Stray Voltages – Concerns, Analysis and Mitigation

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SECTION 1

HANDBOOK OVERVIEW

This Handbook on Stray Voltages provides a comprehensive resource for the electric utility engineer to understand the sources of stray voltages, their effects on animals and humans, techniques for field measurement and investigation procedures, and the mitigation strategies and equipment available. Four actual case studies are also included, provided by our NEETRAC members, to illustrate mitigation solutions through computer models for Dairy Farms, Residential Subdivisions, Boat Docks, and Parallel Transmission Lines.

With fifty years of experience, the electric utility industry has accumulated a tremendous amount of research data on the subject. Pertinent technical papers, standards, and publications are summarized and referenced in this Handbook. Descriptions of the different types of distribution systems and grounding methods are also provided as well as the fundamentals and sources of stray voltage.

Also identified as “neutral-to-earth voltage” or “neutral-to-ground voltage”, **stray voltage** is defined as the difference in potential between animal or human contact points such as a cow’s body and feet or a child’s hands and feet. This definition obscures the two-fold nature of the problem, that of identifying a source for the voltage and path for the current. The voltage source is often hidden by a multitude of contributing factors, some endemic to the particular farm or household. Although the path that the current takes is the one of least resistance, it is not constant because of the changes in the path resistances.

The problems related to “stray voltage” do not end with just investigating the voltages on the neutral or the equipment connected to the neutral. The case in point is a recent investigation in response to a complaint from a residential customer. The complainant’s children were getting shocked while playing in the backyard. Approximately 18 volts were measured from the faucet to ground. After an exhaustive investigation involving three different utilities for over three months, it was determined that the source was a high resistance fault on a buried street light circuit.

Electric utilities need to be mindful of several court settlements that have been awarded to farmers identifying “stray voltage” as the culprit that caused poor animal performance. Faced with a customer choice business environment, the complaints from residential customers about “stray voltage” are also not to be taken lightly by the utility companies. Cow udders exploding and individuals dying in their bath tubs were the manner in which millions of people were indoctrinated to the problem of “stray voltage” (television program *Picket Fences*, October 23, 1992). Newspapers regularly carry headlines with sensational statements, “stray currents of up to 3 volts caused Cook’s cows to go wild and bend the bars of the milking parlor” (*USA Today*, October 7, 1992). As they have done in other areas, the media has branded what previously was known as “tingle voltage” as “killer voltage”. Utilities must be able to respond rapidly to stray voltage complaints with knowledgeable field personnel prepared to analyze the problem and provide effective and timely solutions to their customers.

SECTION 2

GROUNDING AND STRAY VOLTAGE RELATED STANDARDS

Overviews of several national, state, international and industry standards are summarized below for convenience. These summaries in no way reflect the full scope or requirement of any of the mentioned codes or standards, but rather give the reader an idea of the scope and content of each code or standard. The latest revision of the appropriate code or standard should be directly consulted to determine the appropriate requirements for any given situation.

US National Codes

ANSI/NFPA 70 National Electrical Code (NEC)

The NEC[7], sponsored by the National Fire Protection Agency, has the stated purpose of "...the practical safeguarding of persons and property from hazards arising from the use of electricity." The NEC states in the Introduction section (Article 90) that the standard does not apply to utility substations or any other installation under the exclusive control of electric utilities. However, it does cover service buildings, office buildings, and other utility-owned facilities not directly involved in power generation, transmission, or metering. Also, it does apply to industrial or other non-utility controlled substations. Therefore, one should be familiar with its contents. However, the NEC states that it may not be sufficient or complete for these installations and refers to the NESC for further guidance.

Article 250 covers requirements for grounding and bonding of electrical installations, which are more detailed and extensive than the NESC requirements due to the larger scope of application.

The NEC is more restrictive for circuits of 1000 volts or less. It requires solid grounding of neutrals or midpoint taps used as neutrals. However, there are some exceptions. For control circuits derived separately from primary circuits below 1000 volts that are maintained and supervised by qualified personnel, ground detectors must be applied. Below 480 volts, power circuits may be high impedance grounded if maintained and supervised by qualified personnel. However, ground detectors must be used and there can be no line-to-neutral loads.

Article 250 covers grounding. Section 250.56 states that additional electrodes must augment a single electrode such as a rod or plate that does not have a resistance to ground of 25 ohms or less. The types of these electrodes include metal water pipes (underground), effectively grounded metal frame of the building, concrete-encased electrode, and any made ground electrode such as ground rod or ground ring (Section 250.50 through 250.54).

Of particular interest to this handbook is Article 547 Agricultural Buildings, Section 547.9 Electrical Supply to Building or Structures from a Distribution Point and Section 547.10 Equipotential Planes and Bonding of Equipotential Planes. With the intent of reducing the N-E (neutral to earth) voltages, Section 547.9 (B) (1) allows isolation between the neutral bus and the ground bus in the distribution panel serving agricultural buildings. However, the following constraints are listed:

1) The equipment-grounding conductor shall be the same size as the largest supply conductor, if of the same material, or shall be adjusted in size in accordance with the equivalent size columns of Table 250.122 if of different materials.
2) The equipment-grounding conductor shall be bonded to the grounded circuit conductor at the disconnecting means enclosure at the distribution point or at the source of a separately derived system.
3) A grounding electrode system shall be provided in accordance with Part III of Article 250 and connected to the equipment-grounding conductor at the building(s) or structure(s) disconnecting means.
4) The grounded circuit conductor shall not be connected to a grounding electrode or to any equipment-grounding conductor on the load side of the distribution point.

Section 547.10 (A) and (B) requires installation of equipotential plane in concrete floors of livestock confinement buildings and areas. It also requires bonding of the equipotential plane to the building grounding electrode system per 547.10 (C).

Another NEC rule, which is relevant to this handbook, is Article 680. The provision of this article applies to the construction and installation of electric wiring for all electrical equipment, fixtures and metallic structures existing in swimming pools. Article 680-21 specifies the requirements for installing the underwater lighting fixtures and making them safe from shock hazards. Of particular interest to stray voltage concerns is the Article 680-22. This article provides for bonding together all metallic parts of the pool structure including the reinforcing metal of the pool shell, coping stones, handrail mounting brackets, electrical equipment casings, metal conduits and lighting fixtures.

National Electrical Safety Code (NESC)

The stated purpose of the NESC[5] is "...the practical safeguarding of persons during the installation, operation, or maintenance of electric supply and communication lines and associated equipment. These rules contain the basic provisions that are considered necessary for the safety of employees and the public under the specified conditions." Grounding is a small part of the provisions that the NESC deems necessary for safe conditions.

Section 9 describes practical methods of grounding for safeguarding employees and the public from injuries caused by differences in potential associated with electric supply and communication facilities. Personnel safety is the goal of this code.

Some of the notable sections for grounding requirements include:

- Section 96 - Describes requirements for grounding electrode resistance and provides criteria for distribution grounds.
  - 96B – Where practical, individual electrodes shall a have resistance of 25 ohms or less.
  - 96C – Not counting the customer service poles, the multigrounded distribution line should have at least four ground points in each mile.
- Section 97 - Describes requirements for separate grounding conductors attached to grounding electrodes.
- Section 99 - Describes grounding methods for telephone and other communication services exposed to electric supply lines or lightning.
- Section 123 - Describes which equipment needs protective grounds.
- Section 151 - Requires instrument transformer secondary to be grounded where permissible.
- Section 192 - Describes surge arrester ground conductor requirements.
- Section 215 - Describes grounding of circuits, structures, and equipment for overhead lines.
- Section 314 - Describes grounding of circuits, structures, and equipment for underground lines.

US State Codes

Wisconsin

Some of the information about Wisconsin's stray voltage rules shown below is obtained from an ASAE paper[72] presented by two authors from the Public Service Commission of Wisconsin (PSCW).

PSCW, in its 1989 docket 05-EI-106, proposes a battery of tests for stray voltage investigation whose goal is to determine the source of the stray voltage. The test consists of a load box test (120 volts and 240 volts), a secondary neutral test, and an equipment signature test, as well as the basic procedure of setting the cow contact measuring points. One must also determine the source resistance for each such point and determine if cow contact voltages can be found above the "level of concern." Although, the exact methodology and the value of the data gathered by the tests were not further explained in the docket nor were the techniques for analyzing the data, the authors in the above paper[72] offered these procedures. This is now known as " The Phase-II Protocol" in the State of Wisconsin.

From the 1996 PSCW docket 05-EI-115, the "level of concern" is defined as 2 mA (ac rms), steady-state or 1 volt (ac rms), steady-state across a 500 Ω resistor in the cow contact area. A cow contact measurement location has been defined as any area where a cow could simultaneously contact two conducting surfaces having a difference in electrical potential.

The state of Wisconsin deems that the above level of voltage/current is an amount of electricity where some form of mitigation is taken on the farmer's behalf, although only a small percentage of cows may actually perceive its presence. The "level of concern" is not a damage level. Instead, it is a conservative level below the point where moderate avoidance behavior is likely to occur and well below the point where a cow's behavior or milk production would be affected. The 2 mA allowable current level is further broken down into two parts. If the current contribution from the utility exceeds 1 mA or 0.5 volt contact voltage across a 500 Ω resistor, a mitigating action must be taken by that utility. Similarly, if the dairy farm's contribution exceeds 1 mA or 0.5-volt contact voltage across 500 Ω resistor, the farmer should be taking action.

PSCW also decided that isolating equipment should be made available to the farmer on request for a trial period of one year. This ensures that an entire lactating period and all seasons of the year are included. The farmer should pay for the installation of the isolator, but the utility should refund the salvage cost of the device if farmer chooses not to keep the isolator after the one-year trial period. A customer may also request permanent isolation at any time with the associated cost borne by the customer. However, for safety reasons, prior to having the isolator installed, the farm should be inspected to insure it is wired in accordance with NEC code [85].

The Commission also determined that the utility should own and maintain the isolator and should be able to determine what type of device is installed. However, a spark gap isolation device cannot be used. An isolator will only be allowed on an operating livestock farm to address stray voltage concerns, and farmers will be required to sign a "hold harmless" clause before receiving an isolator [85].

Michigan

There have been efforts in the past to establish stray voltage standards in the state of Michigan. These efforts included development of standards and public hearings on the proposed codes. However, there is no sanctioned protocol for stray voltages resulting from these hearings. The testing and the code that are followed by the utilities are much like the state of Wisconsin.

Canadian National Codes

Canadian Electrical Code, Part-I (CSA C22.1.94)

This code [19] contains safety standards for electrical installations. It is a voluntary code for adoption and enforcement by regulatory authorities. Briefs of some of the pertinent sections and subsections are provided below.

Section 10 of this code primarily deals with protecting lives at electrical installations by providing grounding at facilities with voltages below 750 V.

- Subsection 10-204 - This subsection describes grounding connections for ac systems, including supply transformers and service entrances.
- Subsections 10-400 through 10-414 - These subsections deal with grounding of equipment (permanent or portable) and their casings.
- Subsections 10-500 and 10-600 - Methods of grounding and bonding are described in these two subsections, respectively.
- Subsection 10-700 - This subsection describes different types of grounding electrodes, which may be used for grounding purposes. These ground electrode systems include two types: (a) the type exclusively installed for grounding purposes, such as rods, plates and counterpoises; and (b) the type whose primary purpose is other than the grounding.
- Subsections 10-800 and 10-900 - These subsections describe materials and connections used in grounding systems, respectively.
- Subsection 10-1000 - Grounding related information for lightning arresters and neutral grounding devices are provided in this subsection.

Grounding and bonding codes related to high voltage supply (indoor and outdoor) stations are described in Section 36. The following is a list of related subsections.

- Subsection 36-300 - This subsection contains material and minimum sizes of riser conductor, ground grid conductor and connections.
- Subsection 36-302 - Requirements for station ground electrodes, including location, minimum size and concrete encased electrodes, are provided in this subsection.
- Subsection 36 - 304 - This subsection specifies the maximum permissible resistance in terms of GPR for a station ground.
- Subsection 36-308 - Connections to the station ground electrode system, including ground grid, cable sheaths, tracks, lightning arresters, and shield wires from dead end structures, are described in this subsection.
- Subsection 36-310 - This subsection contains the requirements for gang-operated switch handle grounds.
- Subsection 36-312 - This section contains the requirements for metallic fence grounding.

CAN/CSA - C22.3 No. 1-M87, Overhead Systems

This standard[12] applies to the overhead lines and associated equipment. The standard, which forms a part of the Canadian Electrical Code, Part III, covers the requirements for construction of overhead systems. It includes power and communication circuits installed alone, in joint use, or in proximity to each other or other facilities. The requirements contained in the standard do not constitute complete construction specifications, but only prescribe the minimum requirements that are important for safety, continuity of service and protection of property.

Some of the grounding related sections are outlined below:

- Section 3.2.5 - This section describes grounding requirements or insulating of guys.

- Section 3.2.10 - This section describes grounding requirements of metal and concrete poles.
- Section 3.2.11 - This section describes grounding requirements for joint-use structures.
- Section 3.5 - Requirement for connecting together the grounds of different systems, such as telephone and cable TV systems are specified in this section.
- Section 3.7 - This section relates to inductive coordination between power and communication lines.

CAN/CSA - C22.3 No. 7-M94, Underground Systems

This standard[13] applies to underground systems and associated equipment. The standard, which forms a part of the Canadian Electrical Code, Part III, covers the requirements for construction of underground systems. It includes power and communication circuits installed alone, in joint use, or in proximity to each other or other facilities. The requirements contained in the standard do not constitute complete construction specifications, but only prescribe the minimum requirements that are important for safety, continuity of service and protection of property.

Some of the grounding related sections are outlined below:

- Section 3.5.6 - Requirements of separation between ground risers of communication and power systems, mechanical protection and insulation covering for grounding and neutral conductors, and grounding of riser pipes and guards are provided in this section.
- Section 3.5.7.4 - This section provides the requirements for bonding the cable sheaths.
- Section 3.6.2.3 - Specifications for grounding of underground circuits are provided in this section.

International Codes

IEEE Guide for Safety in AC Substation Grounding (Std 80)

This standard[6] provides guidance and information pertinent to safe grounding practices in ac substation design. This guide is primarily concerned with outdoor substations. However, used in conjunction with ANSI/IEEE 142 (the IEEE Green Book)[51], it can be applied to indoor substations as well. Also, this guide contains the generally accepted criteria for determining safe touch and step voltages in all applications, including distribution grounding systems. The stated purposes of this standard are:

- To establish, as a basis for design, the safe limits of potential differences that can exist in a substation under fault conditions, between points that can be contacted by the human body.
- To review substation grounding practices with special reference to safety and to develop criteria for safe design.

- To provide a procedure for the design of practical grounding systems based on these criteria.
- To develop analytical methods as an aid in the understanding and solution of typical gradient problems.

IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System (Std 81)

This standard [50] presents techniques for testing ground systems. The testing methods covered in this guide include:

- Measurement of the resistance and impedance of ground electrodes to earth.
- Ground potential surveys, including measurement of step and touch voltages and potential contour surveys.
- Scale-model tests for laboratory determination of the ground resistance and potential gradients for an idealized design.
- Measurement of earth resistivity.

IEEE Standard for Qualifying Permanent Connections Used in Substation Grounding (Std 837)

This standard[53] provides direction and methods for qualifying permanent connections used for substation grounding. It particularly addresses the connectors used within the grid system, connectors used to join ground leads to the grid system, and connectors used to join the ground leads to equipment and structures. Though developed for substation applications, the requirements and information on connections are applicable to all permanent grounding connections.

The purpose of this standard is to give assurance to the user that connectors meeting the requirements of this standard will perform in a satisfactory manner over the lifetime of the installation, provided that the proper connectors are selected for the application and that the connectors are installed correctly.

Detailed procedures are given for conducting the tests and recording test data and results.

IEEE Guide for Protection of Wire-Line Communication Facilities Serving Electric Power Stations (Std 487)

The stated purpose of this guide[52] is to present workable methods for protecting wire-line communication circuits entering power stations.

The major causes of disturbances in communication circuits are given as follows:

- Ground potential rise (GPR) at the power station.
- Longitudinal induction.

- Electrical contact between power and communication conductors.
- Lightning and switching surges affecting the communication system.

The following sections discuss protective device application to the various types of communication circuits:

- Section 3 - Protection Apparatus: The type of protective devices used in any particular case, would be dictated by the nature, magnitude, and frequency of occurrence of the interference, and the nature of the service requirements, considerations of personnel and plant safety, and by general protective policies employed by the organizations concerned.
- Section 4 - Service Types, Reliability, Service Performance Objective (SPO) Classification, and Transmission Considerations:
  The SPO Classification of the communication circuits with respect to disturbances caused by power system faults is as follows:
  - Class A. Non-interruptible Service Performance (must function before, during, and after the power fault condition). The non-tolerable service interruptions include both loss of dependability (failure to deliver a valid trip or control signal) and loss of security (delivery of a false trip or control signal). This class of service includes pilot-wire protective relaying, audio-tone protective relaying, and critical supervisory circuits.
  - Class B. Self-Restoring Interruptible Service Performance (must function before and after power fault condition). This class of service includes emergency telephone circuits, telemetering and data circuits, supervisory control circuits, and signal and alarm circuits.
  - Class C. Interruptible Service Performance (can tolerate a station visit to restore service). This class of service includes basic exchange telephone service, non-critical telemetry and data circuits, and some signal and alarm circuits.

IEEE Recommended Practice for Grounding Industrial and Commercial Power Systems (Std 142)

This standard[51] provides guidance and information pertinent in commercial and industrial power systems. It discusses the how's, where's, and why's of grounding in an industrial distribution setting. The purpose of this standard is to present basic reasons for grounding or not grounding and reviewing the practices and methods of system grounding. The following is a partial list of topics in the standard:

- Methods of system neutral grounding
- Grounding of generators, transformers, and uninterruptible power supplies
- Equipment grounding
- Static and lightning protection grounding
- Ground electrodes
- Sensitive electronic equipment grounding

While referring to other applicable standards on the subject, this standard deals more with grounding in terms of system operation than safety.

IEC/TR (International Electrotechnical Commission) Report 60 479

The *IEC Report 479 Effects of Current Passing Through the Human Body* [48] [49] contains six chapters dealing with acceptable body currents to avoid ventricular fibrillation in humans due to electrical shocks. The report is divided into two parts, each with three chapters.

Part 1: General aspects:
- Chapter 1: Electrical impedance of the human body
- Chapter 2: Effects of alternating current in the range of 15 Hz to 100 Hz
- Chapter 3: Effects of direct current

Part 2: Special aspects:
- Chapter 4: Effects of alternating current with frequencies above 100 Hz
- Chapter 5: Effects of special waveforms of currents
- Chapter 6: Effects of unidirectional single impulse currents of short duration

This report includes information on the latest research on the effects of current on the human body, including the effects of voltage, current path, and current frequency on the body impedance in the shock circuit. It does not, however, consider the effects of external additional shock circuit impedances, such as the insulation provided by gloves, shoes, boots or the resistivity of the soil or rock on which the person is standing. It also does not address the effects of shock current or voltage on animals.

SECTION 3

DISTRIBUTION SYSTEMS

A distribution system is a configuration of conductors and equipment designed to transfer energy from the distribution substation to the user, safely and effectively. The types of loads that they serve, the type of construction, the system voltage levels, and system grounding methods characterize distribution systems.

Types of Loads

The optimum location for a distribution substation is as close to the load as possible. However economics do not always allow this to occur. Several classifications of loads have been developed over the years that defined the types of distribution systems, which serve them. The types of loads that distribution systems serve can be broadly classified as follows:

- Residential
  - Urban
  - Suburban
  - Rural
- Commercial
  - Downtown Areas
  - Shopping Malls
  - Commercial Buildings
  - Small Shops
- Industrial
  - Large Plants
  - Small Plants

Types of Construction

The distribution feeders mostly are radial feeders separated by sectionalizing switches. However, the neutral generally continues across the sectionalizing switch.

Distribution construction methods consist of overhead, underground, and a combination of the two methods. The type of overhead construction is determined by load density in the area. Because of right-of-way limitations in densely populated areas, it is sometimes necessary to locate more than one circuit, with different voltages on the same poles. When the poles carry two or more distribution circuits, it is called a multiple circuit distribution system. When a distribution circuit runs below the transmission circuit, it is commonly referred to as an "underbuilt distribution circuit." Rural distribution systems, on the other hand, are characterized by longer spans between poles, taller poles to accommodate sag requirements and fewer transformers.

Underground distribution is becoming more popular, especially in residential areas, in spite of its higher cost compared to overhead distribution. This popularity is largely due to its minimal impact on residential environment and its operational reliability in adverse weather conditions such as storms, wind and rain. Because the costs involved in installing and maintaining an underground system are significantly higher than its overhead counterpart, care should be taken during the design phase, including selection of the cable and its accessories.

Three single-phase cables are normally chosen over three-phase cable because of the cost, reliability and flexibility of operation. Three single-phase cables are more flexible when splitting the load and also cost effective due to less expensive single-phase taps and accessories.

The types of cable insulation vary from lead and paper to various types of rubber and synthetic compounds to prevent damage from moisture ingress. Most primary underground residential systems are of the single-phase, concentric neutral type (bare or jacketed) that employ polyethylene or cross-linked polyethylene insulation. Normally, three polyethylene-insulated cables (triplex) are used for a secondary service. In some cases, a bare copper wire is used for the neutral in lieu of the insulated cable. The use of two single-phase cables with concentric neutral can also be found at some secondary installations.

Voltage Levels

Table 3-1 below lists the primary and secondary distribution system voltages currently in use in the United States and Canada.

Table 3-1 Typical Primary and Secondary Distribution Voltages in U.S.A. and Canada

NOMINAL SYSTEM VOLTAGE		
THREE PHASE FOUR WIRE $V_{LINE - LINE} / V_{LINE - NEUTRAL}$		SINGLE PHASE THREE WIRE
PRIMARY - kV	SECONDARY - V	SECONDARY - V
4.16 / 2.4	208 / 120	120 / 240
12.47 / 7.2	416 / 240	
13.2 / 7.6	480 / 277	
13.8 / 8.0		
24.94 / 14.4		
34.5 / 19.92		

Number of Conductors

The most common type of distribution system in North America is the three-phase, four-wire, multigrounded system, which consists of three phases and a neutral. The neutral is common for the three phases of the primary, as well as the single- phase secondary. The neutral is grounded in many places. Single-phase loads are served by distribution transformers, of which the primary windings are connected between one phase and the neutral. One three-phase transformer or three single-phase transformers can serve three-phase loads. In terms of protective devices required and overall reliability, this may be the most economic distribution system. Each single-phase transformer requires one primary fuse and may have one surge arrester for protection. The common multigrounded neutral allows this system to freely function as single-phase distribution where needed. The common neutral is sometimes used for more than one circuit on the same pole such as in underbuilt applications.

The three-phase, three-wire system may also serve single-phase loads by means of connecting a single-phase transformer between two primary phases. In such cases, each single-phase transformer requires two primary fuses and two surge arresters (where applied) for protection.

Depending on the customer and the type of the load served, two-phase (with neutral) systems may prove more economical. The "open delta" secondary system is typical with this type of primary system.

Limitations including the economics on the early dc distribution systems have caused most of them to be replaced with more flexible and efficient ac distribution systems.

System Grounding Methods

Evolution of Distribution Systems

Historically, there has been a gradual trend in the North American practice from ungrounded system to unigrounded system and finally to the multigrounded or effectively grounded distribution system. The evolution of distribution systems in other parts of the world started since the late nineteenth century. These systems included solidly multigrounded, ungrounded, resonant grounded, solidly unigrounded, and resistively or reactively grounded systems. Picking the best distribution system among these is not an easy task because each approach has its advantages and disadvantages. However, the main factors, which brought the multigrounded system in the forefront, were the system reliability, system flexibility, safety and the economics.

The main reason for the existence of ungrounded system in early days was that it allowed utility companies to operate the system even if one phase faulted to ground. Also, fault currents were comparatively low, and for temporary faults the arcs would self-extinguish. These resulted in fewer power supply interruptions and avoided prolonged outages.

Limitations to ungrounded operation began to develop with the growth of the system, both in terms of distribution voltage levels and feeder lengths. The fault current (generated by line to ground capacitances of sound phases) was no longer small and more importantly no longer self-clearing. The phenomenon known as "arcing grounds" and its resulting transients and safety issues were a concern to the utility engineers. A majority of the distribution system was grounded either solidly or through resistance by 1920 as a result [82].

Solidly Multi-Grounded System

A solidly multi-grounded system is the most widely used method in North America. Figure 3-1 shows a schematic of Solidly Multi-grounded System. It provides power for single-phase and three-phase loads and is very cost effective especially for rural areas where loads are widely scattered.

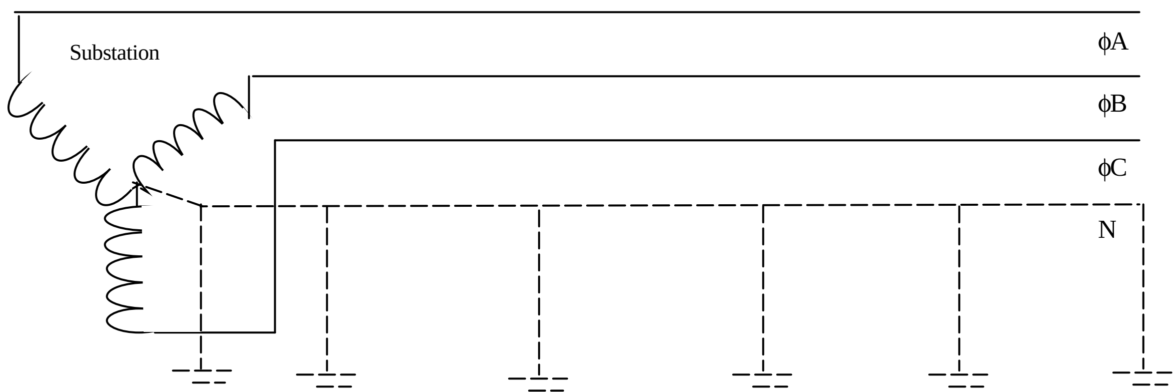


Figure 3-1 Schematic of a Solidly Multi-grounded Distribution System

Phase-to-ground faults do not excessively affect voltages on the two unfaulted phases because the neutral is solidly grounded. Ground fault currents are high, but the majority of the fault current returns via neutral and can be quickly cleared. This and grounding electrodes connected to the neutral keep touch and step voltages within acceptable limits. Ground fault protection is provided by ground overcurrent relays set more sensitively than the phase overcurrent relays. As a result, the relaying is reliable, simple, and cost effective, unlike the ungrounded system.

