease in the neutral-to-earth voltage along the distribution line in the local area of the ground fault depending upon whether the secondary ground fault current is in-phase or out-of-phase with the primary current. The change in neutral-to-earth voltage is location dependent along the distribution line.
10. An AC distribution line model operated with line inductance and an equivalent transformer circuit replacing the load resistor in the DC model produced a neutral-to-earth voltage profile which was higher in magnitude but similar in shape to the DC profile.

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