For all system configurations, this system is an effectively grounded system meeting the following requirements:

- The ratio of the zero-sequence reactance to the positive-sequence reactance (X_0 / X_1) is positive and less than three.

- The ratio of the zero-sequence resistance to the positive-sequence reactance (R_0 / X_1) is positive and less than one.

If the above conditions are met, ground fault currents will be of approximately the same magnitude as three-phase fault currents. During a ground fault, voltages between the sound phases and ground are limited such that surge arresters with less than line-to-line voltage ratings can be applied. Application of lightning arresters with lower ratings offers the most efficient and reliable protection at the lowest possible cost.

In summary, the following are some advantages and disadvantages of Solidly Multi-grounded System:

Advantages:
- Provides the most cost-effective power distribution, especially in rural areas
- Overvoltages during ground faults are low
- Allows application of lower rated lightning arresters providing better protection against lightning surges
- System protection is simple, reliable and cost-effective.

Disadvantages:
- Results in a neutral to earth (N-E) voltage, which can contribute to stray voltage.
- Ground fault currents are high and must be quickly interrupted.

The four-wire distribution system with multi-grounded neutral is commonly used in North America because of the economic, safety, and operating advantages that this type of system offers. The windings of the substation transformers servicing the primary system are wye connected and the neutral point is solidly grounded. The neutral circuit is a continuous metallic path along the primary routes of the feeder and to every user location for better and efficient system protection. Where primary and secondary systems are both present, the same conductor is used as the common neutral for both systems. The neutral is grounded at each distribution transformer serving the customer and also connected to the metallic water pipes and/or driven grounds at the customer location. The neutral is grounded at intermediate points (at the poles) along the primary circuit as called for by the National Electric Safety Code (NESC) ANSI C2-2002, Rules 96C and 97D2. Regulations governing neutral grounding in the user premises are given in the National Electric Code (NEC) ANSI/NFPA70-2002.

The primary purpose of grounding the neutral is to limit the overvoltages caused by lightning, line surges, or unintentional contact with high-voltage conductors such as primary to secondary faults. Grounding also serves as a reference point to stabilize the voltage under normal operating conditions. The grounding system serves as a back-up for the neutral wire, and in some instances helps facilitate the operation of overcurrent devices, such as fuses or circuit breakers.

Ungrounded System

Figure 3-2 represents a schematic of Ungrounded Distribution System.

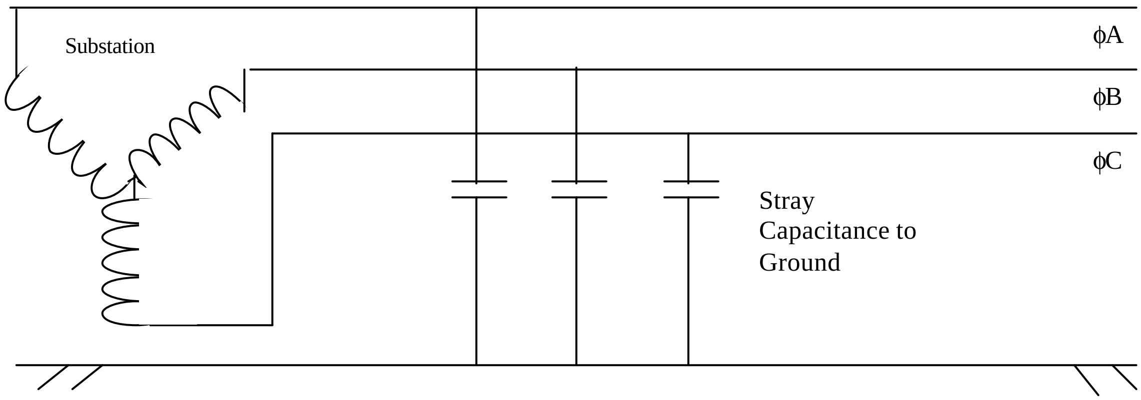


Figure 3-2 Schematic of Ungrounded Distribution System

Ungrounded distribution systems are widely used in Europe and many other parts of the world where ground fault currents are still small (less than 20 A in a 10 kV system). Because the transformer neutral is floating, its magnitude and phase angle with respect to ground can freely shift. Under balanced load conditions, phase-to-ground voltages are equal in magnitude and separated by 120°. In this ideal condition, there is no voltage difference between the transformer neutral point and the ground. In the case of a phase-to-ground fault, the current would flow from the faulted phase to the fault, and back to the source through system's stray capacitance as shown in Figure 3-3.

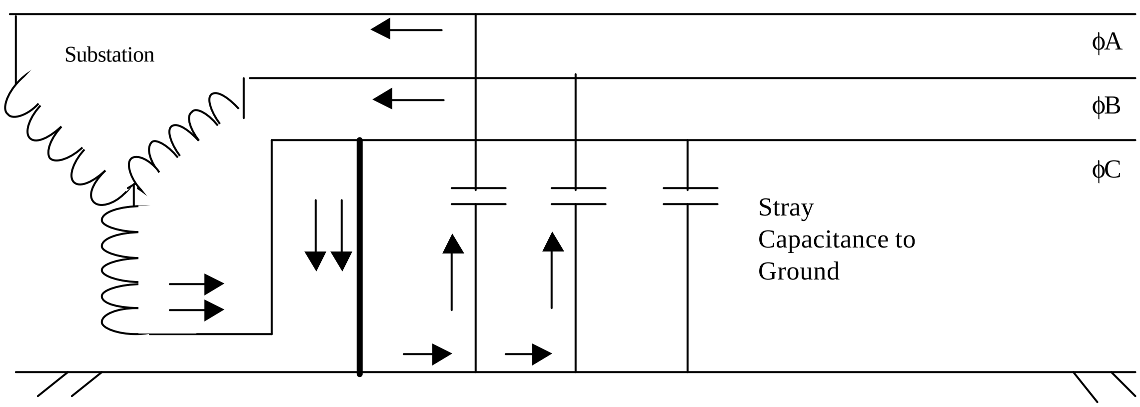


Figure 3-3 A Ground Fault in an Ungrounded Distribution System

The system condition, which must be met to limit transient overvoltages due to an arcing fault requires the ratio of the zero-sequence resistance to the distributed per phase capacitive reactance to ground of the system (R_0 / X_0) to be less than two. The ground fault current is usually limited to less than 20 A with a minimum at least equal in magnitude to the total system capacitance to ground charging current. Full rated surge arresters suitable for use on ungrounded neutral circuits must be applied.

As shown in Figure 3-3, the fault current magnitude depends on the source voltage and phase-to-ground stray capacitance of the system's two unfaulted phases. Due to system growth (system voltage and expansion), the ground fault current increases causing uninterruptable arcing and system overvoltages. The system overvoltages may cause the second ground fault resulting in high fault currents similar to a solidly unigrounded system. Also, the ground fault causes a voltage rise from phase-to-ground to phase-to-phase on the unfaulted phases. The insulation level of feeders, as a result, must be designed to accommodate this higher voltage. Application of higher rated lightning arresters to protect the equipment against lightning not only adds to the cost but also offers less protection.

For an ungrounded system to operate safely, sensitive ground detection must be applied to protective relaying. Effective ground fault protection is provided by directional overcurrent relays that compare the difference in phase angle between the transformer neutral to ground and the fault current. Normally, this phase angle difference is approximately 90°.

The following is a summary of advantages and disadvantages of an ungrounded distribution system:

Advantages:
- Fewer interruptions
- Does not contribute to stray voltage
- Easy to convert to higher voltage unigrounded system or solidly multigrounded system

Disadvantages:
- All system hardware including protection must be fully insulated resulting in a very expensive system
- For higher ground fault currents (higher than 20 A in 10 kV, 15 A in 20 kV, and 10 A in 35 kV systems) the arcs are not self-extinguishing and overvoltage escalation may occur
- Non-extinguishing arcing at the fault location is a safety concern.
- Probability of double faults is high, which may produce high fault currents similar to unigrounded or multigrounded systems.

Solidly Unigrounded System

When capacitive currents in ungrounded systems become high, transformer neutrals must be grounded. Unigrounded systems are grounded only at the transformers as shown in Figure 3-4. The unigrounded system is intended mainly for three-phase loads. Single-phase loads are provided from single-phase transformers connected phase to phase.

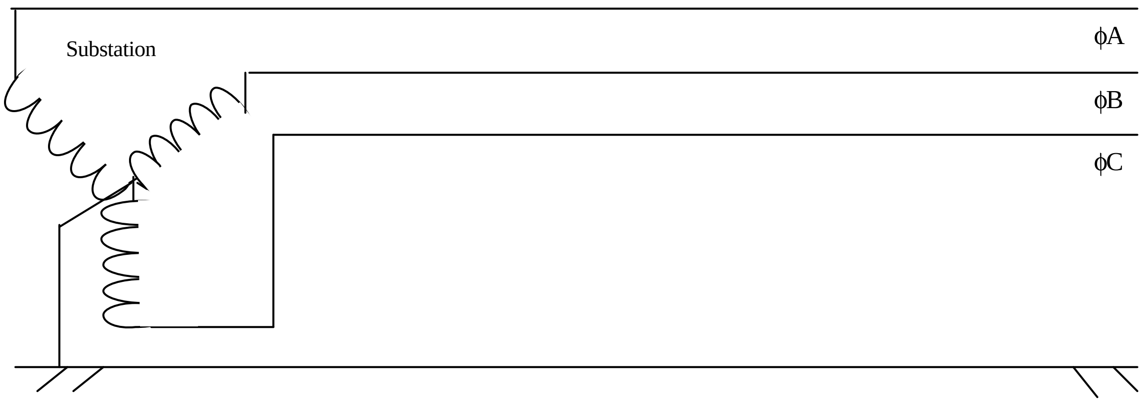


Figure 3-4 A Schematic of Solidly Unigrounded Distribution System

This system can be classified as an effectively grounded system provided that the same constraints as listed for solidly multigrounded systems are met. In this case, ground fault currents will be of approximately the same magnitude as three-phase fault currents. During a ground fault, voltages between the sound phases and ground will be limited such that surge arresters with less than phase-to-phase voltage ratings can be applied. Application of lightning arresters with lower ratings will offer the most efficient and reliable protection at the lowest possible cost.

A major disadvantage of this system is that the voltage at the fault point can rise to an extremely high level with respect to remote or reference ground. This is due to 100 % of the fault current returning through the earth (no neutral path available). This high voltage level may create intolerable step and touch voltage gradients around the fault location.

In summary, the following are advantages and disadvantages of this system:

Advantages:
- Overvoltages on sound phase are small (usually below 1.4 PU)
- Does not contribute to stray voltage
- Substation transformers can be designed with graded (less expensive) insulation on the winding

Disadvantages:
- Step and touch voltages around the fault location are definitely safety concerns and must be dealt with.

- High probability of high impedance faults exists and clearing these faults is a challenge.

Resistively or Reactively Grounded System

To limit ground fault currents and reduce thermal and mechanical stresses on the substation transformer, a resistor or reactor is normally installed between the transformer neutral and ground. Figure 3-5 shows a schematic of this type of system.

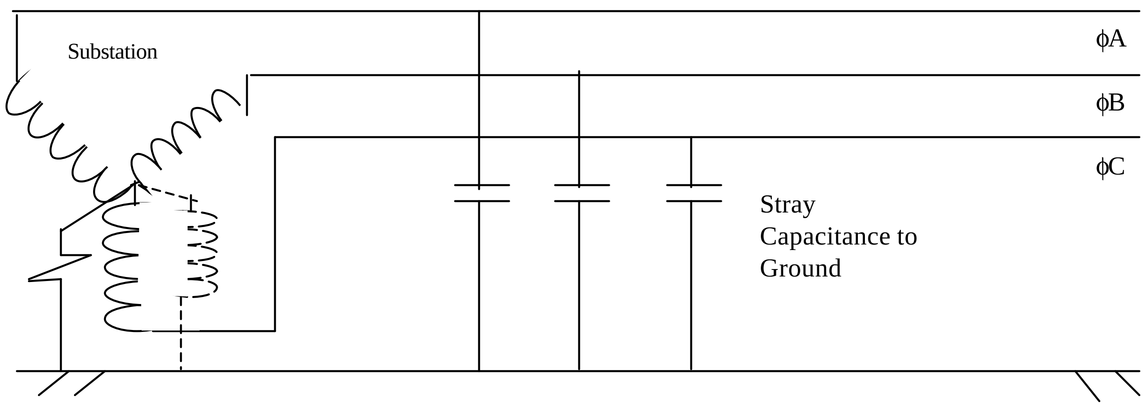


Figure 3-5 A Schematic of Resistively or Reactively Grounded Distribution System

As commonly installed, the resistance has a considerably higher ohmic value than the system reactance at the resistor location. Consequently, the resistor itself primarily limits the line-to-ground fault current. The resistor, on the other hand, must permit sufficient ground fault current to allow selective relay performance. Ground fault currents are in the range of approximately 50 to 1200 A.

The use of neutral resistance increases the transformer neutral voltages during ground faults. For example, a 40% reduction in ground fault current with a resistor would increase the neutral-to-ground voltage to 80% of the phase-to-ground voltage. The system condition for limiting overvoltages on sound phases requires the ratio of zero-sequence resistance to zero-sequence reactance (R_0 / X_0) to be greater than two. However, the full rated surge arresters suitable for use on ungrounded neutral circuits must be applied on the transformer.

Like solidly unigrounded system, concerns for step and touch voltages around the ground fault location exist in this system. For this reason, a combination system consisting of resistively grounded transformer supplying power over four wires (three phase and one or more ground conductors) is commonly used particularly for industrial customers where a reduction in fault currents is required.

System conditions for reactance-grounded systems are:

- The ratio of the zero-sequence reactance to the positive-sequence (X_1 / X_0) is between 3 and 10.

- The ratio of the zero-sequence resistance to the zero-sequence reactance (R_0 / X_0) is less than one.

Ground fault currents are in the range of 25 % of the three phase-fault current (X_0 = $10X_1$) to 60% of three-phase fault current ($X_0 = 3X_1$). Reactance grounding system becomes an effective grounding system if the ratio of the zero-sequence reactance to the positive-sequence (X_1 / X_0) is three or less. In practice, reactance grounding is generally used for a generator neutral, which is being connected to a four-wire system. The ground fault current in such a system must be limited to a value no greater than the three-phase fault current for which the generator is protected.

The list below summarizes advantages and disadvantages of this type of system:

Advantages:

- Does not contribute to stray voltage
- Less thermal and mechanical stresses on the transformer due to reduced fault current
- Overvoltages on unfaulted phases are less compared to ungrounded system

Disadvantages:

- Step and touch voltages around the fault location are less compared to unigrounded system but are still of concern.
- Use of neutral resistor or reactor increases the neutral voltage during a ground fault and as a result higher transformer insulation is required.
- Lightning arresters with higher voltage ratings are required to protect the transformers.

Resonant Grounded System

This type of system is often found in Europe[56]. In this method, the transformer neutral is grounded through a variable reactance, also known as Peterson Coil as shown in Figure 3-6. The reactance is tuned with the system stray capacitances for power frequency, 50 Hz or 60 Hz.

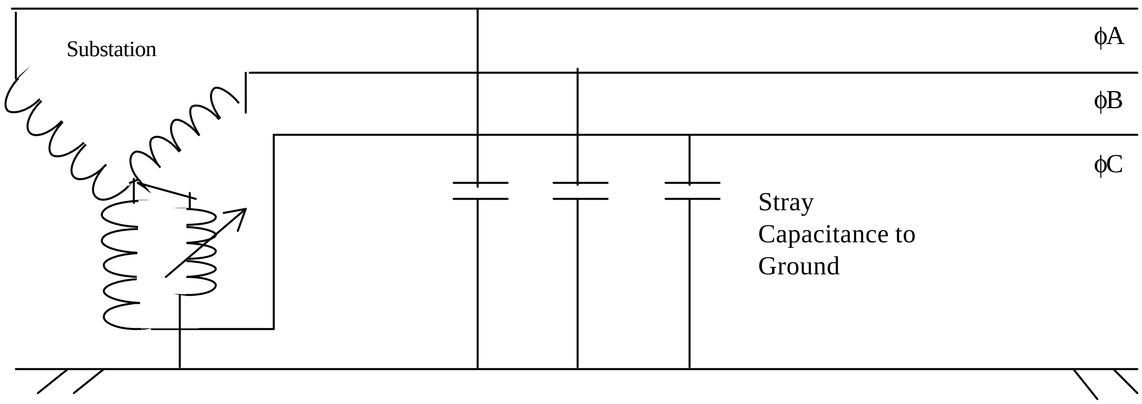


Figure 3-6 A Schematic of Resonant Grounded Distribution System

In the case of a ground fault, as shown in Figure 3-7, the reactance and stray capacitance will cause the same amount of fault current to flow in opposite directions through the fault, canceling each other and reducing the fault current to a very small magnitude. Thus, a small portion of current will flow through the fault (due to small tuning mismatch) and the rest will return to the source through the reactance.

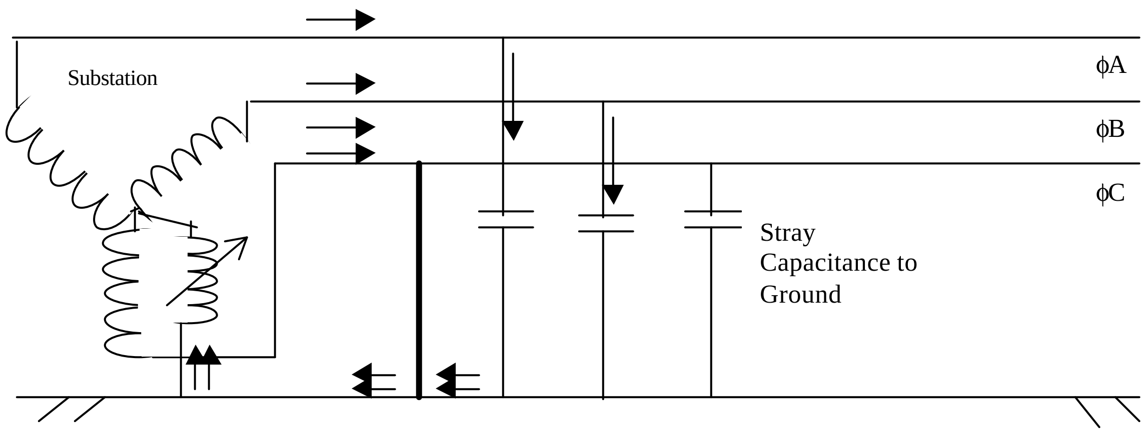


Figure 3-7 A Ground Fault in a Resonant Grounded Distribution System

The following are Resonant Grounded System's advantages and disadvantages:

Advantages:

- Does not contribute to stray voltage
- Ground fault currents are small and as a result arcs are self extinguishing
- Step and Touch voltages are small

Disadvantages:

- Phase-to-ground voltages on unfaulted phases can be high due to resonance.
- Use of neutral resistor or reactor increases the neutral voltage during a ground fault and as a result higher system insulation is required.

- Lightning arresters with higher voltage ratings are required to protect the transformers.

Coefficient of Grounding

The coefficient of grounding for a power system is the ratio V_{LG} / V_{LL} expressed as a percentage.

- V_{LG} is the highest root-mean-square (rms) line to ground power frequency voltage on a sound phase, at a selected location, during a phase-to-ground fault affecting one or more phases.
- V_{LL} is line-to-line power frequency rms voltage, which would be obtained, at the selected location, with the fault removed.

Historically, power systems have been referred to as effectively grounded when the coefficient of grounding does not exceed 80 percent, or non-effectively grounded or ungrounded when the coefficient of grounding exceeds 80 percent. The effectively grounded system usually prevents the voltages on the unfaulted phases from exceeding 138 percent of its nominal phase-to-ground voltage during a line-to-ground fault.

Solidly Multigrounded System and Solidly Unigrounded System are mostly Effectively Grounded Systems. To achieve this status, the X_0 / X_1 and R_0 / X_1 ratio requirements stated in their description sections should be met.

On the solidly multigrounded system, where transformer neutrals and neutral conductors are directly grounded at frequent points along the circuit, the positive sequence resistance (R_1) may be significant due to small conductors, and should be considered. Neglecting R_1 may result in higher rated surge arresters than normally required. In the case of the four-wire multi-grounded distribution system, the system would be effectively grounded if the following conditions were met:

- The ratio of the zero sequence reactance to the positive sequence impedance (X_0/Z_1) is positive and less than three.

- The ratio of the zero sequence resistance to the positive sequence impedance (R_0/Z_1) is positive and less than one.

The lower the arrester rating, the greater the protective margin is for the insulation of the protected equipment. Effectively grounded systems allow use of surge arresters rated at about 80 percent of the line-to-line operating voltage. Ungrounded and unigrounded wye connected systems and delta connected systems require surge arresters rated at a minimum of full line to line voltage. The resulting difference in BIL requirements of major equipment provides a substantial financial advantage for an effectively grounded system.

Distribution Transformer Connections

Depending on the load being served, there are several types of transformer connections practiced in North America. Description of all these connections is beyond the scope of this handbook. However, this section describes a few transformer connections that are widely used and are relevant to the field of stray voltage.

The customers with small loads are typically served using single-phase service drops. These loads can be served by a single-phase, two-phase, or a three-phase feeder as shown in Figure 3-8. These customers mostly include residential customers, small farms, or small commercial customers.

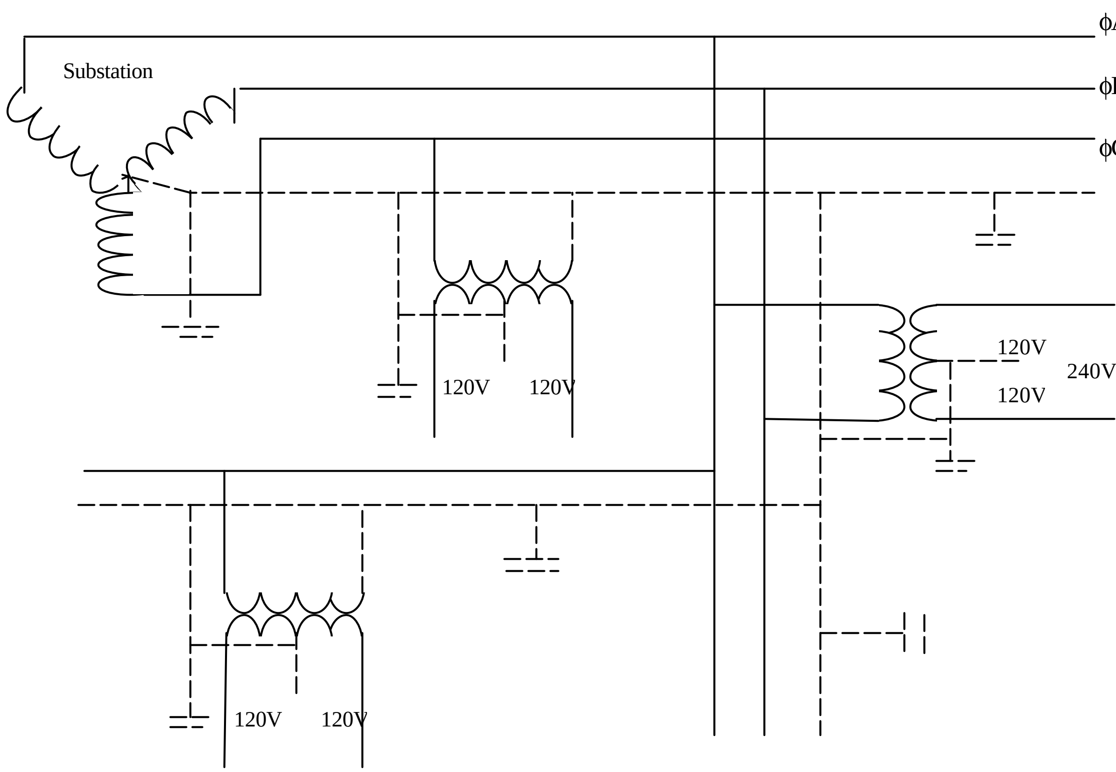


Figure 3-8 Secondary Distribution – Single Transformer Connections

Some larger loads are served with two single-phase transformers. These connections also yield one more voltage level. In addition to 240-volt and 120-volt levels, the two-transformer connections can also make 208-volt level available for the customer. See Figure 3-9.

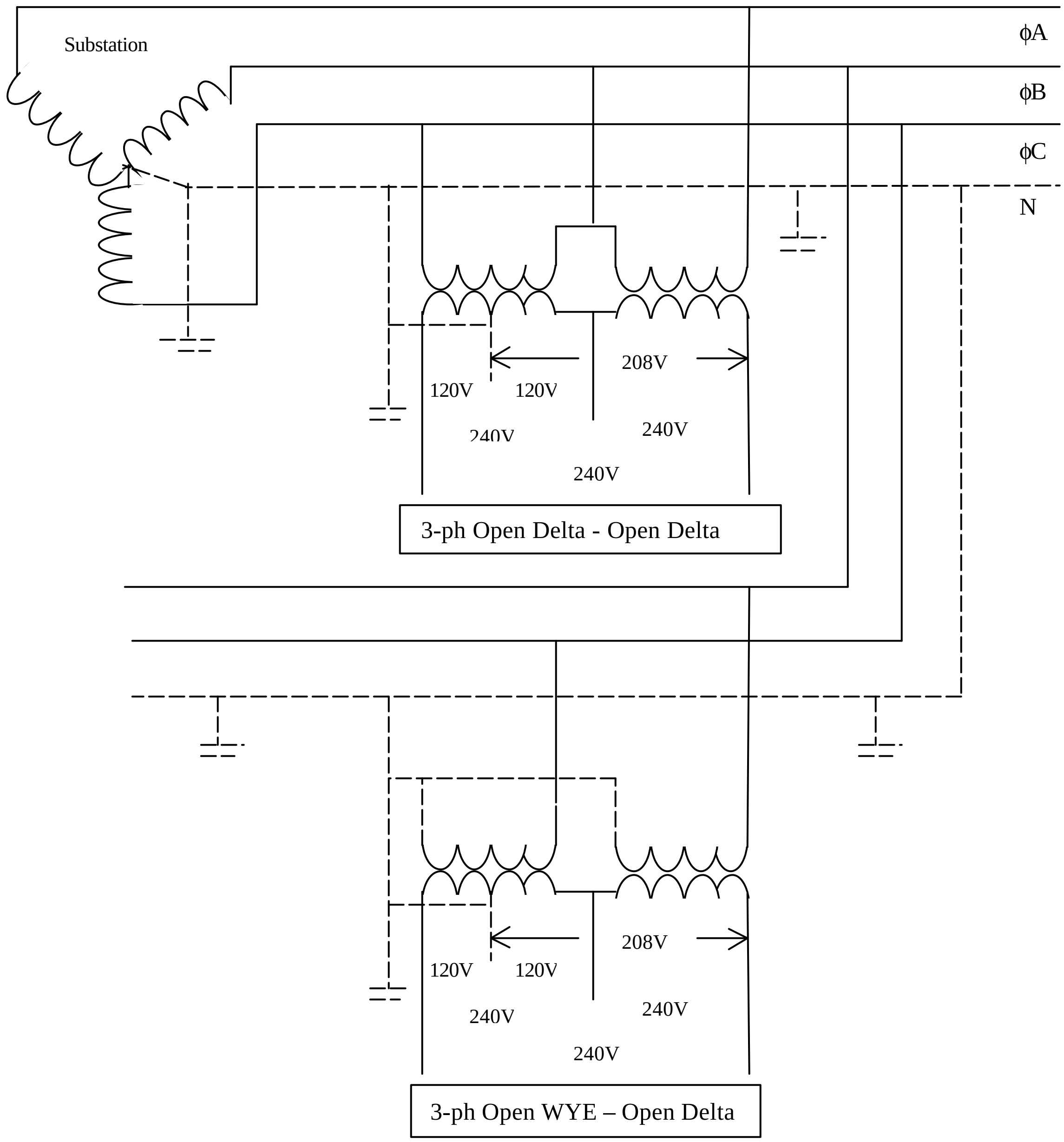


Figure 3-9 Secondary Distribution – Two Transformer Connections

The loads in the range of 100 kva and above are typically served by three transformers. Figure 3-10 shows widely used wye-wye connection consisting of three single-phase transformers.

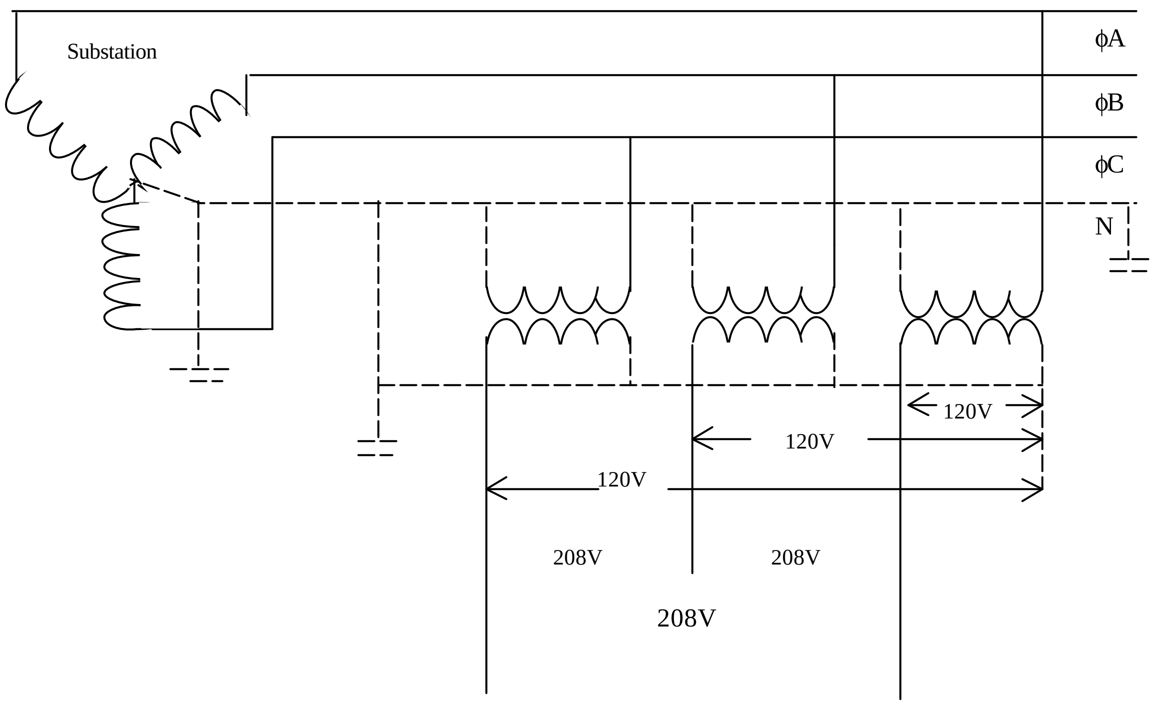


Figure 3-10 Secondary Distribution – Three Transformer Connection (wye-wye)

SECTION 4

FUNDAMENTALS AND SOURCES OF STRAY VOLTAGE

In a multigrounded distribution system, there will always be stray voltages and currents. At the customer's facility, these voltages result from the interaction of multiple parameters of the primary and secondary systems. Some of the most influential parameters include unbalanced loads, neutral wire sizes and lengths, and grounding electrode systems at the customer's facility. Basically, the magnitude of N-E voltage would depend on the current flowing in the grounded neutral paths and their impedance. This N-E voltage would ultimately determine the current flow and resulting earth gradients in the customer's facility.

Starting with the definitions of some commonly used variables, this section describes the fundamentals involved in determining the stray voltages and also various ways in which stray voltages and resulting currents may occur in animal farms and in residential areas.

Definitions

The following paragraphs define and describe some commonly used variables in the stray voltage field. These variables may be further defined, at their appropriate places, depending on whether they belong to the primary side or secondary side. It should also be noted that the following is not a complete list of the variables. Additional variables, as needed, may be defined at their proper locations throughout this handbook.

All voltages and currents defined below are expressed in 60 Hz, ac, rms values.

Neutral-Earth Voltage (N-E Voltage, V_{NE})

This is the voltage measured between any point on a neutral or its extension (a connected metallic pipe for example) and an isolated reference electrode placed in the earth with "zero" or "nearly zero" potential, a remote earth. The neutral-earth voltage may be different at different points on the neutral system. This is due to the flow of currents and the resulting voltage gradients through out the complex neutral / grounding system.

Grounding Electrode Current (Ground Current, I_g)

In a multigrounded system, a portion of neutral current flows into ground (earth) via the grounding electrode system. A grounding electrode system may consist of a single ground rod or interconnected multiple ground rods. An equipotential plane connected with the service panel ground is another example of a grounding electrode system.

The "grounding electrode current" is the total current flowing in the surrounding earth via the grounding electrode system. Note that this is the current, which develops voltage gradients on the surface of the earth.

Grounding Electrode Resistance (R_g)

"Grounding Electrode Resistance" is a resistance of a grounding electrode system with respect to remote ground (earth). By virtue of Ohm's law, the following relationship exists:

$$V_{NE} = I_g x R_g \tag{4-1}$$

Neutral Current (I_n)

This is the current, which flows in a neutral conductor.

Stray Voltage (Source Voltage, Open Circuit Contact Voltage, V_{oc})

"Stray voltage" or "contact voltage" is a small open circuit voltage (usually less than 10 volts) measured between two points that can be simultaneously contacted by a human or an animal[79]. For a cow, the open circuit contact voltage can be between the mouth and four hooves. For an adult standing and touching an outdoor faucet, this voltage can appear between the hand and the feet.

Depending on how far the grounding electrode system is from the subject making the contact, this voltage can be as low as a small fraction and as high as the full value of the N-E voltage responsible for the stray voltage. As an example, this voltage measured over an equipotential plane can be 2-4% of the barn N-E voltage. With the equipotential plane and the rebars from the concrete removed, this voltage can approach the N-E voltage value.

Closed Circuit Contact Voltage (V_{cc})

"Stray voltage" or "contact voltage" when measured with the current flowing through the human or the animal is defined as the "closed circuit contact voltage". Typically, in dairy farm cases, this voltage is measured across a 500 Ω resistor and is always less than or, in the extreme case involving a high impedance source, is equal to the open circuit contact voltage.

Stray Current (Body Current, Contact Current, I_c)

The "stray current" or "contact current" is defined as the current passing through a human or an animal upon contact. Note that it is not the contact voltage but the current, which is perceived by a human or an animal.

Grounding Electrode System

60 Hz Resistance of Grounding Electrode System Low resistance grounds are necessary to ensure the proper operation of equipment during abnormal circumstances such as lightning strokes and phase-to-ground faults, as well as to meet appropriate codes and standards. Due to the variations in soil resistivity and installation practices, it is impossible to predict the installed impedance of a grounding system. However, many sufficiently accurate equations have been developed to assist in the design of grounding systems.

The resistance to remote earth of a grounding electrode is a function of the geometry of the electrode, the soil resistivity and the number of interconnected electrodes. Dwight[25] developed approximate formulae for several common shapes and arrangements of grounding electrodes, as shown in Table 4-1[28].

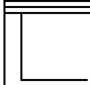
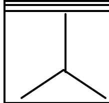
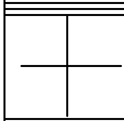
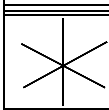
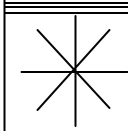
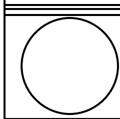
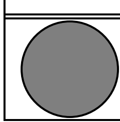
A number of practical design tips can be noted from examining Dwight's equations. For example, it is important to note that increasing the depth of penetration will result in a decrease of resistance (or an increase in conductance) practically equivalent to that of connecting together in parallel an increasing number of grounding electrodes. As a rule of thumb, doubling the rod length in uniform soil reduces resistance by about 40 percent. Increasing the ground rod length may also have the benefit of reaching lower resistivity soils.

Ground rods in parallel can also be used to reduce the equivalent resistance. However, the parallel rule of electrical circuits does not exactly apply. Two ground rods with resistance R_g in parallel do not necessarily have an equivalent resistance $R_g/2$. The calculated resistance of a single ground rod in uniform soil, using the second equation in Table 4-1, assumes that the ground rod is surrounded by conductive soil with no other grounding electrodes in that soil. A second ground rod in the area of influence of the first ground rod creates a mutual resistance between the two, resulting in a higher resistance than expected for two resistances in parallel. This is evident from the equations for two rods in Table 4-1. Therefore, care must be taken to locate parallel ground rods out of the influence of each other to obtain maximum effectiveness. As a rule of thumb, ground rods should be placed at least as far apart as their length.

A similar result is also true for buried conductors in parallel; they are more effective if placed farther apart. Due to the nature of the horizontal buried conductors, however, this is usually the case, as the conductors are typically installed running in opposite directions away from the pole.

Although, more efficient reduction in resistance can be achieved by increasing the spacing between individual grounding electrodes, the voltage gradients in and around the grounding system may be adversely affected. For example, an equipotential plane with larger mesh spacing may yield higher animal contact voltage compared to equipotential plane with smaller mesh spacing.

Table 4-1 Formulae for the Calculation of Resistance to Ground [28]

	Hemisphere of radius a	$R = \dfrac{\rho}{2\pi a}$
	One ground rod length L, radius a	$R = \dfrac{\rho}{2\pi L}\left(\ln\dfrac{4L}{a} - 1\right)$
	Two ground rods, spaced s, s > L	$R = \dfrac{\rho}{4\pi L}\left(\ln\dfrac{4L}{a} - 1\right) + \dfrac{\rho}{4\pi s}\left(1 - \dfrac{L^2}{3s^2} + \dfrac{2}{5}\dfrac{L^4}{s^4}\cdots\right)$
	Two ground rods, spaced s, s < L	$R = \dfrac{\rho}{4\pi L}\left(\ln\dfrac{4L}{a} + \ln\dfrac{4L}{s} - 2 + \dfrac{s}{2L} - \dfrac{s^2}{16L^2} + \dfrac{s^4}{512L^4}\cdots\right)$
	Buried horizontal wire length 2L, depth s/2	$R = \dfrac{\rho}{4\pi L}\left(\ln\dfrac{4L}{a} + \ln\dfrac{4L}{s} - 2 + \dfrac{s}{2L} - \dfrac{s^2}{16L^2} + \dfrac{s^4}{512L^4}\cdots\right)$
	Right-angle turn of wire, length of arm L, depth s/2	$R = \dfrac{\rho}{4\pi L}\left(\ln\dfrac{2L}{a} + \ln\dfrac{2L}{s} - 0.2373 + 0.2146\dfrac{s}{L} + 0.1035\dfrac{s^2}{L^2} - 0.0424\dfrac{s^4}{L^4}\cdots\right)$
	Three-point star, length of arm L, depth s/2	$R = \dfrac{\rho}{6\pi L}\left(\ln\dfrac{2L}{a} + \ln\dfrac{2L}{s} + 1071 - 0.209\dfrac{s}{L} + 0.238\dfrac{s^2}{L^2} - 0.054\dfrac{s^4}{L^4}\cdots\right)$
	Four-point star, length of arm L, depth s/2	$R = \dfrac{\rho}{8\pi L}\left(\ln\dfrac{2L}{a} + \ln\dfrac{2L}{s} + 2.912 - 1071\dfrac{s}{L} + 0.645\dfrac{s^2}{L^2} - 0.145\dfrac{s^4}{L^4}\cdots\right)$
	Six-point star, length of arm L, depth s/2	$R = \dfrac{\rho}{12\pi L}\left(\ln\dfrac{2L}{a} + \ln\dfrac{2L}{s} + 6.851 - 3.128\dfrac{s}{L} + 1758\dfrac{s^2}{L^2} - 0.490\dfrac{s^4}{L^4}\cdots\right)$
	Eight-point star, length of arm L, depth s/2	$R = \dfrac{\rho}{16\pi L}\left(\ln\dfrac{2L}{a} + \ln\dfrac{2L}{s} + 10.98 - 5.51\dfrac{s}{L} + 3.26\dfrac{s^2}{L^2} - 117\dfrac{s^4}{L^4}\cdots\right)$
	Ring of wire, diameter of ring D, diameter of wire d, depth s/2	$R = \dfrac{\rho}{2\pi^2 D}\left(\ln\dfrac{8D}{d} + \ln\dfrac{4D}{s}\right)$
	Buried horizontal strip, length 2L, section a by b, depth s/2, b < a/8	$R = \dfrac{\rho}{4\pi L}\left(\ln\dfrac{4L}{a} + \dfrac{a^2 - \pi ab}{2(a+b)^2} + \ln\dfrac{4L}{s} - 1 + \dfrac{s}{2L} - \dfrac{s^2}{16L^2} + \dfrac{s^4}{512L^4}\cdots\right)$
	Buried horizontal round plate, radius a, depth s/2	$R = \dfrac{\rho}{8a} + \dfrac{\rho}{4\pi s}\left(1 - \dfrac{7}{16}\dfrac{a^2}{s^2} + \dfrac{33}{40}\dfrac{a^4}{b^4}\cdots\right)$

Parametric Analysis of Commonly Used Grounding Electrodes The selection of the grounding electrode for a particular location will be dependent on the availability of space, a knowledge of the soil stratification and an individual utility's policy. It is also important to understand the influence of the basic parameters (such as length, diameter, electrode spacing and soil resistivity) on the overall resistance to earth of a grounding electrode. Additionally, comparing grounding effectiveness of different electrode types may help in making an intelligent selection for locations where options are available. To address these needs, a parametric analysis of commonly used grounding electrodes in distribution systems is presented in this section. Note that the parametric analysis presented here has been performed using the computer program of reference [27].

Many times, ground rods are driven close to each other without realizing the loss of efficiency. Also, when lateral space is limited, how beneficial is it to drive a single ground rod deeper compared to driving multiple rods in parallel? Table 4-2 below compares the resistance to earth of various ground rod arrangements in a uniform soil of 300 Ω-m resistivity. Each arrangement includes an appropriate length of lead conductor.

Table 4-2 Resistances of Typical Ground Rod Electrodes in 300 Ω-m Soil

Grounding Electrode Description	**Total L (Ft)**	**Rg (W)**
Single rod @ 5/8 in X 10 ft long	12	93
Two rods, 2 ft apart, @ 5/8 in X 10 ft long	24	63
Two rods, 4 ft apart, @ 5/8 in X 10 ft long	26	57
Two rods, 6 ft apart, @ 5/8 in X 10 ft long	28	54
Two rods, 8 ft apart, @ 5/8 in X 10 ft long	30	51
Two rods, 10 ft apart, @ 5/8 in X 10 ft long	32	48
Three rods, 1 ft apart, @ 5/8 in X 10 ft long	34	57
Single rod, @ 5/8 in X 20 ft long	22	54
Single rod, @ 5/8 in X 30 ft long	32	39

Table 4-2 leads to two main conclusions with regards to ground rod electrodes. To achieve the maximum efficiency (minimum resistance to earth per foot of buried conductor) for parallel ground rod arrangements, the distance equal to the depth of the ground rods should separate the rods at the minimum. For a uniform soil, deep-driven ground rods are more efficient per unit length in achieving lower resistance to earth than an equivalent length of buried conductor near the surface.

Chemical rods or special low resistivity backfills are often used to achieve a low resistance ground. These special grounding electrodes offer low resistance to earth by increasing cross-sectional areas in contact with the soil. Usually, one pays more to achieve a low resistance ground using a chemical rod or a conductive backfill. To determine whether the special grounding electrode or the conventional electrode is more effective, the influence of "diameter" and "length" parameters on electrode resistance to earth was determined. Table 4-3 compares the effectiveness of a grounding electrode as a result of increasing the diameter versus increasing the length in a 300 Ω-m soil.

Table 4-3 Effectiveness of Grounding Electrodes in 300 Ω-m Soil - Increasing Diameter versus Increasing Length

Grounding Electrode Description	**Rg (Ω)**
Single Rod @ 5/8 in. X 10 ft long	93
Single Rod @ 12 in. X 10 ft long	55
Single Rod @ 5/8 in. X 20 ft long	54
2/0 Cu. Counterpoise, 10 ft long	112
12 in. dia, Cu. Counterpoise, 10 ft long	59
2/0 Cu. Counterpoise, 20 ft long	63

As indicated in Table 4-3, the diameter of a ground rod electrode will have to be increased approximately 18 times to reduce the resistance to earth by 40 percent. On the other hand, doubling of the length of the ground rod yields the same resistance. Note that the same conclusions can be drawn for the counterpoise electrode. The effectiveness of increasing the electrode length will be even more in a stratified soil with low resistivity subsoil.

The grounding electrodes behave differently in different soils. It is commonly known that the resistance to earth of a ground rod driven into the water table would be lower than for the same ground rod driven in a dry sandy soil. The effectiveness of three commonly used grounding electrodes in uniform and non-uniform (stratified) soils was determined by computing their resistances. Table 4-4 lists the calculated resistance values.

Table 4-4 Effectiveness of Grounding Electrodes in Soils with Different Resistivity

Grounding Electrode Description	*__Rg (Ω)__ **ρ_1 =300 Ω-m** **ρ_2 =300 Ω-m** **h = n/a**	*__Rg (Ω)__ **ρ_1 =300 Ω-m** **ρ_2 =60 Ω-m** **h =15 feet**	*__Rg (Ω)__ **ρ_1 =60 Ω-m** **ρ_2 =300 Ω-m** **h =15 feet**
Single Rod, @ 5/8 in X 20 ft long	54	12	16
2/0 Cu Counterpoise, @ 22 ft long (1.5' deep)	63	58	15
2/0 Cu Square Mesh, @ 5 ft X 5 ft (1.5' deep)	76	72	18

* ρ_1=Upper layer soil resistivity, ρ_2=Lower layer soil resistivity, h=Depth of upper layer

Referring to Table 4-4, driving ground rods in series (end-to-end) is the most efficient way of grounding compared to a counterpoise or mesh type of grounding electrode in typical soil conditions with $\rho_1 > \rho_2$. However, in the case of subsoil consisting of a rock bed ($\rho_1 < \rho_2$), a counterpoise or a mesh type of grounding electrode has approximately the same resistance as the equivalent length of the ground rod.

Evaluation of the grounding electrodes in previous sections was based on their resistance to remote earth. It is interesting to see how these grounding electrodes behave with respect to voltage gradients on the surface. The same three electrodes shown in Table 4-4 were evaluated in a 300 Ω-m uniform soil using the computer program. Figure 4-1 displays the surface voltages at specific points around the pole, expressed in percent of N-E voltage (V_{NE}).

Referring to Figure 4-1, the square-mesh grounding electrode fares significantly better than the normally used ground rod and counterpoise electrodes. In the case of the mesh electrode, the current is distributed more uniformly, resulting in controlled voltage gradients around the pole. These results can be used to select the grounding electrode arrangement for padmounts and transformer poles located in high traffic areas.

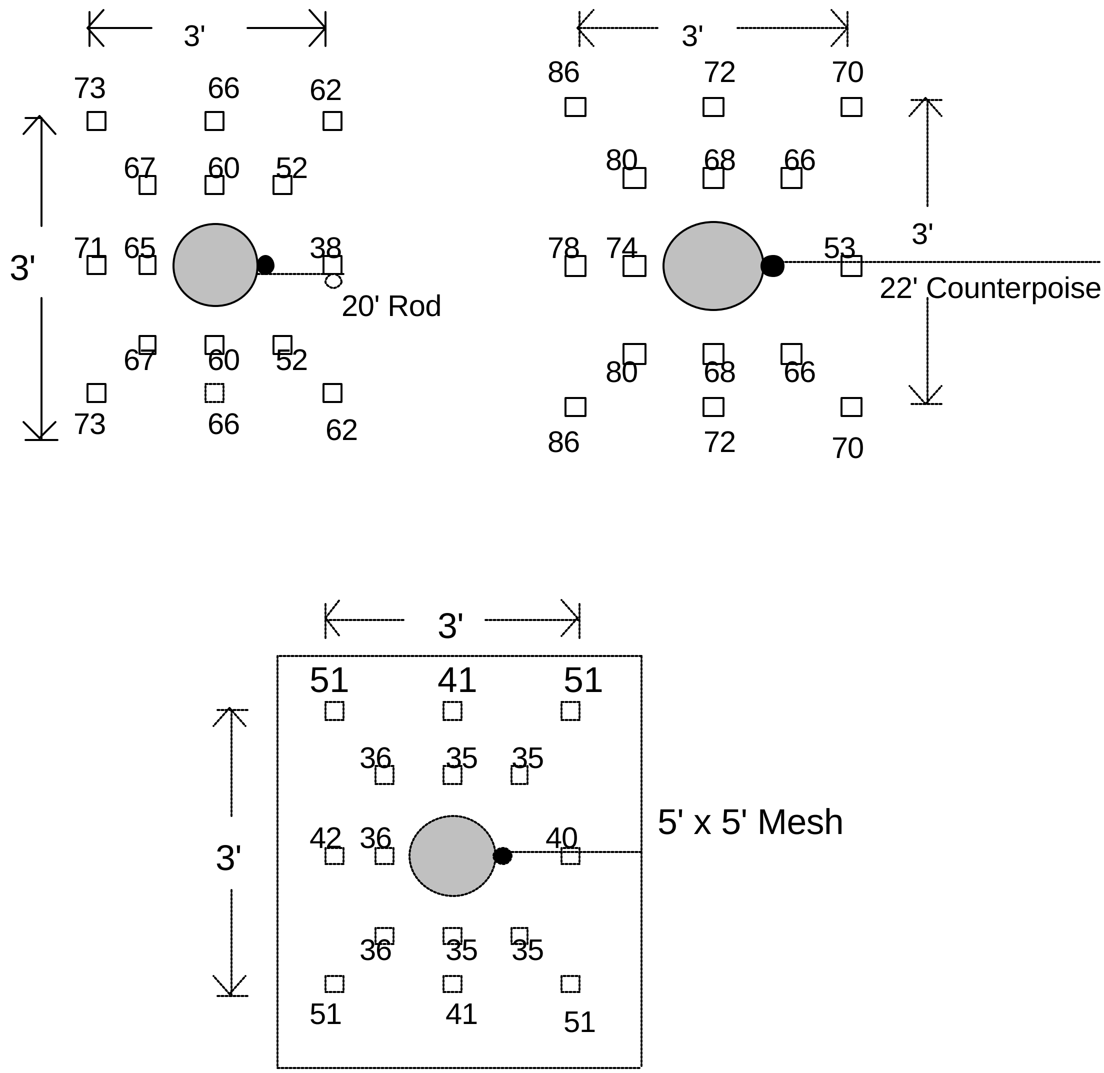


Figure 4-1 Surface Voltage Gradients (in Percent of N-E Voltage) around Grounding Electrode

N-E Voltage, Voltage Gradients and Contact Voltage

In a multigrounded distribution system, a phase-to-ground fault or unbalanced steady-state current causes current to flow between a grounding electrode and the surrounding soil. Current flow through the soil resistivity results in a voltage gradient in the vicinity of the electrode, with the value of the gradient generally inversely proportional to the distance from the electrode. The fundamental relationships between N-E voltage, voltage gradients and the contact voltage (open circuit) will be illustrated in this section.

Figure 4-2 illustrates the flow of system currents and resulting voltage gradients in the vicinity of a single-phase transformer with 120-volt load on one of the secondary legs, L1. Obviously, a major portion of the load current will return though the secondary neutral and the rest will return from the ground rod at the service panel. The magnitude of this current will depend on the voltage drop across the secondary neutral.

The following is assumed in Figure 4-2:

- Primary neutral is tied with the secondary neutral.
- Current flowing in the primary neutral is due to the secondary load only and is equal to the secondary load times the transformer turns-ratio, n_s / n_p.
- Current in the transformer pole downlead flows from earth towards the transformer.

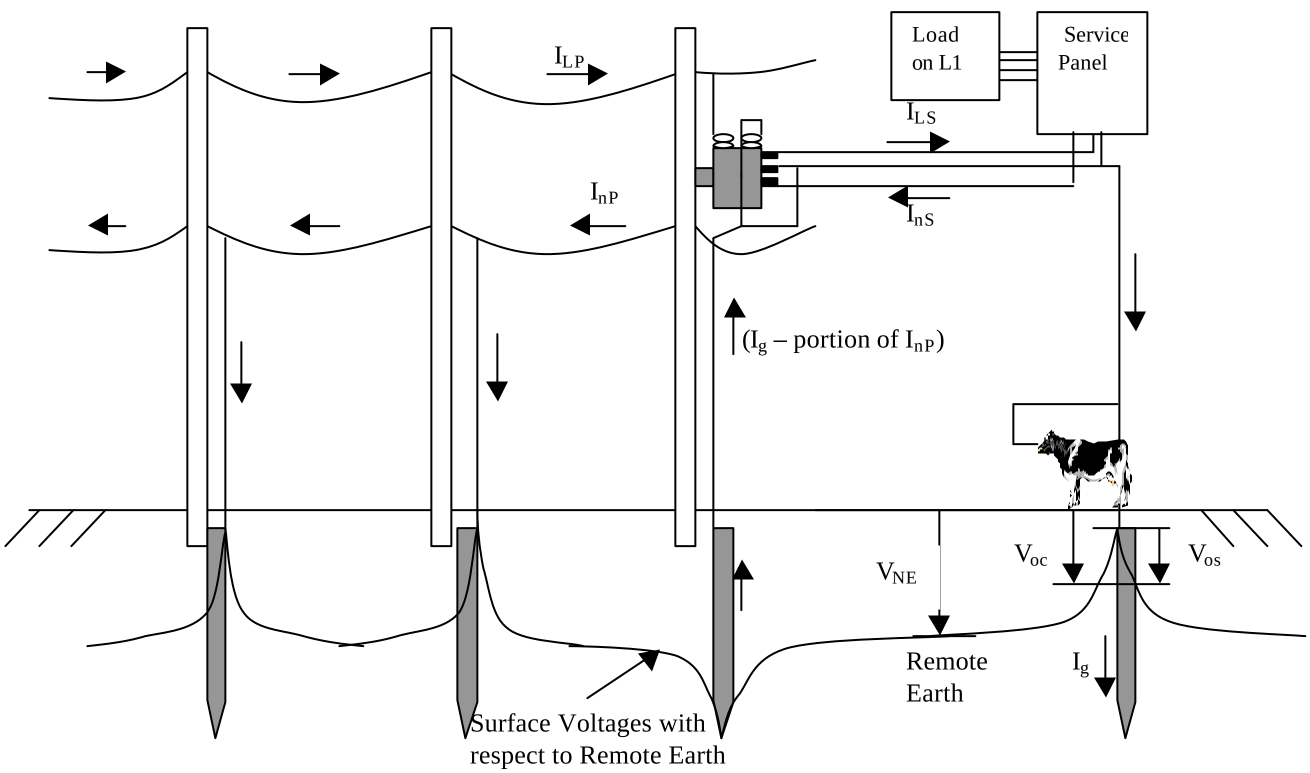


Figure 4-2 Illustrations of Voltage Gradients, N-E Voltage (V_{NE}), Contact Voltage (V_{oc}), and Step Voltage (V_{os}) in and around a Dairy Farm

Sunde[76] developed the relationships presented in this section. He developed these equations for simple grounding systems such as a ground rod or a buried counterpoise. User should refer to Figure 4-3 for the assumed co-ordinate system for these equations.

For a vertical ground rod or pipe, the potential on the earth's surface a distance y from the top of the rod is:

$$U(y) = \frac{I_g \mathbf{r}}{2pL} \ln \frac{\sqrt{L^2 + y^2} + L}{y} \quad \text{(V)} \tag{4-2}$$

where

U = the surface potential of the earth at point y
y = distance from the rod, measured on the earth's surface
L = the length of the ground rod
ρ = soil resistivity (uniform)
I_g = current into ground rod

For a buried horizontal wire, the potential on the surface of the earth at a point (x, y) measured from the midpoint of the wire is:

$$U(x, y) = \frac{I_g \mathbf{r}}{2pL} \ln \frac{\sqrt{(x + L/2)^2 + y^2 + d^2} + x + L/2}{\sqrt{(x - L/2)^2 + y^2 + d^2} + x - L/2} \quad \text{(V)} \tag{4-3}$$

where

U (x, y) = surface potential of the earth at point (x, y)
x = distance from the midpoint of the wire, measured along the wire length
y = horizontal distance from the midpoint of the wire
d = depth of wire
and L, ρ, and I_g are as previously defined.

Also, the N-E voltage of the vertical pipe or buried wire can be estimated, respectively, by the equations shown below.

For a vertical ground rod or pipe:
when L>>a

$$V_{NE} = \frac{I_g \mathbf{r}}{2pL} \left(\ln \frac{4L}{a} - 1 \right) \quad \text{(V)} \tag{4-4}$$

and for a single buried wire, with d<<L:

$$V_{NE} = \frac{I_g \mathbf{r}}{pL} \left[\ln \frac{2L}{\sqrt{2ad}} - 1 \right] \quad \text{(V)} \tag{4-5}$$

where

a = radius of the rod or wire

and I_g, L, d and ρ are as previously defined.

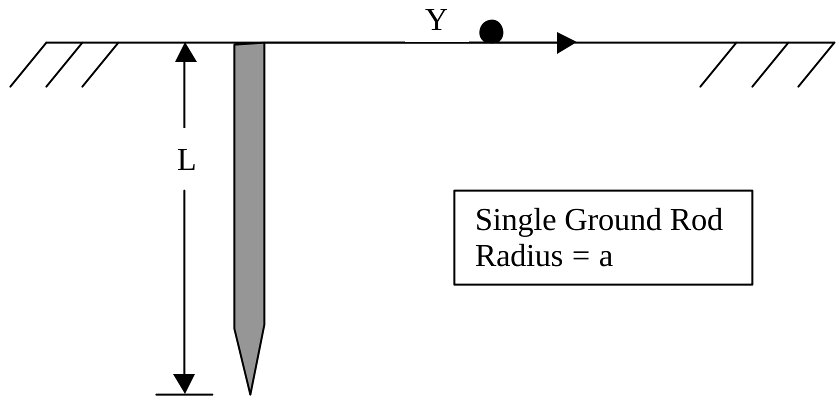
Because the open circuit contact voltage (V_{oc}) is defined as the difference between the N-E voltage and the voltage (with respect to remote earth, see Figure 4-2) where the person or animal is standing, the contact voltage for these simple electrodes can be estimated.

For a single ground rod, the open circuit contact voltage at a distance y from the top of the rod is:

$$V_{oc} = \frac{I_g\, r}{2pL}\left[\ln\left(\frac{\dfrac{4L}{a}}{\dfrac{\sqrt{L^2+y^2}+L}{y}}\right)-1\right] \quad \text{(V)} \tag{4-6}$$

and for a single buried wire, the open circuit contact voltage at point (x, y) is:

$$V_{oc} = \frac{I_g\, r}{2pL}\left[\ln\left(\frac{\dfrac{2L^2}{ad}}{\dfrac{\sqrt{(x+L/2)^2+y^2+d^2}+x+L/2}{\sqrt{(x-L/2)^2+y^2+d^2}+x-L/2}}\right)-1\right] \quad \text{(V)} \tag{4-7}$$



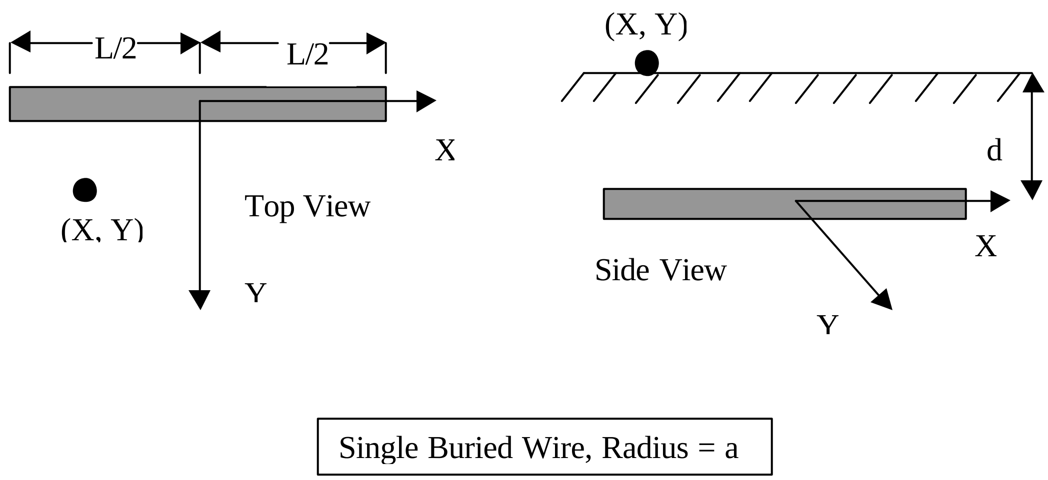


Figure 4-3 Assumed Coordinate System for Single Ground Rod and Buried Wire

The stray voltage fundamentals in the preceding section were illustrated using simple grounding electrode systems. In practice, a grounding electrode system may consist of several interconnected grounding electrodes. For example, the animal area in a dairy farm may have ground rods, rebars and an equipotential plane forming a complex grounding system. The voltage gradients for such a case can only be analyzed using computers. The computer's help is also unavoidable when dealing with complex distribution system to determine the distribution of currents and voltages on the neutral system.

To aid the user in understanding the architect of the computer software used in this project[28], the following synopsis is provided:

1) The resistance (R_g) of each grounding system is computed with the assumed current value and user defined grounding electrode systems and soil resistivity model.

2) System network analysis is performed with user defined distribution system and R_gs computed in (1).
3) The system analysis performed in 2) yields the current (I_g) in each grounding electrode system.
4) The complex grounding electrode system is cut in to small elements and the current distribution in each element is determined by solving a large matrix.
5) The surface voltage at any user-defined point is computed by superimposing the voltage due to each element.

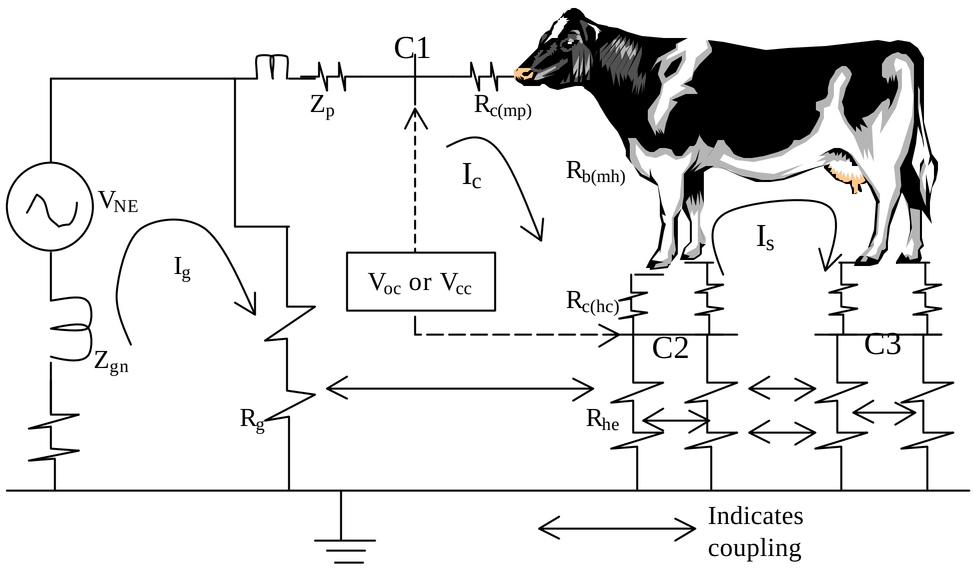
Path Impedances and Contact Current for Animals

Electrical current will flow through an animal if the animal comes in contact with two points that are at different voltages. Also, it has been demonstrated in many studies that the current flow through the body is the critical factor affecting animal response. The level of perception or type of response will depend on the magnitude of the current flow and the location of the contact points on the body. Therefore it is desirable to know the animal current for a given condition of the cow and surrounding environment.

The contact current is limited by several resistances and impedances, which comprise the current delivering system. Figure 4-4 identifies these circuit elements in a dairy farm where a cow standing on a concrete floor is touching a metal pipe in the barn area.

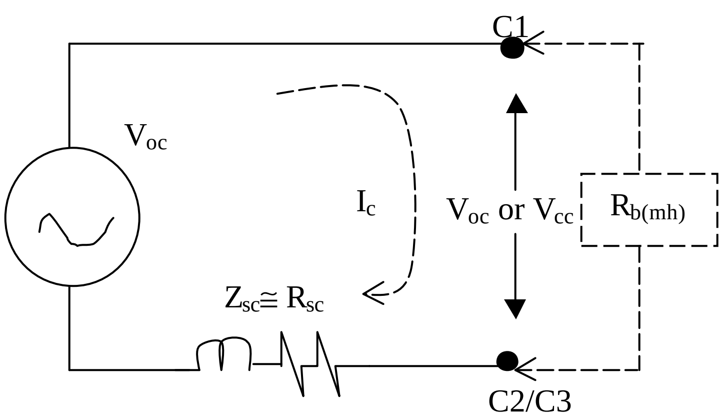
In a typical dairy farm environment, the most influential resistance limiting the current through the animal is the resistance from hooves to remote earth (R_{he}) including their mutual coupling with the barn grounding system. For example, the cow standing on a wet soil may experience significantly more current compared to standing on a wet concrete floor. In the farm environment, contact resistances ($R_{c(mp)}$ and $R_{c(hc)}$) are likely to be of much lower values. This is because cows' hooves are mostly in contact with urine and water on the concrete floor and also they eat and drink with moist mouths. For simplification, these values are typically included in the body resistance ($R_{b(mh)}$) values of the cow. As discussed in the measurement section, this arrangement also coincides with the way the measurements of contact voltage and current are performed. The impedance of the grounded piping system (Z_p) in the barn area is relatively of low value provided all joints are properly maintained and the pipes themselves are free of corrosion. Similarly, the grounded neutral system also offers a low impedance path (Z_{gn}) provided the neutral wire is continuous with no high resistance connection.

The circuit of Figure 4-4 describes the various electrical parameters and their interactions with each other in determining the cow body current. However, this complex network is far from providing a simplified approach to solve for the current. One approach, which provides considerable insight, is to reduce the entire circuit of Figure 4-4 into a two-port network, typically known as Thevinin's equivalent circuit. The Thevinin's equivalent circuit looking from the two contact points C1 and C2/C3 (see Figure 4-4) is shown in Figure 4-5. Similarly, a two-port network can be established between contact points C2 and C3 to represent a step voltage that may exist between cow's front and rear hooves. See Figure 4-6.



V_{NE}= N-E voltage at the barn
Z_{gn} =Z of grounded neutral system
R_g = Ground resistance at barn
C1 &C2=Cow contact points
I_c = Contact current
V_{oc}=Open circuit contact voltage
V_{cc}=Closed circuit contact voltage
Z_p =piping system impedance
I_g = Ground current in barn
I_s = Current due to step voltage
$R_{c(mp)}$=Contact resistance (mouth to pipe)
$R_{b(mh)}$=Body resistance (mouth to four hooves)
$R_{c(hc)}$= Contact resistance (each hoof to concrete)
R_{he}=Resistance (hooves to remote earth)

Figure 4-4 Identifications of Various Path Impedances for a Cow Touching a Grounded Pipe



Z_{sc} or R_{sc} = Thevinin's equivalent resistance or Source Resistance for contact voltage (V_{oc} or V_{cc}) and current (I_c)
$R_{b(mh)}$=Body resistance from mouth to hooves

Figure 4-5 Thevinin's Equivalent Circuit to Represent Contact Voltage and Current for Animal

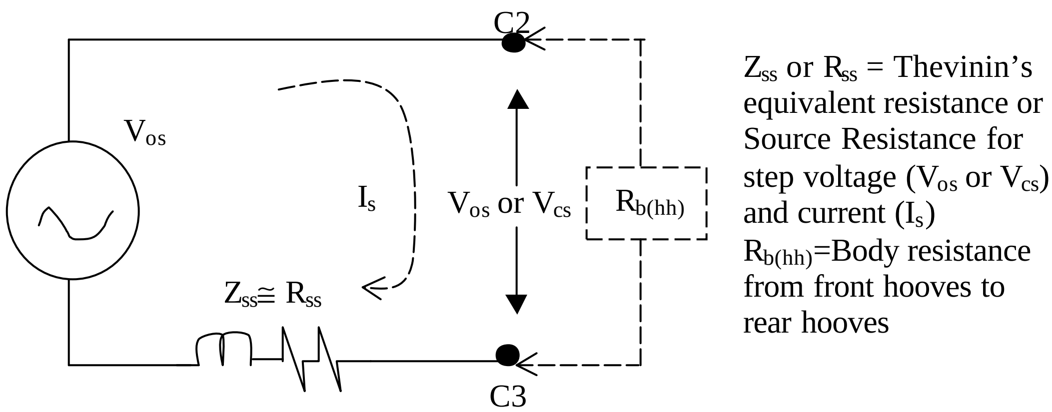


Figure 4-6 Thevinin's Equivalent Circuit to Represent Step Voltage and Current for Animal

Referring to Figure 4-5, the Thevinin's principle replaces the entire circuit of Figure 4-4 by an equivalent circuit consisting of a source, V_{oc}, in series with an equivalent impedance Z_{sc} behind the two points contacted by cow. When these two points are contacted by the cow, the current I_c would flow through the body developing voltage V_{cc} across the body.

In general, the components comprising of hooves to remote earth resistances including their mutuals would dominate the equivalent source impedance, Z_{sc}. As a result, the symbol R_{sc} would be used in place of Z_{sc} from now on.

From Figure 4-5, two equations can be easily established:

$$V_{oc} = I_c\left(R_{sc} + R_{b(mh)}\right) \text{ (V)} \tag{4-8}$$

$$V_{cc} = I_c \times R_{b(mh)} \text{ (V)} \tag{4-9}$$

Combining equations (4-8) and (4-9), an important relationship evolves[16].

$$R_{sc} = R_{b(mh)}\left(\frac{V_{oc} - V_{cc}}{V_{cc}}\right) \text{ }(\Omega) \tag{4-10}$$

Equation (4-8) suggests that $V_{oc} > V_{cc}$. The difference would be larger with higher value of R_{sc}.

Equation (4-10) is independent of the body current, I_c. Sometimes this equation is used in determining the value of R_{sc} for a dairy farm. More details on this are provided in the measurement section (Section 6).

To estimate the contact or body current (I_c) from equation (4-8), the open circuit contact voltage (V_{oc}), cow's body resistance ($R_{b(mh)}$), and the equivalent source resistance (R_{sc}) at the contact points must be known. The measurement of the open circuit contact voltage is a relatively easy task and is routinely performed. If this voltage is obtained by measurement and if typical body and source resistance values are known, estimation of body current is then a straight forward task. For this purpose, typical body resistance (R_b) and source resistance (R_s) values as found in the literature are presented next.

Cow body impedances vary with the path taken by the current. Several experimental studies have been carried out between 1963 through 1985 determining the impedances of cows along different paths. The impedances reported for 50 Hz and 60 Hz differed among cows and among body paths and they ranged from 250 Ω to 3000 Ω. Table 4-5 lists these impedances[79].

Table 4-5 Resistances of Various Electrical Paths through Cow

Body Path	**No. of Animals Tested**	**Resistance (W)**		**Frequency**
		Mean	**Range**	
Mouth to all hooves	70	350	324-393	60
	28	361	244-525*	60
Mouth to rear hooves	28	475	345-776*	60
Mouth to front hooves	28	624	420-851	60
Front leg to rear leg	5	300	250-405	60
	13	362	302-412	60
Front to rear hooves	28	734	496-1152*	60
Rump to all hooves	7	680	420-1220	50
Chest to all hooves	5	980	700-1230	50
	?	1000	?	50
Teat to mouth	28	433	294-713*	60
Teat to all hooves	28	594	402-953	60
	4	880	640-1150	50
Teat to rear hooves	28	594	402-953*	60
Teat to front hooves	28	874	593-1508	60
All teats to all hooves♣	6	1320	860-1960	50
	?	1000	?	50
Udder to all hooves	12	1700	650-3000	60

* Ranges given are for 10-90% percentile or percent of cows with measured resistance between the reported limit.
♣ Measured during milk flow.

As shown in Figure 4-4, the source resistance is comprised of a complex network of several resistances and impedances at the points of contact. The hooves to remote earth resistance including its mutuals, however, is the most dominant component of this circuit. Due to its dependancy on the resistivity of the soil or concrete on which the animal may be standing, this resistance can vary greatly.

The equivalent source resistance values can be determined either by computer methods or by measurements. The study cases presented in Section 7 show the examples of computed vlaues. A review of source resistance values presented in Section 7 clearly indicates that with a wet concrete floor or wet soil, the source resistance values would be much lower compared to those with dry concrete or soil (higher resistivity). The source resistance values would also be lower if an equipotential plane is installed in the concrete.

Determination of source resistance values by measurements includes measuring the open circuit and closed circuit contact voltages and hand calculating the values from equation (4-10). One research[17] performed these measurements in 43 farms (100 stalls) in the State of Wisconsin and determined a range of equivalent source resistances. At each stall, the measurements included seven different mouth to hooves simulations. For each of these simulation, the equivalent source resistance was calcualted using equation (4-10). Table 4-6 lists these equivalent source resistance values.

Selection of particular values for the body resistance and the equivalent source resistance is a difficult task. However, most experts recommend selecting both of these values for the mouth to four hooves path. The user would notice that these values, if selected, would yield a most conservative value for the animal current (I_c).

Table 4-6 Statistical Values for Source Resistance (R_{sc}) Determined for 101 Stalls on 43 Farms

	Equivalent Source Resistance, R_{sc} (W)						
Stastical Category	**Mouth to Left Front Hoof**	**Mouth to Right Front Hoof**	**Mouth to Right Rear Hoof**	**Mouth to Left Rear Hoof**	**Mouth to Both Front Hooves***	**Mouth to Both Rear Hooves***	**Mouth to All Four Hooves§**
Average	372	362	265	249	239	196	150
Median	296	312	209	199	200	154	115
Std. Dev.	230	209	159	146	139	116	98

* Measurements taken with two floor plates in parallel

♣ Measurements taken with four floor plates in parallel

The equations for the step voltages (V_{os} and V_{cs}) and resulting current can be developed in an identical manner as those developed for contact voltages (see equations (4-8), (4-9), and (4-10)). These equations are not written up separately . Users of this handbook can easily form these equations by replacing the “Contact Voltage” variables with “Step Voltage” variables as defined in Figure 4-6.

Path Impedance and Contact Current for Humans

Path impedances for a human essentially remain the same as that of an animal. Figure 4-7 shows the various path impedances for a man contacting a metal pipe around the house.

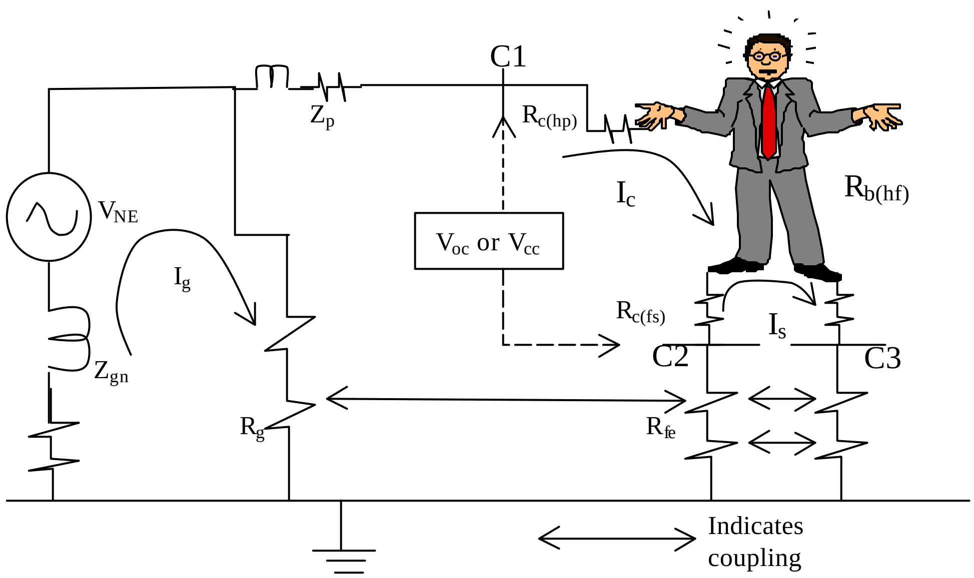
Figures 4-8 and 4-9 represent the Thevinin's equivalent circuits for the contact voltage and the step voltage, respectively.

The relationship between the open circuit contact voltage and resulting current is shown in equation (4-11) below. With the exception of different source and body rsistances, this relationship is the same as that shown in equation (4-8) for a cow.

$$V_{oc} = I_c \left(R_{sc} + R_{b(hf)} \right) \quad \text{(V)} \qquad (4\text{-}11)$$

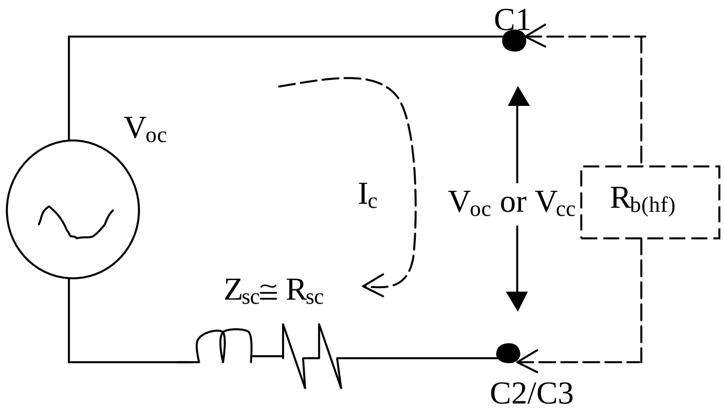
Similarly, the step voltage and current relationship is expressed as:

$$V_{os} = I_s \left(R_{ss} + R_{b(ff)} \right) \quad \text{(V)} \qquad (4\text{-}12)$$



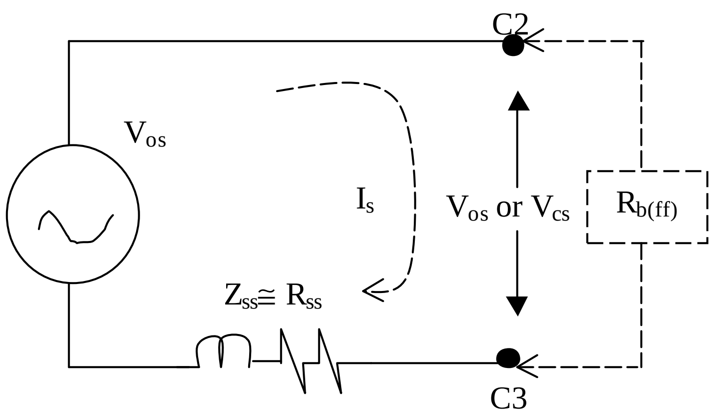
V_{NE}= N-E voltage at the barn
V_{oc}=Open circuit contact voltage
Z_{gn} =Z of grounded neutral system
V_{cc}=Closed circuit contact voltage
R_g = Ground resistance at house
Z_p =piping system impedance
C1,C2,C3=Human contact points
I_g = Current in house ground
I_s = Body current due to step voltage
I_c = Contact current
$R_{c(hp)}$= Contact resistance (hand to pipe)
$R_{b(hf)}$= Body resistance (hand to two feet)
$R_{c(fs)}$= Contact resistance (each foot to soil or concrete)
R_{fe}=Resistance (feet to remote earth)

Figure 4-7 Identifications of Various Path Impedances for a Human Touching a Grounded Pipe



Z_{sc} or R_{sc} = Thevinin's equivalent resistance or Source Resistance for contact voltage (V_{oc} or V_{cc}) and current (I_c)
$R_{b(hf)}$=Body resistance from hand to feet

Figure 4-8 Thevinin's Equivalent Circuit to Represent Contact Voltage and Current for Human



Z_{ss} or R_{ss} = Thevinin's equivalent resistance or Source Resistance for step voltage (V_{os} or V_{cs}) and current (I_s)
$R_{b(ff)}$=Body resistance from foot to foot

Figure 4-9 Thevinin's Equivalent Circuit to Represent Step Voltage and Current for Human

Similar to determining animal contact current, the hand to feet body resistance ($R_{b(hf)}$) and the equivalnet source resistance (R_{sc}) must be known for a human contacting across the stray voltage points.

The electrical resistance of the human body is a very difficult and controversial subject. While IEC 479-1[48] recommends a value based on the shock voltage, IEEE Std 80-2000[6] presently uses a constant value of 1000 Ω, which is mid-range for the values suggested by IEC for most of the statistical population and for typical contact voltage levels. If the skin is not punctured, the resistance may range from 500-3000 Ω. The actual value depends on a number of factors, including the current path.

If the skin is punctured, the current sees only the resistance of the internal organs, which is about 300 Ω. Whether or not the skin is punctured depends on the magnitude of the shock voltage directly across the body contact points. However, skin puncturing may not be a concern for low voltages such as found in stray voltage cases.

In the human case, the equivalent source resistance of one foot to remote earth (R_{sf}) can be determined by representing the foot as a circular metallic disk with a radius b in meters. The equation[6] for the source resistance of the foot (circular disk) on uniform soil with resistivity ρ (Ω-meters) is

$$R_{sf} = \frac{r}{4b} \quad (\Omega) \tag{4-13}$$

for the usual assumption of b=0.08 m (3 in), R_{foot} = 3ρ Ω. Although an equation is also given for the mutual resistance between the feet (ρ/2πd_f, where d_f is the separation of the feet in meters), it has negligible effect and the omission of the mutual resistance gives pessimistic results for contact voltage situations with two feet in parallel.

Ignoring the mutual resistance between the feet and using b=0.08 meters as the radius of the foot, the source resistance of two feet in parallel (R_{sc} for contact circuit) is approximately 1.5 ρ. The source resistance of two feet in series (R_{ss} for step circuit) is approximately 6.0 ρ.

If the assumptions regarding the body resistance and the equivalent source resistance as discussed in previous paragraphs are made, the relationships shown in equations (4-11) and (4-12) can be alternatively expressed as:

$$V_{oc} = I_c (1.5\, r + 1000) \quad \text{(V)} \tag{4-14}$$

$$V_{os} = I_c (6\, r + 1000) \quad \text{(V)} \tag{4-15}$$

In the cases related to humans, the resistance of shoes or boots provides additional safety margin over the assumption of a perfect contact with the soil. Along the distribution system, however, there is no control over who might be subject to stray voltages. Most shocking incidents related to humans occur in wet conditions such as swimming pools or water faucets with wet soil below them. Thus, the assumption of no contact resistance (barefoot) is valid. However, if there is some type of surface cover (gravel, asphalt, etc.) present, this surface cover may add significant resistance to the foot resistance. Table 4-7[6] gives some typical values of resistivity for some frequently used surface covers. These values are from specific measurements for specific (unknown) conditions and should be taken as typical values only. The conductivity of the water in the surface cover may have a significant impact on the overall resistivity of the wet surface cover. The actual resistivity of any material will vary with its moisture and chemical content, as well as the temperature.

Table 4-7 Typical Values for Surfacing Material Resistivity

Description of Surfacing Material (U.S. State where found)	**Resistivity (W-m)**	
	Dry	**Wet**
Crusher run granite with fines (NC)	140×10^6	1300 (ground water, 45 Ω-m)
1.5” crusher run granite with fines (GA)	4000	1200 (rain water, 100 Ω-m)
0.75”-1” granite (CA) with fines	--	6513 (10 min after 45 Ω-m water drained
#4 (1”-2”) washed granite (GA)	1.5×10^6 – 4.5×10^6	5,000 (rain water, 100 Ω-m)
#3 (2”-4”) washed granite (GA)	2.6×10^6 – 3×10^6	10,000 (rain water, 100 Ω-m)
Size unknown, washed lime stone (MI)	7×10^6	2000-3000 (ground water, 45 Ω-m)
Washed granite similar to ¾” gravel	2×10^6	10,000
Washed granite, similar to pea gravel	40×10^3	5,000
#57 (0.75”) washed granite (NC)	190×10^6	8,000 (ground water, 45 Ω-m)
Asphalt	2×10^6 - 30×10^6	10,000 - 6x106
Concrete	1×10^6 - 1×10^9 *	50 to 100

* Oven dried concrete. Values for air-cured concrete can be much lower due to moisture content.

An EPRI sponsored research project, performed in 1992[26], provides better insight into the relationship between the resistivity of the surfacing material or soil below the feet and the equivalent source resistance. The project consisted of injecting about 150 amperes in a distribution substation ground grid from a remote substation continuously and measuring the current in a simulated human (500 Ω or 1000 Ω resistors). An actual human carrying the resistor box helped acquired the data. The data were gathered over a one year period, which included three different seasons. Table 4-8 shows the measured data.

Table 4-8 Seasonal Variation in Resistivity (ρ), Open Circuit Contact Voltage (V_{oc}), Simulated Human Body Current (I_c), and Equivalent Source Resistance from Feet to Remote Earth (R_{sc})

Surfacing Material	**Surface Condition**	**Resistivity of Surfacing Material (W-m)**	***V_{oc} (Volts)**	**I_c (mA) or § V_{cc} (Volts)**	**¨ R_{sc} (W)**
1.5” granite w/fines (GA)	Rain (Wet)	1183	15.12	7.24	1089
	Winter (Dry)	3850	21.75	0.745	28200
	Summer (Dry)	3925	12.62	0.967	12052
#4 (1”-2”) washed gravel (GA)	Rain (Wet)	4950	22.42	2.13	9526
	Winter (Dry)	$1.45x10^6$	30.3	0.003	$9.2x10^6$
	Summer (Dry)	$4.0x10^6$	15.05	0.004	$3.4x10^6$
#3 (2”-4”) washed gravel (GA)	Rain (Wet)	10120	11.88	0.82	13508
	Winter (Dry)	$2.6x10^6$	21.1	0.001	$16.21x10^6$
	Summer (Dry)	$3.1x10^6$	8.6	0.009	$1.0x10^6$
Native soil, red clay (GA)	Rain (Wet)	490	28.37	21.24	342
	Winter (Dry)	1049	37.7	15.35	1456
	Summer (Dry)	3557	24.7	1.57	14732
Asphalt pad	Rain (Wet)	--	--	--	--
	Winter (Dry)	--	11.54	0.001	$10.5x10^6$
	Summer (Dry)	--	6.96	0.001	$7.7x10^6$
Concrete pad	Rain (Wet)	--	--	--	--
	Winter (Dry)	--	8.77	0.067	$0.1x10^6$
	Summer (Dry)	--	4.36	0.007	$0.6x10^6$

* N-E voltage (V_{NE}) of substation ground grid ranged from 40 volts to 43 volts.
♣ Closed circuit voltage (V_{cc}) was measured across 1000 Ω resistor.
♦ Equation (4-11) was employed to calculate R_{sc}.

Referring to Table 4-8, the wet (native) soil below the feet offers the lowest source resistance (R_{sc}=342 Ω) and maximum body current (I_c=21.24mA). The table also shows the advantages of using washed gravel as a surfacing material. The research was unable to obtain wet measurements for asphalt and concrete. However, comparing asphalt with concrete for the dry measurements from Table 4-8 and wet resitivity measurements from Table 4-7, asphalt should be a preferred choice for the surfacing material.

Sources of Stray Voltages

In general, the stray voltage originates from the N-E voltages, which exist on the multigrounded neutral system. As explained previously, these N-E voltages cause a current (I_g) to flow in the grounding electrode system developing voltage gradients around its location. When a human or an animal contacts these gradients, stray current results. In an extreme case when the point being contacted is far from the grounding electrode system, the stray voltage (or open circuit contact voltage) may approach the N-E voltage.

The source of varying N-E voltages along the neutral wire is the flow of returning current from three phase, two phase or single-phase loads. The current flow through the impedance of the neutral system develops the voltage gradients of its own along its length, the highest N-E voltage being at the load end. With this basic process at the core, the remainder of this section illustrates how various parameters influence N-E voltages at the customer location.

Most of these illustrations are presented with computer-generated data. Where a system cannot be modeled due to limitations or where the outcome is obvious, only a textual description is provided.

Stray Voltage Sources on Primary Side

Figure 4-10 shows the modeled system to illustrate the influence of primary-side parameters on N-E voltages at customer location. Depending on the parameter being studied, this general model may be changed in the illustrations. Also, to provide a better understanding of the primary-side parameters, the customer's load at bus PB2 is assumed zero.

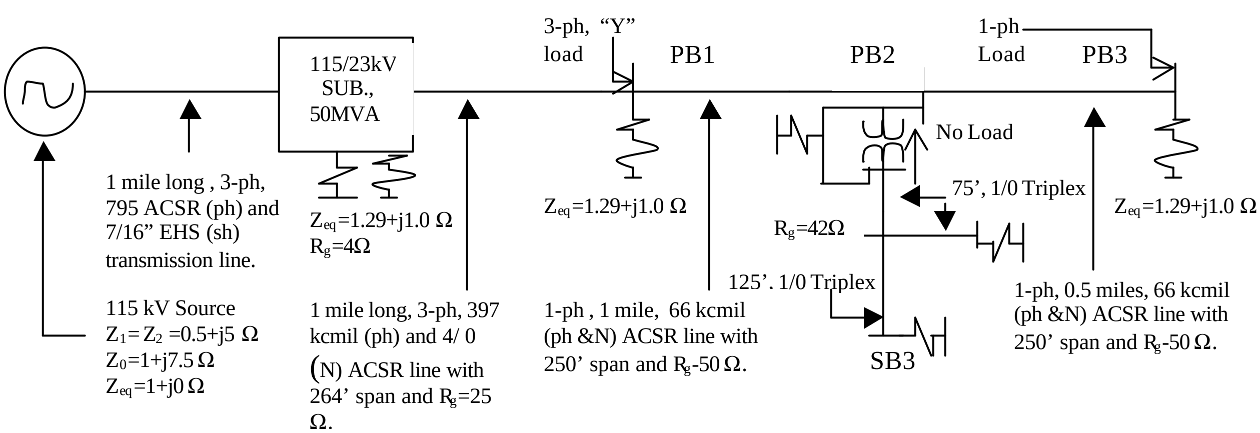


Figure 4-10 Modeled Distribution System to Illustrate Influence of Primary-side Parameters

Influence of Load Current In the first illustration, the load current on the system is such that the minimum current flows in the neutral system. The user should consider this illustration as a reference to compare the results of other illustration.

Following load conditions on the system exist:

- Balanced 3-ph load at PB1 – each phase 400+j300 kva
- 1-ph load at PB3 - 50+j25 kva on ϕA
- No load on PB2 (from customer)

Figure 4-11 shows various currents and N-E voltages on the system.

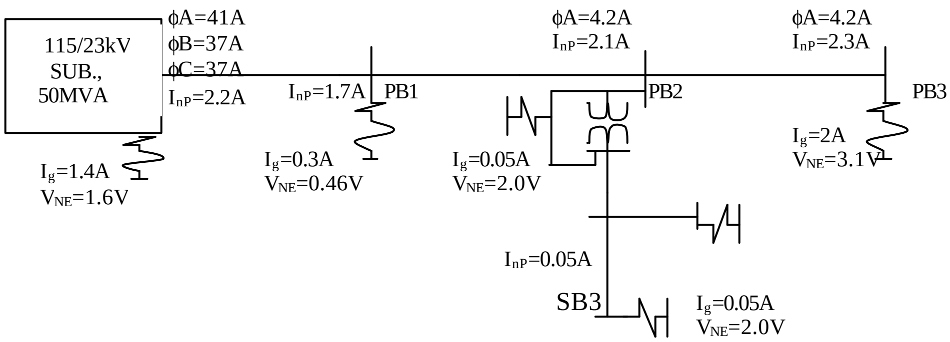


Figure 4-11 System Currents and Voltages – Minimum Current in the Neutral System (Base Case for Primary Sources)

Load in the neutral system increases in several ways. On a single-phase feeder, adding the loads increases the neutral current by the same amount. On the other hand, adding a three-phase load or adding a single-phase load in a three-phase system would increase the neutral current in proportion to the unbalance among the phases. Also, the unbalanced load condition would vary substantially depending on what month, date or time of the year it is considered. The next two illustrations consist of increasing the neutral current by doubling the single-phase load current at PB3 first and, second, by making the three-phase load at PB1 unbalanced.

In first illustration, the load at PB3 is doubled.

Following load conditions exist:

- Balanced 3-ph load at PB1 – each phase 400+j300 kva
- 1-ph load at PB3 - 100+j50 kva on ϕA
- No load on PB2 (from farm)

Figure 4-12 shows various currents and N-E voltages on the system.

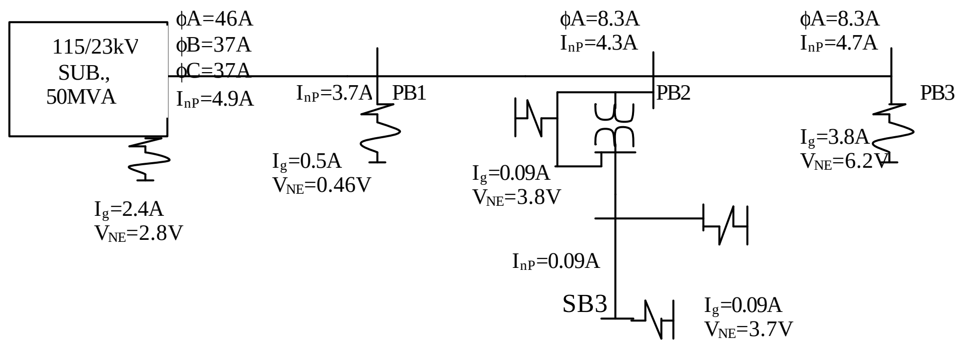


Figure 4-12 System Currents and Voltages – Single-phase Load at PB3 is Doubled
(Compare with Figure 4-11)

In this illustration, PB1 is delivering an unbalanced three-phase load.

The system load condition is as follows:

- Unbalanced 3-ph load at PB1 – ϕA= 400+j300 kva, ϕB= 200+j150 kva, and ϕC= 200+j150 kva
- 1-ph load at PB3 - 50+j25 kva on ϕA
- No load on PB2 (from farm)

Figure 4-13 shows the system currents and voltages.

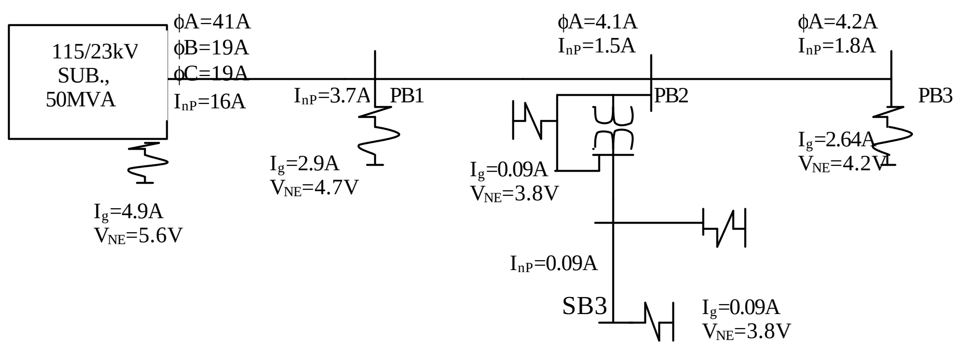


Figure 4-13 System Currents and Voltages – Unbalanced Three Phase Load at PB1
(Compare with Figure 4-11)

Influence of Neutral Impedance It is not uncommon to hear the stray voltage complaint from a customer whose facility is at the end of a long single-phase feeder. Obviously, the longer neutral wire develops a higher voltage gradient along its length. The next illustration is designed to illustrate this influence by increasing the length of the single-phase line from bus PB1 to PB2.

For this illustration, the following system conditions are modeled:

- Balanced 3-ph load at PB1 – each phase 400+j300 kva

- 1-ph load at PB3 - 50+j25 kva on ϕA
- No load on PB2 (from farm)
- The length of the single-phase feeder, PB1-PB2, is increased from 1 mile to 3 miles.

Figure 4-14 shows the system currents and voltages.

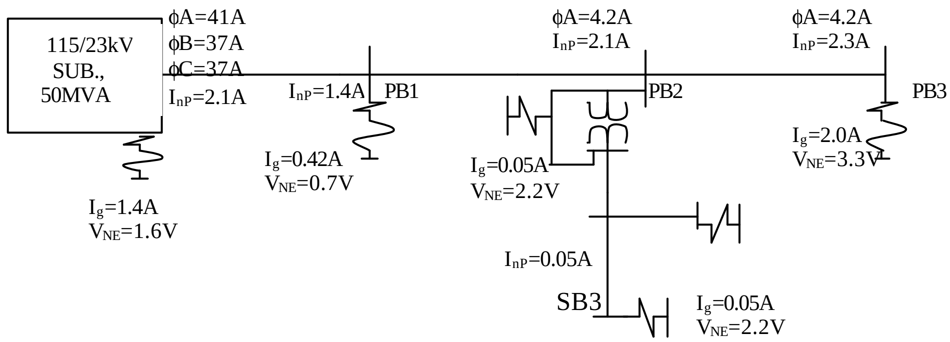


Figure 4-14 System Currents and Voltages – PB1-PB2 Feeder Length Increased from 1 Mile to 3 Miles (Compare with Figure 4-11)

Sometimes, smaller size neutral conductors are responsible for higher N-E voltages. To illustrate this influence, the neutral conductor size from bus PB1 to PB3 is reduced.

The following system conditions are modeled:

- Balanced 3-ph load at PB1 – each phase 400+j300 kva
- 1-ph load at PB3 - 50+j25 kva on ϕA
- No load on PB2 (from farm)
- Neutral conductor size from PB1 to PB3 is reduced from 66 kcmil (#2 AWG) ACSR to 26 kcmil (#6 AWG) ACSR.

Figure 4-15 shows the system currents and voltages.

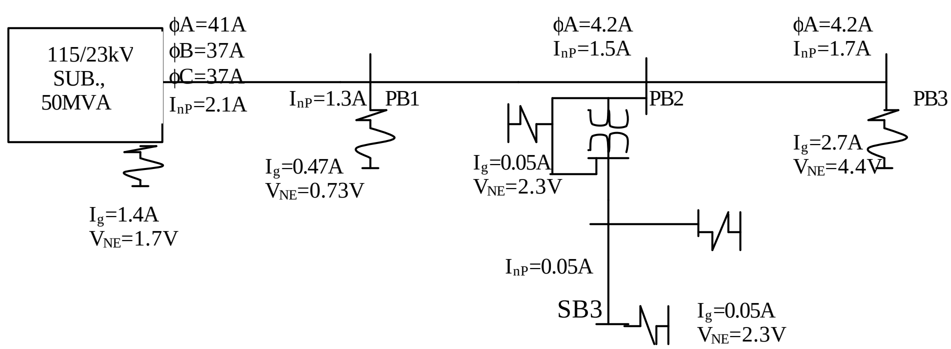


Figure 4-15 System Currents and Voltages – PB1-PB3 Neutral Conductor Size Reduced from 66 kcmil to 26 kcmil (Compare with Figure 4-11)

Influence of Corroded Splice or Connection Corrosion in the neutral conductor, particularly at the splices, can add a series resistance in the neutral path. This in turn can increase the N-E voltages on the load side of the connection. The source or substation side of the neutral, on the other hand, would show a reduction in N-E voltages.

The increase in N-E voltages would obviously depend on the resistance of the corroded connection. However, the rate of increase in the N-E voltages would depend on whether the connection is located somewhere in the middle of a primary feeder or located in the secondary neutral. For example, the high resistance splice existing on one of the secondary neutrals, each terminated in a ground rod (high resistance), would cause a greater rise in the N-E voltage compared to that caused by the same connection located in the middle of the primary neutral.

In this section, the illustration consists of representing a corroded splice (with 0.5 Ω resistance) at the transformer pole, PB2. This high resistance connection is placed on the side of PB1 such that the customer facility remains on the load side of the connection. The influence of a corroded splice in a secondary neutral is demonstrated later in Figure 4-24.

For this illustration, the following system conditions exist:

- Balanced 3-ph load at PB1 – each phase 400+j300 kva
- 1-ph load at PB3 - 50+j25 kva on ϕA
- No load on PB2 (from farm)
- A corroded splice with 0.5 Ω resistance is inserted in the neutral wire at PB2 (on PB1 side).

Figure 4-16 shows the system currents and voltages.

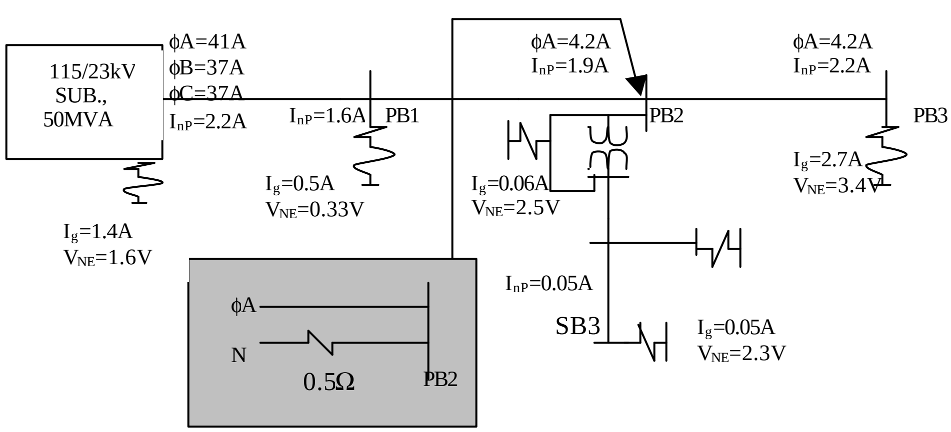


Figure 4-16 System Currents and Voltages – O.5 Ohms Corroded Connection Inserted at PB2 on PB1 Side (Compare with Figure 4-11)

Influence Leakage Earth Current Underground street light circuits (120 volts) normally run from dedicated transformers (overhead or padmount) located at the primary poles.

Sometimes, the insulation of the phase conductor may crack or the cable may be unknowingly cut resulting in a high resistance fault in the earth. Due to the high impedance fault, the fault current may not be large enough to blow the fuse and may continue to influence the N-E voltages on the system.

The return path of the leakage current generally consists of earth, grounding electrodes and, finally, the neutral. This current may add to or subtract from the current already flowing in the grounding electrodes. The next two illustrations represent such a fault on a street light circuit supplied from a separate transformer located at PB2. In both illustrations, the fault current returning to its source, subtracts from the ground currents, I_g, already flowing. In the first illustration, the fault current is of small magnitude which causes reduction in N-E voltages in the area while in the second illustration, the fault current magnitude is made large enough to nullify the existing current and also cause an increase in the N-E voltages. In reality, the fault current would depend on the soil resisitivty around the fault point and/or the presence of a metalic extension of the neutral system such as a water pipe.

The system parameters for the first illustration are:

- Balanced 3-ph load at PB1 – each phase 400+j300 kva
- 1-ph load at PB3 - 50+j25 kva on ϕA
- No load on PB2 (from customer)
- A separate transformer (15 kva) located at PB2 supplies the street light circuits. L1 of one of these circuits has a fault to soil, 50' from the pole ground. The fault current magnitude is small and subtractive such that it reduces the N-E voltages in the area.

Figure 4-17 shows the system currents and voltages.

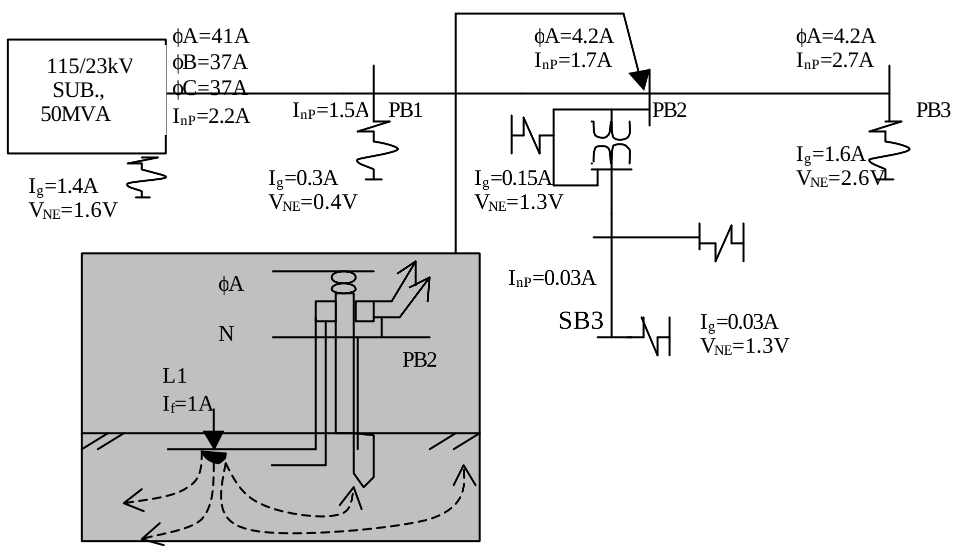


Figure 4-17 System Currents and Voltages – High Impedance Fault on Street Light Circuit 50' from PB2, Low Fault Current Magnitude (Compare with Figure 4-11 and Figure 4-18)

The system parameters for the second illustration are:

- Balanced 3-ph load at PB1 – each phase 400+j300 kva
- 1-ph load at PB3 - 50+j25 kva on ϕA
- No load on PB2 (from customer)
- A separate transformer (15 kva) located at PB2 supplies the street light circuits. L1 of one of these circuits has a fault to soil, 50' from the pole ground. The fault current magnitude is large and subtractive such that it increases the N-E voltages in the area.

Figure 4-18 shows the system currents and voltages.

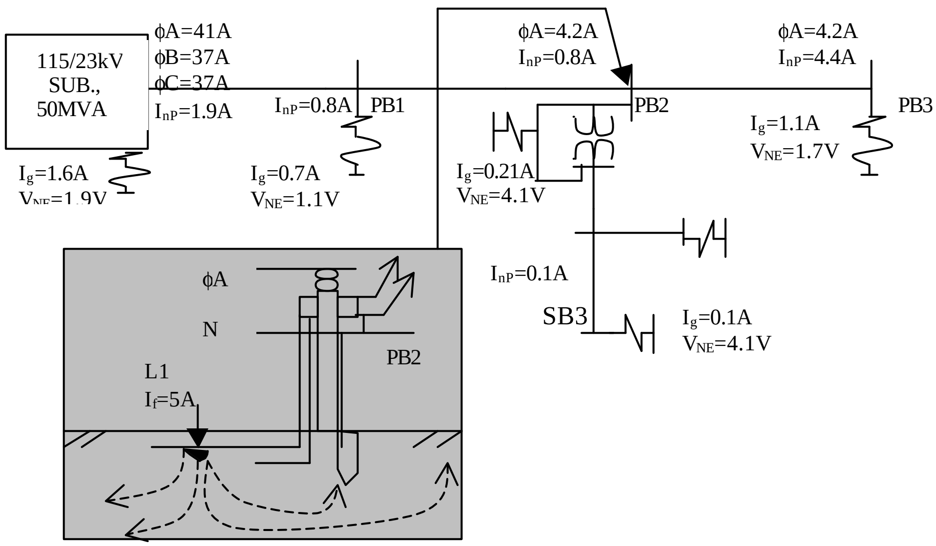


Figure 4-18 System Currents and Voltages – High Impedance Fault on Street Light Circuit 50' from PB2, High Fault Current Magnitude (Compare with Figure 4-11 and Figure 4-17)

Influence of Primary Voltage Levels Many stray voltage problems exist on systems with lower primary voltage levels. This obviously is due to higher neutral currents flowing in the systems with lower voltage levels. For this reason, upgrading the system voltage can be an effective solution against stray voltage problems provided the cost involved is justifiable.

The influence of system voltage on N-E voltages is illustrated by reducing the voltage level from 23 kV (ph-ph) to 12 kV (ph-ph). All other parameters are kept the same as the base case.

The following system parameters are modeled:

- Balanced 3-ph load at PB1 – each phase 400+j300 kva
- 1-ph load at PB3 - 50+j25 kva on ϕA
- No load on PB2 (from customer)
- 12 kV (ph-ph) replaced 23 kV (ph-ph) system.

Figure 4-19 shows the system currents and voltages.

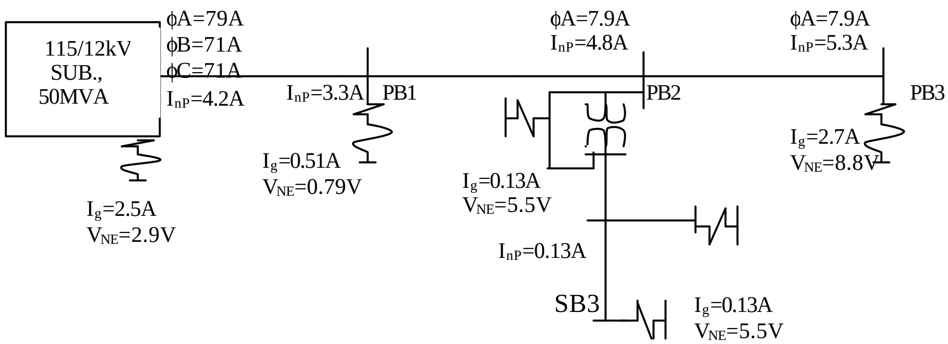


Figure 4-19 System Currents and Voltages – Distribution System Voltage Changed from 23 kV to 12 kV (Compare with Figure 4-11)

Influence of Energized Transmission Line The induced voltage and resulting current from a neighboring transmission line is one of the strongest source of stray voltage for the parallel distribution circuit. The induced voltages are significantly higher, if the distribution line is an underbuilt circuit. Among the variables that influence the induced voltage, the transmission line phase currents and their direction, length of parallel, and the separation distance are the most noteworthy.

The influence of a 500 kV line carrying approximately 900 amperes in each phase is illustrated here. With the exception of the parallel section between PB1 and PB2, the enitre distribtuion circuit was modeled as shown in Figure 4-10. The computer model illustrating the parallel section is shown in Figure 4-20.

The distribution system carries the same load as the base case. For convinience, the distribtuion system loads are repeated below.

- Balanced 3-ph load at PB1 – each phase 400+j300 kVA
- 1-ph load at PB3 - 50+j25 kVA on ϕA
- No load on PB2 (from customer)

The illustration consists of two scenarios. In the first scenario, the transmission currents flow from Source-1 to Source-2 and the corresponding system voltages and currents are presented in Figure 4-21. In the second scenario, the currents are reversed while keeping the magnitude the same. In this case, the power flows from Source-2 to Source-1. The resulting N-E voltages and currents are shown in Figure 4-22.

Regrdless of the direction of the power flow in the transmission line, the N-E voltages along the distribution circuit increases. However, with the direction of the power flow as shown in Figure 4-21, the induced voltage is subtractive and as a result produces relatively less N-E voltages compared to the additive influence as shown in Figure 4-22.

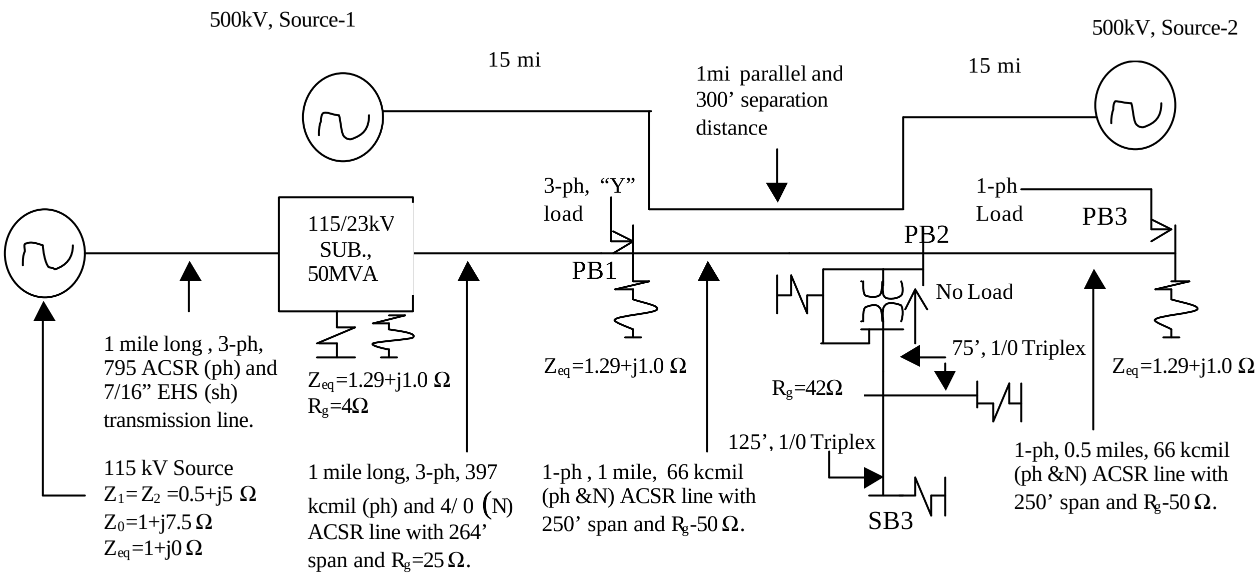


Figure 4-20 Modeled Distribution System to Illustrate the Influence of Parallel Transmission Line

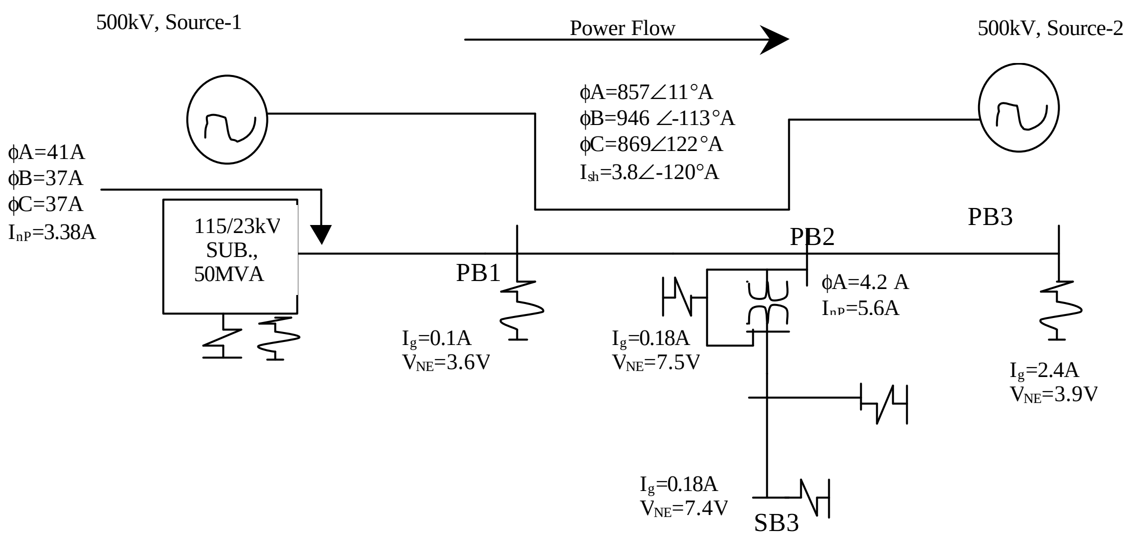


Figure 4-21 System Currents and Voltages – Influence of Parallel Transmission Line, Power Flow from Source-1 to Source-2

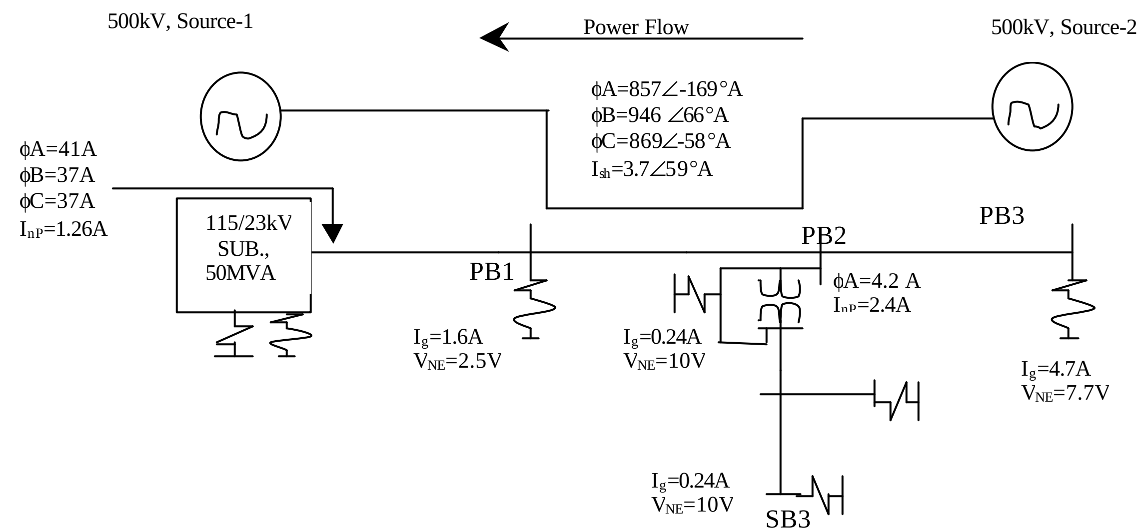


Figure 4-22 System Currents and Voltages – Influence of Parallel Transmission Line, Power Flow from Source-2 to Source-1

Stray Voltage Sources on Secondary Side

Stray voltage sources on the customer side are basically similar to those on the primary side. Like the primary system, the main source of stray voltage is the voltage gradient (drop) in the secondary neutral wire, the higher voltage level being on the load side. Although the secondary neutrals are relatively short compared to the primary neutrals, typically more current flows through these neutrals. Corroded connections in the neutral circuit, high impedance fault, and defective wiring are some the other sources of stray voltages generally encountered on the secondary side.

Similar to illustrating the primary side sources, the secondary side sources will also be analyzed using the computer. Where modeling is not feasible, illustration would be textual only. To provide a better understanding of the secondary system and its influence on N-E voltages, the influence due to the primary system parameters is kept to a minimum.

The sources are analyzed using the same system as shown in Figure 4-10. To keep the N-E voltages from the primary side to a minimum, all its loads are removed. The computer results indicate that the loadless primary system contributes only 0.007 volts (N-E voltage) to customer's neutral system.

Influence of 240 Volt Load Application of 240-volt load does not cause any current to flow in the secondary neutrals. However, the transformer primary flows the equivalent current (secondary load current times turns ratio, n_s / n_p) in the primary neutral system. Because the primary and secondary neutrals are tied together at the transformer, a portion

of the primary neutral current flows in the secondary neutral system as shown in Figure 4-23.
The following loads are modeled for the illustration:

- 240 volts load at SB2 – 1+j0.2 kva
- 240 volts load at SB3 – 2+j5 kva

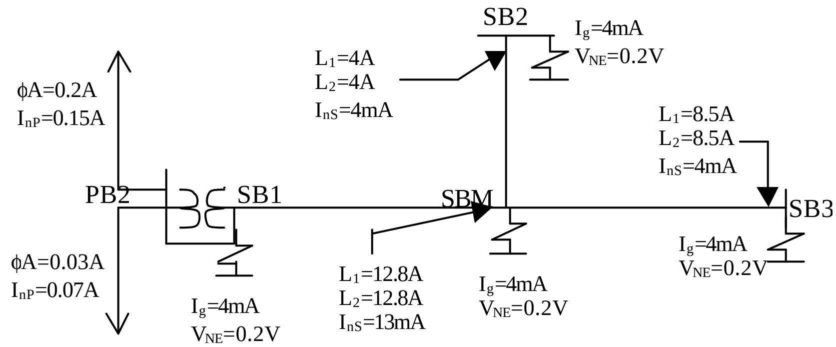


Figure 4-23 Secondary system Currents and Voltages –
only 240-Volt Loads at the Customer Facility

Influence of 120 Volts Load A 120-volt load on the secondary side is equivalent to the single phase load on the primary system. The entire load current returns to the source via neutral and ground paths. The neutral conductor being a much lower impedance path, the majority of the return current would flow through the neutral condutor and a small fraction of that current would take the ground path. The magnitude of the current flowing in the ground path would be proportional to the voltage gradient (drop) on the neutral conductor from load end to the source end (source transformer).

Next two illustrations describe the influence of 120-volt loads in customer facility.

The first scenario attempts to illustrate a worse scenario for the customer. In this scenario, the load distribution between L1 and L2 is uneven resulting in increased N-E voltages.

The following load conditions are modeled in this scenario:

- At SB2 – load on L1=2+0.3 kva and load on L2=0.5+j0.0 kva
- At SB3 - load on L1=4.5+j 2.5 kva and load on L2=1+j0.5 kva

Figure 4-24 shows system currents and N-E voltages.

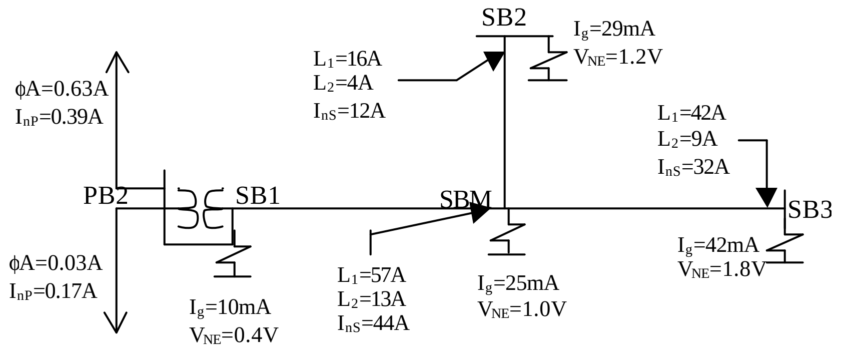


Figure 4-24 Secondary System Currents and Voltages – Unbalanced 120 Volt Loads at the Customer Facility (Base Case for Secondary Sources)

Assuming at a certain time of the day in customer's facility the loads are more balanced between L1 and L2. Obviously, more balanced load would cause less current flow in the neutral system and that, in turn, would result in reduced N-E voltages.

The influence of balanced 120-volt load is ilustrated next. The following loads are assumed:

- At SB2 – load on L1=1.5+0.3 kva and load on L2=1.25+j0.0 kva
- At SB3 - load on L1=3.5+j 1.5 kva and load on L2=2.75+j1.5 kva

Figure 4-25 represents the system currents and N-E voltages.

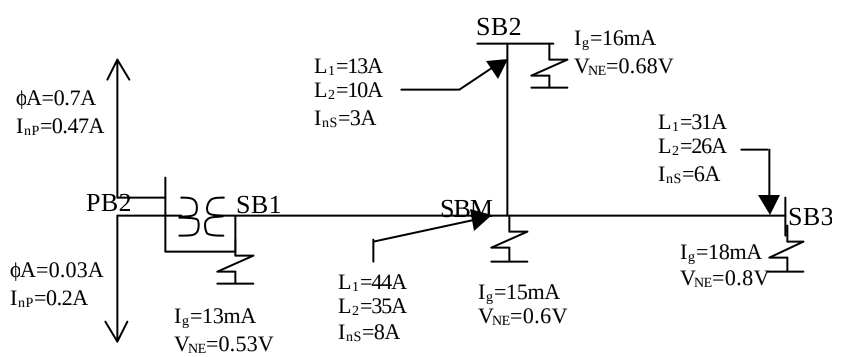


Figure 4-25 Secondary System Currents and Voltages - Balanced 120-Volt Loads at the Customer Facility (Compare with Figure 4-24)

Influence of Neutral Impedance

Neutral impedance is one of the two parameters which influences the voltage gradient (voltage drop) along the conductor length. As illustrated before, the second parameter affecting the voltage gradient is the magnitude of the current. There are two physical parameters which determine the impedance of a neutral wire. The impedance is directly proportional to the length of the neutral wire and inversely proportional to the crosssectional area of the wire. One parameter at a time, the influence of each of these parameters will be illustrated, next.

First, neutral impedance is increased by increasing its length. Specifically in the illustration, the neutral length from bus SBM to SB3 is doubled.

The following system conditions apply:

- At SB2 – load on L1=2+0.3 kva and load on L2=0.5+j0.0 kva
- At SB3 - load on L1=4.5+j 2.5 kva and load on L2=1+j0.5 kva
- Service cable length between SBM and SB3 increased from 125' to 250'

Figure 4-26 shows the system currents and N-E voltages.

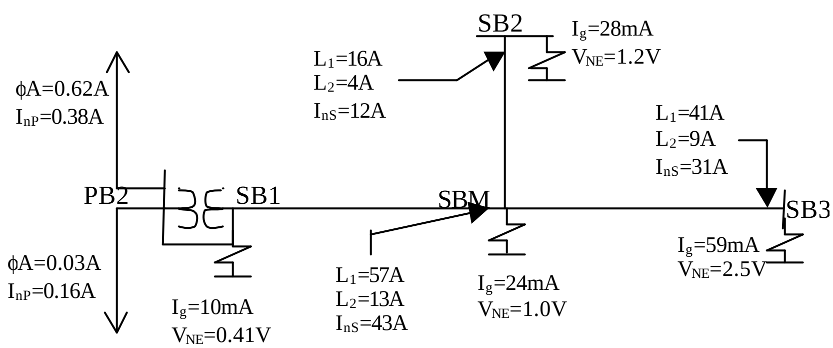


Figure 4-26 Secondary system Currents and Voltages – Service Cable Length from SBM to SB3 Doubled (Compare with Figure 4-24)

In the following illustration, the impedances of all secondary neutrals are increased by replacing them (1/0 triplex conductors) with #4 triplex conductors. The 120-volt loads remain the same as listed above.

Figure 4-27 shows the system currents and N-E voltages.

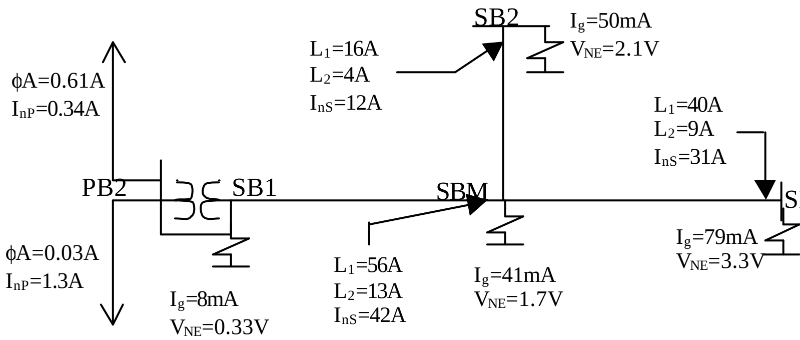


Figure 4-27 Secondary System Currents and Voltages – 1/0 Triplex Neutrals Replaced #4 Triplex Neutrals (Compare with Figure 4-24)

Influence of Corroded Splice or Connection Influence of corroded connection on the primary neutral has been demonstrated earlier. In this section, the same influence is illustrated for the secondary neutrals. A corroded splice with 0.5 Ω is inserted in the neutral entering the SB2 facility.

The system parameters including the loads are as shown below.

- At SB2 – load on L1=2+0.3 kva and load on L2=0.5+j0.0 kva
- At SB3 - load on L1=4.5+j 2.5 kva and load on L2=1+j0.5 kva
- A splice in the neutral entering the SB2 facility is corroded with 0.5 Ω resistance

Figure 4-28 shows the system currents and N-E voltages.

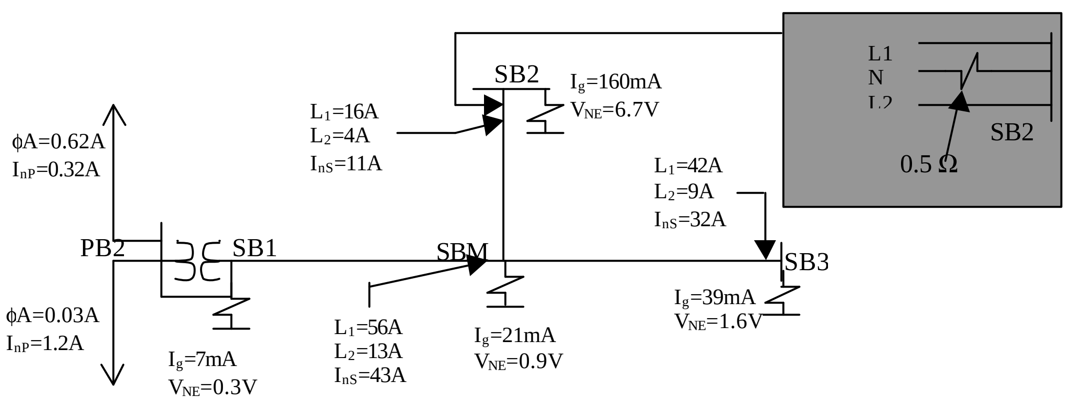


Figure 4-28 Secondary System Currents and Voltages – Neutral at SB2 Facility has a Corroded Splice with 0.5 Ω Resistance (Compare with Figure 4-24)

In an extreme case, the corroded splice can heat up and burn open. The resulting voltages in the customer facility would be devastating. Not only the N-E voltage would be extremely high, but the voltage between one of the phases (L1 or L2) and the floating neutral would be high enough to overvoltage the connected equipment such as heating elements in a water heater.

The above extreme case is analyzed by opening up the neutral entering the SB2 facility. All other system conditions remained the same as the previous case.

Figure 4-29 shows the system currents and voltages.

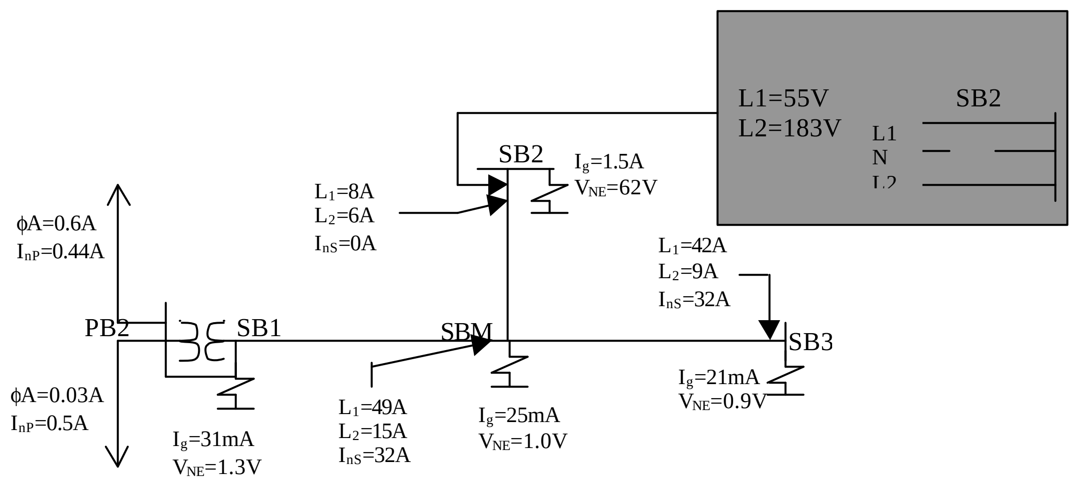


Figure 4-29 Secondary System Currents and Voltages – Open Neutral at SB2 (Compare with Figure 4-24)

SECTION 5

STRAY VOLTAGE SENSITIVITY AND CONCERNS

Stray voltages are inherent in a multigrounded neutral system and affect both humans and farm animals in a similar manner. Contact with electricity by a human or animal is generally made across a part of an impedance network to which a voltage source is attached. The current delivered by the voltage source will depend upon the voltage magnitude, the Thevinin's equivalent source resistance, and the resistance of the body path. Because humans and animals are both currents sensitive, all of these variables are important in determining the effect of stray voltage.

Interestingly, the concerns for animals and humans are not the same. Although farm animals such as cows and pigs typically experience higher currents due to lower body resistance values compared to humans, the concerning current levels for them are those at which behavioral changes resulting in production losses occur. On the other hand, humans initiate action (complaint) upon perceiving the electric current. As to the value of the body resistance limiting the current, fowl, such as hens, have resistance value almost two to three orders of magnitude higher than that for four legged animals or that for humans. Several researchers have shown that hens can sustain significantly higher stray voltage magnitudes.

There has been a multitude of research performed on the subject of human and animal sensitivities to electric current over past two decades. Providing detailed descriptions of this research in this section is neither possible nor practical. The research summaries, as a result, are presented in most cases. The focus of this section, however, remains to present the permissible voltage / current levels as clearly as possible for the users. To acquaint the users with actual court cases, this section also presents summaries of a few cases related to stray voltages.

Stray Voltage Concerns for Farm Animals

Dairy Farms (Cows)

The stray voltages are of particular interest in systems supplying power to dairy milking facilities, livestock confinement buildings, and other neutral to earth voltage sensitive equipment. The concerns for the dairy farmers are that cows may be exposed to stray voltages during milking, drinking, and feeding.. The concerning voltage, for example, may appear between the hooves which are normally resting on wet concrete and the mouth which is contacting a metal feeder or metal water trough. The impressed voltage produces a current through the animal that has a magnitude determined by the voltage magnitude, the animal's body resistance, and the Thevinin's equivalent source impedance value. Many published data indicate that approximately 10 % of dairy cattle perceive electrical currents corresponding to 0.35 volts (rms) and, in addition, milk production seems to be adversely affected when cows are subjected to both intermittent and irregular shock patterns. These types of shock patterns occur on farms because of random starting of numerous motors. The effects on cows that have been reported from field observations include:

- Reluctance to enter milking parlor
- Uneasiness inside milking parlor
- Uneven milk output
- Reduced milk production
- Animal health and breeding problem

In the world, the nature of stray voltage problem has been recognized since 1948 when Australian researchers[15] reported that the current resulting from electrical equipment in the milking area might have affected the cows negatively. New Zealand researchers published a similar statement in 1962[65]. Investigators from the Washington State University first reported stray voltages in the United States in 1969[18]. Canadians reported stray voltage incidences in 1975[30]. Stray voltage was not widely recognized as a phenomenon in the United States until the early 1980's and the majority of the research on stray voltage has been performed since that time. The remainder of this section summarizes several controlled research projects performed on cows to establish the permissible stray current or voltage levels.

Physiological and Behavioral Responses to Current Behavioral changes are manifestations of physiological reactions occurring within the organism. The basic behavioral response of any organism to an annoying stimulus is avoidance. On the other hand, the response to a pleasurable stimulus is to seek it out for re-exposure. In cows, the extent of behavioral change resulting from exposure to stray voltage can range from subtle (leg lifting or twitching) to dramatic (muscle spasms or seizures) and is related to the magnitude of the current. The research has shown that a subtle to moderate exposure to stray voltage has no effect on milk production or a loss of any cattle. The resulting behavioral changes mostly are temporary and are problematic for the herdsmen only. However, a partial or permanent aversion may take place at higher stray voltage levels. Refusal to drink from the waterer is the problematic result. Since milk is 87% water, a reduction in water consumption reduces the milk production. Feed consumption also reduces when water intake decreases, thus decreasing the milk yield even more.

Hormones in the cow's body influence many biological functions such as growth, development, and metabolism. Certain endocrine hormones (produced in ductless glands) are very important for development of the udder and its day-to-day function. These hormones include insulin, growth hormones, adrenal glucocorticoids, prolectin, thyroid hormones, ovarian hormones, oxytocin, and catecholamines such as epinephrine. Ovarian hormones, insulin, growth hormones, prolactin, and glucocorticoids are also involved in mammary development. Oxytocin and catecholamines are involved in milk ejection, or letdown. Cortisol and prolactin, and oxytoxin are released during normal milking of dairy cows. During stress (due to stray voltage), catecholamines can block the effects of oxytocin and thereby decrease milk yields. Incomplete milk removal, in turn, can increase the chance that the cows will get mastitis if their udders are exposed to microorganisms.

Research on Cow's Body Resistance Within an individual cow, the body resistance varies both with current pathway and with the individual cow. Several experiments have been carried out to characterize the resistances of different pathways within the cow's body. Table 4-5 in Section 4 summarizes the resistance values of various pathways measured by these researchers. The table shows that the resistances vary between the pathways and between the individual cows. The resistance values ranged from 250 ohms to 3,000 ohms. Among the pathways, the mouth-to-four-hooves path offers the lowest resistance (mean value of 350 Ω) to the current.

Research on Sensitivity to Stray Voltage / Current Stray voltage has been associated with cow behavioral problems and resulting decrease in milk production. Also, if stray voltages are stressful to lactating dairy cows, one would assume that exposure to these voltages under controlled experimental situations would result in elevation of stress hormone levels in blood. Workers at USDA, Cornell University, and other institutions have carried out several experiments which were specifically designed to measure the effects of various currents and voltages on the levels of hormones released during stress in dairy cows and on their relationship to blood flow, milk flow, milk yield, milk composition, and release of oxytocin, prolactin, cortisol, and catecholamines. The experiments to study the behavioral changes affecting the milk production also have been conducted by these and other researchers.

In 1991, a group of agricultural scientists published the USDA Agricultural Handbook 696[79] summarizing all the research works performed in the area of animal susceptibility to electric current up to that time. The purpose of this handbook was a) to prevent the research results from being misinterpreted and misconstrued, and b) to improve understanding of causes and effects of stray voltage on farms.

In 1996, the Michigan Agricultural Electric Council (MAEC) completed a review of all available research including that completed prior to 1991[32]. The document provides summaries of the studies where variables other than the treatment were controlled (repeatable research), and presents the results to address the following:

a) Provide a summary of conclusions of research findings.
b) Explain how the different research trials were conducted.
c) Explain the different methods used by researchers to determine if animals were being affected.

All the researches that were reviewed by MAEC are described in a table by the authors of the publication. This table is attached in its entirety as Appendix A at the end of this handbook. The summary of each research in the table contains:

a) Description and size of herd.
b) Description and type of voltage or current that was applied – 60 Hz (short duration, long duration or continuous), pulse, transient.

c) Type of treatment – magnitude of current or voltage, how long, before milking, after milking.
d) Results – perception, behavioral response, production loss.

For convenience, a summary of the research review by MAEC attached in Appendix A is presented below.

- Animals may perceive currents through the body below 3 mA at 60 Hz without any resulting behavioral problems. Under unusual circumstances, an animal may be able to perceive currents below 1 mA. The perception level for an animal will vary greatly depending on the animal circuit pathway such as mouth to hooves or front hooves to rear hooves. Lefcourt[59] had an individual cow that responded to 0.7 mA. The current was applied intrusively between two points on the legs that had been shaved and sanded.

- Behavioral changes that were found by researchers in the 3 mA to 6 mA range (60 Hz) caused only short-term effects and did not affect overall production. Management or handling concerns may occur when an animal's body current exceeds 4 mA.

- None of the research showed changes in production or feed or water consumption for currents at or below the 4 mA level. Lefcourt[59] measured a production decrease in one study at 5 mA, but a subsequent study measured no decrease in milk production at 6 mA level. The currents of 5 mA and 6 mA had no effects on long-term production in any other study.

- As frequency is increased above 60 Hz, the response threshold rises[71][2]. The average threshold for animal response when exposed to a 0.017-second pulse every two seconds for thirty seconds was 5 mA at 60 Hz, 26 mA at 6000 Hz, and 132 mA at 50,000 Hz[70].

- Based on the research conducted, it is improbable that currents can be sustained through an animal during milking at a level that will decrease milk production, without behavioral problems first becoming prevalent.

- Physiological effects on animals can be determined by observing changes in hormone levels due to an electrical stimulus. No hormone level changes were observed at 5 mA or below. Henke-Drenkard[47] and Aneshansley[1] have observed the changes in cortisol levels at 8 mA.

- Limited research has been done with direct current (dc). Based on two sets of experiments for perception and behavior by Gustafson[40][44], the threshold values for dc are 20% to 30% higher compared to those for ac.

Above researchers conducted their experiments by flowing known values of currents through the animals. In most field investigations, measurement of current through an animal's body is difficult and is avoided. On the other hand, open circuit voltage (V_{oc}) measurement between the contact points is easier and is always performed. Realizing this practical necessity, some researchers conducted their research by applying various voltages between the animal contact points. Although current flowing through the animals is not known, the voltage levels from these experiments can be related directly to the field measurements provided that the experimental voltage values are interpreted correctly. For the user's convenience, the interpretation of voltage levels is included with each research summary.

- Water or feed consumption did not reduce for any livestock below 4 volts (60 Hz) applied continuously between animal contact points. However, two of 30 animals in one test by Gorewit[36], refused to drink at the 4 volt level for 36 hours and were given an alternate water source. No other research found any statistical effect on overall consumption or production at 4 volts and below. Because the voltages were applied between the waterer and a metal grate embedded in the concrete floor, these voltage levels should be interpreted as open circuit voltage levels when comparing with the field measured voltage levels.

- Gorewit [35] and Gumprich[37] evaluated in full lactation studies the reproductive parameters including days to first estrus, conception rates, calving interval and number of claves born dead. No change in any breeding parameter was found for any treatment. Gorewit applied the maximum voltage of 4 volts while Gumprich applied the maximum voltage of 5 volts between the animal contact points.

  Both of the above researchers applied the voltages between the waterer and the metal plate or grate below the cows' hooves. As a result, the voltage levels used in their experiments should be interpreted as the closed circuit voltage (V_{cc}) levels for comparison purpose. Recall from Section 4 that the closed circuit voltage between the contact points will always be less than or equal to the open circuit voltage (V_{oc}). The difference in magnitudes will depend on how high the Thevinin's equivalent source impedance is. Because of this relationship between V_{oc} and V_{cc}, accepting the above voltage levels as permissible levels will always be on the conservative side.

The Minnesota Legislature authorized the Minnesota Public Utilities Commission (MPUC) to establish a committee of science advisors in response to claims by some dairy farmers that electric currents in the earth from electric utility distribution systems are somehow responsible for problems with behavior, health and production of dairy cows. A multidisciplinary group with expertise in the field of agricultural engineering, animal physiology, biochemistry, electrical engineering, electrochemistry, epidemiology, physics, soil science, and veterinary science were assembled to serve as science advisors. The consensus of the science advisors was that currents in the earth can only interact with dairy cows through their associated electric fields, magnetic fields and voltages, and that these parameters should be the focus of any analysis. A field study was then conducted to investigate the magnitude of these hypothesized electrical factors on 19 Minnesota dairy farms. The combined electrical data from the field study indicated that while none of the factors could be ruled out, only one of them was a priority for research. This factor is the continuous or frequently repeated contact of confined cows to sources of low level stray voltage resulting in the current levels high enough to produce biological effects without producing observable or measurable behavior modifications.

Upon the science advisors' recommendations, the MPUC awarded a research grant to a group who has previously performed several research projects in the stray voltage field. The research and research results were submitted to MPUC in June of 1999[68][69]. The research was divided in three parts. Following is a summary of the research:

- The specific objectives of Part 1 were to investigate the relationship between behavioral responses and the plasma cortisol concentration in cows and to compare cow sensitivity to current applied from hoof-to-hoof with that applied from muzzle-to-hoof pathway.

  The results of Part 1 indicated that the dairy cows were more sensitive to current applied from one front to two rear hooves (3 mA) than current applied from muzzle to four hooves (5.4 mA). Note that the reaction level in this experiment was defined as the current level at which two observers observed a flinch.

  No increase in cortisol level was observed for a cow subjected to 5 minutes of 1.5 times the current required to produce a behavioral response. A cortisol increase was observed in response to hoof trimming. As to which parameter is a better indicator, the researchers concluded that behavioral responses are a more sensitive indicator of perception or annoyance than cortisol levels in dairy cows.

- The specific objective of Part 2 of the research was to compare commonly encountered milking machine problems to exposure to electrical current. The current exposure was 1 mA applied from front to rear hooves during milking. The milking machine problems consisted of either failing the pulsator producing no message, or the use of excessively aged liners.

  While several significant effects were measured when commonly encountered milking machine problems were applied to cows, no adverse effects were observed for cows exposed to 1 mA of current from front to rear hooves. Exposure to 1 mA current produced no significant change in milk yield, milk flow rate, strip yield, and cow activity or liner slip. Some interactions between milking machine problems and current exposure were significant in some experiments, bur the magnitudes were small and they were not repeatable across the experiments.

- The specific objective of Part 3 experiment was to measure the immune function response of dairy cows to continuously applied hoof-to-hoof current exposure below the level that would produce a behavioral response as determined in Part 1.

  Collectively, the results of Part 3 experiment suggest that exposure to 1 mA current for two weeks had no significant effect on the immune function of dairy cattle. One of 13 response variables was statistically significant but did not appear to be entirely consistent with other observations.

Permissible Levels for Stray Voltage/Current The MAEC, after a thorough review of all the research (see Appendix A), concluded that the findings of USDA Handbook 696, Effects of Electrical Voltage/Current on Farm Animals, are accurate and Figure 3-4 in the handbook is a realistic representation of the responses to stray currents. For reference, this figure is duplicated in Appendix B of this handbook. The diagonal line in the figure represents the biological variability that exists in farm animals.

Based on the graph of Appendix B, the MAEC further concluded that to eliminate the possibility of production loss, the amount of stray current that can flow though cow's body should be kept below 4 mA (60 Hz rms). None of the research showed a decrease in feed or water consumption or milk production below this level. Also, 1000 Ω for the total circuit impedance (Thevinin's equivalent impedance plus the cow's body resistance, see Section 4) can be assumed based on the research that showed no feed, water or production loss below 4 volts across the animal's body. This assumption thus allows 4 volts as the permissible voltage level to correspond with the permissible stray current level of 4 mA.

While no research has found production losses for 60 Hz animal body currents below 4 mA or open circuit contact voltage below 4 volts, the MAEC suggests taking a conservative approach and providing a safety margin. In suggesting keeping the animal currents at or below 2 mA and open circuit contact voltages below 2 volts, the MAEC feels that this margin will insure stray voltage from causing any problem including some minor behavioral responses in cows.

The State of Wisconsin has already adopted 2 mA as the permissible level for the stray current (see Section 2). As to the permissible voltage level, the Wisconsin rule defines the level in terms of closed circuit contact voltage (V_{cc}) measured across a 500 Ω resistor. Note that this differs from the definition provided by MAEC and the USDA Handbook 696, which defines the permissible voltage level in terms of the open circuit voltage, V_{oc}. In accordance with the Wisconsin rule, the permissible voltage level would be 1 volt measured across the 500 Ω resistor. In accordance with MAEC and USDA Handbook the permissible voltage level would be a 2 volts measured between the contact points without the resistor. Remember that the procedure described in Section 6 (see Figure 6-1) will have to be followed to obtain the stray current or closed circuit voltage measurements as required by the Wisconsin rule.

A Summary of Court Cases Involving Dairy Farms

In 1984, the Journal of American Veterinary Medical Association (JVMA, August 15 issue) [46] published the results of stray voltage investigations in Michigan dairy farms. Since publications of these results, there had been a number of lawsuits by dairy farmers against electric utilities as well as against the equipment suppliers. The following is a summary of the cases that have arisen between 1984 and 1990.

- In a number of cases decided in 1984 and 1985, the plaintiff dairy farmer did not win because it could not be proved that the defendant utility supplier knew or should have known of the stray voltage risk. The cases include:
  - Kohli vs. Public Utilities Commission of Ohio, 479 NE 2d 840; Wells vs. French Broad Electric Membership Corporation, 315 SE 2d 316 (NC App. Ct.); Western Pennsylvania Power Company vs. Pennsylvania Public Utilities Commission, 478 A2d 947.

- When defendant utilities or equipment manufacturers have been found to be negligent in installing or maintaining electric lines or equipment on the farm, plaintiffs have been successful. Examples of these cases are:
  - In Shriver vs. Pennsylvania Power and Light Company, 501 A2d 1129, the plaintiff recovered on counts of strict liability and negligence.
  - In Potomac Edison Company vs. Burdette, 521 A2d 1276 (Maryland App. Ct.) the issue hinged on negligence installation of a milking parlor.
  - In Public Service of Indiana Inc. vs. Nichols, 494 NE 2d 349, an award of $340,000 against the electric utility was upheld.
  - Negligent installation of milking machines was proved, and the plaintiff recovered damages in Hoovers' Dairy Inc. vs. Mid America Dairymen Inc., 700 SW 2d 426 (Mississippi Supreme Ct.).
  - In Babson Bros Company vs. Tipstar Corporation 446 NE 2d 11 (Indiana App. Ct.), plaintiff recovered $ 580,000 in damages for negligent installation of milking machines.

- In Otte vs. Dayton Power and Light Company, 37 Ohio St 2d 33, decided in 1988, the Ohio Supreme Court found that strict liability in tort for damages caused by neutral to earth voltage was not a cause of action that could be successfully asserted against a public utility. In reversing the lower court's decision, it said that the public policy reasons that justify strict liability claims were not appropriate against a highly regulated public utility. On a technical point, the court also found that the utility was selling a service rather than a product. Therefore, there could be no strict product liability claim.

- In a case arising in Pennsylvania in 1983 but not decided until 1989, Slater vs. Pennsylvania Power Company, 557 A2d 368, the Superior Court of Pennsylvania upheld an award of $108,000 to the plaintiff in a trespass action against the utility. Plaintiffs were able to show a decline in milk production, unusual behavior of the cows, reluctance of the cows to enter the barn, failure to go to their stalls, and kicking off milking machines. The plaintiffs also testified that a veterinarian's treatment produced no results. The culprit in this case was the ground wire that ran from the utility pole. When the plaintiff's electrician disconnected it, the stray voltage disappeared and did not reappear when the wire was reconnected with modifications (a neutral isolator was probably installed).

  On the issue of proof of economic loss, the court noted that the Slaters had the burden of proving damages by a preponderance of the evidence, but they needed only to provide the jury with a reasonable amount of information to enable it to estimate damages without resorting to speculation. In this case, proof of economic loss was established by testimony of the dairy farmer himself, relying on personal knowledge, books and records of the business.

- In litigation that originated in 1977 but not concluded until 1990, Freeman vs. Consumers Power Company, Michigan Court of Appeal, No. 11050, the court held the utility not liable, but on technical grounds. The complaint against the utility had been filed on a trespass theory – that is, permitting stray voltage to come onto the property. The court held that this was not trespass because the plaintiff had given Consumer Power consent to supply an electrical hookup and the electricity necessary to run the milking system. In this case, however, the system's manufacturer was also a defendant and the court ruled for the plaintiff against it.

In 1993, a Wisconsin newspaper published a stray voltage case, a Mt. Hope Farmer vs. Grant-Lafayette Electric Company. While the jury found that fair compensation to the farmer was $150,000 (the farmer started with the claim of $ 600,000), it also ruled that the farmer was negligent in failing to mitigate the severity of the problem, and was therefore responsible for $ 88,000 of his problem. Pending the outcome of a motion filed by the farmer's attorney, the farmer's final reward was in the amount of $ 62,000.

Some of the salient points of the above case are listed below:
- The farmer pressed charges against the Power Company in 1991 after isolating his farm neutral as a means to counter decreased milk production.
- The farmer claimed that the milk production was again on the rise following the neutral isolation.
- A 7.2 kV single-phase line tapped from a three-phase line served the farm. In 1989, the Power Company upgraded the half-mile of neutral wire going into the farm in response to the farmer's requests. Apparently the problem continued.
- According to the Power Company, the measured stray voltages were always lower than 3 to 4 volts considered harmful by USDA.
- To the jury, the replacement of the neutral wire and other repairs by the Power Company looked as if the Power Company was admitting the problem.
- The farmer's veterinarian had the herd on a nutrition program and the farmer stopped it due to high cost. The milk production declined as a result.
- Three electricians testified against the farmer claiming that they had advised the farmer to change out the farm's poor wiring. The farmer did not do it.
- A farm employee testified that the farmer abused the cows.

Swine Facilities (Pigs, Hogs)

Stray voltage research has concentrated primarily on dairy animals. However, the problems are not limited to dairy operations. Cases have been documented where stray voltage has affected other livestock, particularly swine. Although little information is available as to the effect of electrical current on swine, the symptoms reported with them are similar to those observed in dairy cattle. Sows (adult female pigs) were described as having a reduced appetite, lower water consumption, and inadequate milk production (increased rate of apparent starve-out per litter). Baby pigs had a lower than normal growth rate.

For both cows and swine, the above symptoms are not unique to stray voltage. They could also be attributed to other factors such as nutritional disorders, disease, or poor treatment. In fact most common problems that some researchers[14] have found in swine facilities are improper ventilation, improper insulation and maintenance of the buildings, over crowding, and lack of adequate feeder and waterer spaces. Another source of problems in swine facilities is poor waste management practices.

Research on Swine Sensitivity to Stray Voltage / Current Compared to dairy cows, there are fewer research projects performed to determine the swine sensitivity to stray currents or voltages. Among the research, Gustafson and others[41] in 1984 conducted the most comprehensive and complete research. The research was conducted on eight growing / finishing pigs in two separate experiment using 60 Hz electrical currents.

The first experiment involved presenting individual pigs with a choice of three nipple waterers from which to drink. The objective of this experiment was to assess at what current level the pigs could sense the electrical current and would, given an alternative, move to a different water source. Of the three nipples, one nipple never had any voltage on it (zero current). The other two nipples were applied with currents ranging from 0.25 mA to 4 mA.

In the second experiment, only one nipple waterer was used. The objective of this second experiment was to assess at what current level the pigs would change their drinking pattern and consumption when no alternative water source were available. The current level on the nipple was varied from 0 to 5 mA. In addition to studying the sensitivity to the currents, the pig’s body resistance from mouth to hooves was also measured.

The following is a summary of the Gustafson’s research results:

- Mean resistance of mouth to all hooves pathway for eight pigs (68 kg to 100 kg) was 789 Ω with a standard deviation of 262 Ω.
- The three nipple experiment showed that the pigs would perceive 0.25 mA and higher currents and, knowing that alternative water source existed, would seek out that source. Using the mean body resistance of 789 Ω this would imply a perception voltage as low as 0.2 volts. (Note that this permissible voltage is the closed circuit contact voltage, V_{cc}. The corresponding open circuit contact voltage, V_{oc}, would be of higher magnitude depending the value of the equivalent source resistance.)
- The second series of experiments using one nipple (no alternative water source) showed that a significantly higher current is required to affect drinking time, consumption, or attempts to drink. Statistically, significant variables were not found in the amount of consumption below the current level of 4.5 mA or in drinking time below 3.5 mA. Using the same 789 Ω value for the path resistance, voltages in the range of 2.8 volts to 3.6 volts would be required to affect drinking and consumption time respectively (Note that these permissible voltages are the closed circuit contact

voltages, V_{cc}s. Depending on the equivalent source resistance value, the corresponding open circuit contact voltages, V_{oc}s, would be of higher magnitudes.)

A few research projects were conducted to determine the sensitivity of pigs to stray voltages. Because the voltages were applied between the waterer and a metallic floor, the voltage levels should be interpreted as the closed circuit voltage (V_{cc}) levels for comparing with the field measured voltage levels. The results of this research are summarized below.

- Godcharles and co-researchers[34] found no losses in water or feed consumption or in production after exposing the pigs to a continuous level of 5 volts with intermittently applied three-second pulses up to 8 volts between feeders or waterer and a metallic floor.

- Aneshansley and co-researchers[2] applied one-second pulses of 8 volts both randomly and intermittently at waterers for twenty-one days with no effect on feed or water consumption or milk production.

- Twelve and thirteen-week studies of voltage effects on fattening pigs by Robert and co-researchers[60] and Godcharles and co-researchers[34] examined blood samples every two weeks and meat and stomach conditions after slaughter. No statistically significant change in blood or tissue samples occurred for voltage treatments up to 8 volts.

Field Investigation in a Swine Farrowing Unit Serious production losses were occurring in an eastern Nebraska swine farrowing unit[75]. Production losses had persisted for more than two years. Mastitis was common, as were scours of baby pigs. Baby pigs had a lower than normal growth rate and a high death rate. Average numbers of weaned pigs per sow were 7.5, even though the average litter size was 10.

Different feed formulations were tried. A veterinarian was employed who analyzed the feed and water and checked the pigs for disease. New gilts were obtained to reduce or eliminate the possibility of a hereditary problem.

All of these efforts did not solve the problem. Sows would avoid drinking water from the watering cups and occasionally got very excited and restless. On several occasions the sows had to be removed from the barn in order to calm them.

An electrical problem was suspected when one of the owners felt a tingle shock when he put a finger (which had a cut) in a watering cup. Measurements with a VOM revealed an ac voltage of approximately 10 volts from the metal piping of the watering system to the concrete floor.

The following were the investigation and remedial steps that were taken:

1) Initial Steps – The Rural Public Power District serving the farmstead was called in to assist in reducing the stray voltage. The modifications by the utility personnel included improving the grounds at the service and meter poles and isolating the primary and secondary neutrals. The farmer's contractor changed suspected connections in the secondary neutral system. These efforts reduced the stray voltage from 10 volts to 5 volts. However, the problems with the pigs and sows still persisted. Two sows injured themselves and had to be destroyed.

2) Secondary Steps – Agricultural and electrical engineers from the University of Nebraska-Lincoln were invited. In order to determine if better grounding would help, one set of eight farrowing crates were bonded together with No. 8 copper wire and connected to a newly driven ground rod with the resistance value of 0.5 Ω. The bonding of the crates reduced the voltage difference between the crates but did not reduce the voltages from each crate to ground.

   All of the circuits in the barn were checked for leakage. Only one circuit serving an electric water heater showed a leakage current. This circuit was suspected in the initial investigation and its fuses were already removed. As a result, this revelation did not matter.

   The ground rod connection for the service entrance to the building was accessible to hogs. On one occasion, the connection had become loose because of the animals rubbing on the rod. No change in the stray voltage occurred when the ground connection at the service entrance was repaired.

   The current measurement of the single-phase, three-wire service to the farrowing barn showed L_1=22 amperes, L_2=14 amperes, and N=10 amperes. A check of the circuit in the panel showed that of the seven 115 volts ventilating fans, five were supplied from L_1. Two fans were operated continuously, timers controlled two fans, and thermostats controlled three fans. The circuits were re-wired such that L_1 supplied to four fans and L_2 supplied to the remaining three fans. This load balancing reduced the stray voltage from 5 volts to 0.5 volts.

   Belly-to-snout resistance of sows was also measured to estimate the potential current flow through the animals. A copper plate (40 cm^2) with a test lead attached was placed under the belly of a sow. A second copper plate (6 cm^2) was wedged between the sow's snout and a water cup. An average belly-to-snout resistance of 360 Ω was measured.

3) Final Steps – During a four week period with a stray voltage of 0.5 volts from the waterer to the concrete floor, sows were still agitated and drank very little water. As a result, the pigs were still not doing well.

   At this point the voltages in the barn area were checked again. A minimum stray voltage of 0.5 volts was present in the farrowing barn at all times with occasionally higher readings. Following these measurements, the transformer primary was

disconnected which dropped the farmstead load. The stray voltage dropped to 0.002 volts. This test indicated that the source is in the farmstead neutral.
The overhead wire serving the farrowing unit was a No.4 triplex approximately 90 meters in length. In order to check for an open or high resistance neutral in the triplex, a No.6 copper wire was connected from the meter pole grounding conductor to the neutral at the weather-head of the farrowing barn. Connection of the parallel neutral reduced the stray voltage from 0.5 volts to 0.002 volts. The sows became more relaxed within a short while.

Later, the No.4 triplex was replaced with No.1/0 Aluminum triplex. Impedance check of the No.4 triplex after removal showed the neutral had normal resistance. The stray voltage in the barn remained at 0.002 volts in subsequent measurements.

Poultry Farms (Chickens, Hens, Turkey)

The history of reported cases of stray voltages affecting fowl's mortality rate and the farmer's poultry production is quite interesting. Prior to comprehensive research involving the investigation of stray voltage levels of concern for fowls, the reported cases were based primarily on field observations. A few measurements and lots of speculation resulted as shown in next four paragraphs. The definitive research determining the average body resistance of a hen (384 kΩ) and also the stray voltage levels (18 volts) below which there is no concern for production or flock loss were published in 1995[81] and 1996[80] by Canadian researchers. Summaries of these two researches are also provided in this section. Worley and Wilson from the University of Georgia published their results in 1998[87]. This research being more recent and more comprehensive is presented in more detail in this section.

Field Observations and Reports The earliest reported field observations claiming to show that small voltage differences have large effects on poultry production was in 1986[84]. The reported case involved 10,280 laying hens in Pennsylvania with a production curve higher than normal and mortality rate of 0.7% per month. At the age of 43 weeks, these hens became nervous, feed intake and egg production decreased, and mortality rate increased. N-E voltages (V_{NE}s) of 0.8 to 0.9 volts were measured between the waterers and a reference ground and 1.3 to 1.5 volts were measured between the cages and the reference ground. Containing only the field observations, this report did not specify the mitigation means or the improvements following their application.

D. Halvorson and his co-researchers[45] in 1989 published the earliest field investigation, which also included a controlled experiment on poultry. The farm owners consulted these researchers because three successive flocks of turkey poults experienced cumulative mortality of 10% to 26% through the fifth week of brooding. Stray voltage was suspected after no definitive laboratory diagnosis could be made and no management deficiency was found. Stray voltages of 0.2 to 2.5 were measured between waterers and the floor and between the water and gas pipelines. When the water line was grounded to the electrical service entrance ground, the subsequent flock had no mortality problem.

After completing the above investigation and recommendation, a series of experiments was conducted to determine the sensitivity of turkey poults to ac current. Based on these experiments, the authors concluded that the voltage levels measured at the farm probably did not cause the mortality experienced in the three flocks. Unfortunately, these authors provided no other data on stray voltage, production or behavior after fixing the problem. Instead they speculated that the reason for the farm problem could have been 1) the poults experienced higher voltage than was present at the time of measurements, 2) the voltage may have been intermittent, or 3) there was a difference between the farm environment and the cage battery environment in the experiment.

G. Vidali and his co-researchers report a field investigation in the "Introduction" section of their 1996 research report[80]. The authors provide no information regarding the source. Instead they state that the information is based on personal communication. The stated case consists of an U.S. utility company being advised of problems attributed to stray voltage in a flock of 65,000 Leghorn females and 6,000 Leghorn males. Before 1991, egg production was at a normal rate of 130 cases of eggs per day and the fertility was between 94 and 95%. In 1992, the production decreased to between 100 and 110 cases per day, the fertility dropped to between 72 and 86%, and the chickens appeared to be in poor condition. In 1993, the fertility decreased to as low as 65%, and the appearance of the chickens worsened. The hens also became nervous to a point that the light had to be maintained at a low level. In the building where the chickens were most excitable, the measured voltage differences (V_{oc}s) ranged from 0.06 to 6 volts. After several changes in the electrical system of the building, the problems disappeared.

In preparing for the experiments, the researchers at the University of Georgia conducted an industry wide survey[87] on histories of stray voltage problems. The survey also included the mitigation means applied and subsequent follow-ups to see how floor egg problems (more hens laying eggs on the slats and on the floor than in the nests) were affected. The authors did not specify the area or states in which this survey was conducted. Refer to Table 7-18 of Section 7 for a summary of this industry survey.

Sensitivity to Stray Voltage – Canadian Research G. Vidali and his co-researchers published the results of the first comprehensive research in 1995[81]. In this research, the effects of normal sinusoidal electrical voltages and impulses on laying hens between 23 weeks and 48 weeks of age were evaluated. The experiment consisted of caging 120 hens in six blocks of 20 birds each. Within each block, the treatments were distributed in a randomized complete block design. Of the total of 7 experiments, Experiments 1, 2, and 3 included application of 0-3 volts, 4-6 volts, and 7-9 volts, respectively. Voltage differences with random amplitudes of 0-9 volts were applied at a frequency of one pulse every 10 seconds in Experiment 4 and a frequency of two pulses every 10 seconds in Experiment 5. In Experiment 6, the hens were subjected to 12-18 volts at a frequency of one pulse every 10 seconds. In Experiment 7, hens were placed three per cage and received either 0 volt or 12 volts with one pulse every 10 seconds. All voltages above were applied between the metallic nipple drinker and the metallic cage. Daily water and feed intake were measured and the behavior of the hens was observed.

The applied voltages did not affect feed or water consumption, laying rate or egg quality. Frequency of eating and drinking behavior, time spent eating and drinking and time spent standing or sitting were not affected by the treatment. The researchers concluded that although poor performance of farm animals is occasionally attributed to stray electrical voltages, in their experiment, stray voltages as high as 18 volts had no effect on the hens' production and behavior. Note that these voltages should be interpreted as the closed circuit contact voltages, V_{cc}s.

G. Vidali and his co-researchers published more research results in 1996. This time the research was on effects of chopped sinusoidal voltages on the behavior and performance of laying hens[80]. One of the experiments in this research consisted of measuring the fowl's body resistance from tongue to feet.

The effects of chopped sinusoidal electrical voltages were evaluated on laying hens between 23 and 43 weeks of age. The experiment consisted of caging 120 hens in six blocks of 20 birds each. Within each block, the treatments were distributed in a randomized complete block design. In Experiment 1, voltage differences of 0, 3, 6, and 9 volts were applied between the metallic nipple waterer and the metallic cage. In Experiment 2, differences of 0, 12, 15 and 18 volts were applied. In Experiment 3, 4 and 5, the hens were placed three per each cage. Voltage differences of 0 or 6 volts were applied in Experiment 3, 0 or 12 volts were applied in Experiment 4, and 0 or 18 volts were applied in Experiment 5.

Reaching the same conclusions as reached in their research with normal sinusoidal voltage waveforms, the authors concluded that the stray voltages as high as 18 volts did not affect the daily water and feed intake, laying rate, and behavior of the hens.

The above research also included determination of electrical resistance of a hen's body. The resistance was determined using a voltage adjusted to limit the current passing through the body to less than 0.5 mA. The resistance of hens of 23 and 40 weeks of age to alternating current (24 hens) and direct current (12 hens) was measured. Electrodes were placed on the tongue and on one or both feet to measure the resistance to alternating current and on the tongue and both feet to measure the resistance to direct current.

The electrical resistance of 23 week and 40 week old hens was found to vary between 350 and 544 kΩ. These values indicate that the hens have an electrical resistance that is approximately 1000 times higher than that of cows or pigs, further explaining the total absence of response to treatments with the voltages as high as 18 volts. Insulating properties of the tongue and the epidermis of the feet can, in part, explain these high resistance values for hens. The authors also reported that the resistance did not significantly change with the age or whether the current passed between the tongue and one or both feet.

Sensitivity to Stray Voltage – Research by the University of Georgia Worley and Wilson at the University of Georgia conducted comprehensive research on broiler breeders (the hens that lay fertilized eggs that become broilers) during 1997-1998. The research results were presented in ASAE meeting in Orlando, Florida in July 1998[87]. A summary of this research is provided in this section.

Houses for broiler breeders typically have a section of wooden slats on each side of the house with feeders, waterers, and nests. A section of earth floor with shavings (called the scratch area) is located between the slatted sections. The hens have a choice whether to lay their eggs in a nest or on the slats or on the ground. If the eggs are laid in the nest, they are kept clean and are automatically collected via belt. The eggs laid on the slats or on the ground, on the other hand, are subject to bacterial contamination, and must be collected by hand in baskets. A significant number of hens laying eggs out of the nest is a costly affair for the farmer. One producer estimated that floor eggs in his two chicken houses were costing him $ 15,000 per year in reduced income. This did not include the extra labor necessary to collect the eggs. The main objective of this research thus was to determine whether the stray voltage might cause the increased floor egg problem in poultry farms.

The fact that hens are very much creatures of habit was given a prime consideration by the researchers in designing the experiments. The hens have a strong tendency to lay their eggs in the same place throughout their lives. Therefore, a larger voltage would be necessary to cause a hen to stop laying eggs in a nest once she has formed that habit than is necessary to discourage her from starting to lay in the nest. On the other hand, once a bird has established the habit of laying on the slats or on the floor, she is most likely not to start laying in a nest even if there is no presence of voltage. The presence or absence of voltages in the nest will most likely not matter until the fresh flock is introduced into the house and comes into lay. For these reasons, the experiment was divided into two parts: one to determine the stray voltage required for mature hens to decrease the usage of nests and second to determine the stray voltage required for young hens to discourage the usage of nests.

In the first part, old hens were obtained from a research flock at 60-65 weeks of age. Hens were housed 35 per pen (96 sq. ft. / pen) with a six-hole mechanical nest unit in each pen. The hens were allowed one week to acclimate to the pens, and starting from the second week eggs were collected and recorded according to nesting site. At the beginning of the third week, nest units had 0, 3, 6, or 9 volts applied between the nest and poultry netting fastened to the slats. The data were collected on each nesting location for two weeks. During the final two week period, the nest units were returned to 0 volts and again nesting location were recorded.

In the second part, five hundred twenty week old pullets (young hens) were grown. The birds were housed 35 per pen with a six-hole mechanical nest unit placed in each pen. They all were provided a 16-hour day including feeding, watering, and lighting. These voltages were applied between the nest and the slats: 0, 3, 6, or 9 volts. Eggs were collected from each pen and nest site and recorded from the onset of production through 40 weeks of age. During the final two week period, the nests were returned to 0 volts and again, nesting location was recorded.

The test results on matured hens showed that the floor egg percentages for the four voltage levels, 0, 3, 6, and 9 volts, were almost unchanged during the three stages of the test, indicating that the birds were unaffected by the application of the voltages. The fact that the voltages applied did not affect the mature hens is not surprising, given the strong habitual nature of breeder hens.

Results of the second test (with young hens) were grouped into two categories: one category consisting of "age range (weeks)" vs. "% of floor eggs" and the second category consisting of "weekly production" vs. "% of floor eggs". There were no statistical differences in any of the groups. The 6 volts pens were slightly higher than the others, but this can easily occur as a random variation. Similar to other controlled research based on applied voltages, the voltages should be interpreted as the closed circuit voltages, V_{cc}s.

Stray Voltage Concerns for Humans

As stated in the beginning of this section, there is a difference between the current levels of concern for farm animals and that for humans. In general, farm animals compared to humans are exposed to higher currents due to their lower body resistance values. The current levels of concern for animals are also higher (>4 mA). This is because the current levels of concern for the farm animals are determined based on the behavioral changes resulting in production losses. Humans, on the other hand, initiate complaints upon experiencing a slight shocking sensation (perception level) when they come in contact with the stray voltage source.

Unlike the cases involving farm animals, there seem to be no documented court cases related to shocking incidents involving humans. This is partly due to the fact that human shocking resulting from stray voltages is more an annoyance than a life threatening incidence. Responding promptly by utility companies to mitigate the problem is perhaps another reason why there are no reported court cases related to human shocking incidences.

Types of Stray Voltage Concerns

Receiving shocking complaints from residential customers is a common event for utility companies each year. Although the incidents may occur inside or outside the house, the complaints received by utility companies mostly are for the outside areas. Typically, the shocking incidences include contacting electrical service equipment, faucets, aluminum siding, gutters, or fences. Sometimes, a person comes in contact with a utility hardware such as a guy wire or a metallic street light pole and experiences a shocking sensation.

The swimming pool shocking incidences are among the most common complaints received by the utility companies. Due to wet areas on the concrete deck or body of water in the pool, the shocking currents are relatively higher in such incidences. Among swimming pool shocking incidences, a child experiencing a shocking sensation while coming out the pool water with the help of handrails is very common. Other common incidences involve a person getting out of the water on the side or a person getting out of the water from the ladder.

Marinas and boat docks are another source of stray voltage complaints for utility companies. Like swimming pools, the shock current values are relatively higher due to the body of water being involved in the circuit. Typical stray voltage problems at marinas are associated with the gas pump at the edge of the dock. Boaters receiving shocks from the gas pump or the nozzle is a common complaint for the marinas. As to private boat docks or ramps, stray voltage incidents may involve a boat owner making a contact with the galvanized steel cables used for lifting the boat or pulling the boat up the ramp. It is not uncommon to see a floodlight mounted at the edge of a dock with a galvanized conduit. A swimmer touching this conduit may experience the shocking sensation if the pipe is energized with sufficient magnitude of stray voltage.

An individual customer initiating a complaint does not always mean that the stray voltage problem is limited to that customer's house or facility only. The same problem may exist around neighbors' facilities also. It is just that the neighbors are not aware of the problem yet. In some instances, the stray voltage problem exists on an entire section of a single-phase feeder and, for which, complaints from several facility owners are received. Adding a phase and balancing the load may be economically justified to mitigate the problem in such a case.

For the user's convenience, a few stray voltage cases involving residential houses, swimming pools and boat docks are described below. Some of the cases have been described in other sections of this handbook. These cases have been referenced to those sections.

- A few residents of a residential subdivision have been complaining about electrical shocks when touching outside water faucets. One woman was even washing her car wearing rubber gloves.

  A 12 kV overhead feeder, 7 miles long, serves several commercial and residential loads including the subdivision under investigation. The last 2.25 miles of this feeder is a single-phase (two wire) line. A single-phase tap, ½ mile long, originates almost at the end of the feeder and serves the subject subdivision.

  The stray voltage problems were mostly due to high load conditions during summer months. Also, several houses (particularly the houses in the newer sections) were constructed with PVC pipes for the water supply. The houses having stray voltage problems belonged to this category. The N-E voltages at the problem houses ranged from 9 volts to 11 volts.

  The computer analysis indicated that improving grounds at the transformer poles would reduce the N-E voltages a little. Similar reduction would be achieved for upgrading the neutral size in the subdivision. The study also indicated that bringing in an additional phase in the subdivision and balancing the load between the two phases would reduce the voltages significantly. This mitigation method was finally implemented.

- Several residents in a subdivision were experiencing shocks resulting from high N-E voltages during the winter season. The houses in this area mostly have heat pumps or strip heaters, which primarily cause this problem. Also, due to expected load growth in the subdivision, there was a concern that this problem may get worse.

  The investigation consisted of measuring the system currents (load and neutral currents) and voltages (N-E voltages) at selected locations. Next, the entire distribution system from the supply substation to the customers was modeled and the measured results were validated. After validating the computer model, several solutions were investigated to determine their effectiveness in reducing the N-E voltages in the subdivision. Among the various solutions that were tested, the most effective and economically viable solution was to add two phases and distribute the loads among the three phases as equitably as practically feasible.

- A resident (in a residential subdivision) has been complaining about annoying shocks while touching the outdoor water faucet. Two single-phase underground cables running side by side serve the entire subdivision. Separate potheads tap both of these cables from Phase-C of the three-phase feeder. The normally open (N.O.) point is located such that one circuit extends approximately 6.5 miles from the pothead to the open point while the other circuit extends approximately 4 miles from the pothead.

  The problem house is located farthest from the pothead poles (approximately 5 miles). This long neutral distance was determined to be the main cause of the stray voltage problem at the house. Measurement of 5.4 volts from the faucet to earth at the subject house was the maximum voltage measured in entire subdivision. On both circuits, the N-E voltages reduced gradually towards the pothead locations.

  The recommendations to mitigate the problem included:
  - Installing a ground ring in the faucet area,
  - Connect one of the two circuits to a different phase, and
  - Move the N.O. point to the padmount near the subject house.

- A resident and his children were receiving scary shocks when touching the outdoor faucet on the backside wall. The severity of the shocking sensation was such that the children were not allowed to even play in the backyard. The house was located at a cul-de-sac in a large residential subdivision. Two UG circuits (two phases) served the entire subdivision.

  The investigation included measuring the contact voltage between the faucet and earth first. This voltage measured 18 volts. Next, N-E voltages were measured at several padmounts in both directions. With the exception of three neighboring houses on one side of the subject house, all N-E voltages measured low, between 2-4 volts. Faucet-to-earth voltages at the three neighboring houses measured between 9-12 volts. After informing the customer, the meter was pulled out. The voltage at the faucet remained the same, 18 volts. Lifting the secondary neutral at the padmount transformer did not change the voltage either. The cable TV and telephone company personnel also disconnected their shield (or neutral) from the power company's ground at the meter. This did not change the voltage at the faucet.

The personnel involved in the investigation scratched their heads for a few days. One afternoon, following a few more failed attempts to determine the source, a lineman suggested checking the street light circuits buried along the main street behind the subject house. A separate padmount transformer located approximately 1.5 miles from the subdivision served all the street light circuits in the area. One after another, each circuit was de-energized at the padmount. Following each de-energization, the voltage at the faucet would be checked. This procedure continued until the street light circuit along the main street was de-energized. The voltage at the faucet disappeared.

Later, a thorough check of the defective lighting circuit revealed a high impedance fault to earth in the vicinity of the subject house. Digging around the fault location showed the cut 120 volt wire lying beside a newly installed water pipe by the county.

- Figure 7-19 in Section 7 summarizes several stray voltage cases including the type of concern, measured voltages, and recommended mitigation means. Of twelve case summaries, ten cases are related to shocking incidents around swimming pools, one case describes the incident in a campground, and one case relates to the shocking incident while installing A/C ductwork in a house.

- Users interested in knowing the stray voltage concerns around boat docks should refer to study case presented in Section 8, Figures 8-10 through 8-17. The study case involves a marina with a gas pump located on the edge of a boat dock. The marina complained that that the boaters receive shocks while pumping gas. The contact points were defined as the gas pump nozzle (connected to neutral) at one end and the wet boat surface or lake water at the other end.

Human Body Resistance

Different parts of the human body – such as the skin, blood, muscle, joints and other tissues – present certain impedance to the flow of electric current. Several variables, such as moisture, skin punctures, physical constitution of the individual (fat, muscularity, size), and area and pressure of contact can appreciably alter the total body impedance value. For example, many researchers have shown that the average body resistance decreases under wet conditions. Also, the resistance of a fat or skinny person would be relatively higher than that of a muscular person[57]. The pathway for the current flow within the body is another variable, which produces different values for the body resistance. For example, the resistance between one hand to trunk (stomach area) is half of that between one hand to one foot.

The main portion of body resistance in low voltage circuits is located at the contact points due to skin. In contrast, skin resistance across a high voltage or high frequency circuit becomes negligible. In fact, higher contact voltages (typically higher than 240 volts) puncture the skin instantly and only the internal resistance (resistance of tissues) impedes the current flow. As to the relationship with higher frequencies, the body impedance decreases due to capacitive shunting, exhibiting non-linear characteristics.

Research on Human Body Resistance In low voltage and low source impedance systems, the body impedance is basically resistive. Unlike the resistance of a metallic conductor, the resistance of the human body has negative non-linear characteristics[20]. It decreases with increasing voltage, current, or time. Of particular interest to the industry is the relationship between:

- Body resistance and the contact voltage,
- Body resistance and the wet or dry skin, and
- Body resistance and the path.

Matthews[61] has investigated the relationship of body resistance with the contact voltage. His study included the voltage levels from 50 volts to 500 volts (50 Hz). The resistance values for voltage levels below 50 volts were extrapolated. Table 5-1 shows the resistance values for three low end voltage levels. It should be noted that the reference does not provide any information regarding the contact area, type of pathway and the population for which these data were obtained.

Table 5-1 Human Body Resistances for Low Contact Voltages (V_{cc})-Matthews

Contact Voltage Volts	Range of Body Resistance (Wet Skin to Dry Skin) Ω	Body Resistance (Mean Value) Ω
25	1800-5500	3650
50	1667-5000	3333
100	1416-4000	2708

In order to find statistically reliable values for the impedance at low contact voltages, a larger number of living persons were tested in Austria and Switzerland[11]. The subjects firmly grasped cylindrical electrodes with left and right hands. The duration of the current flow was limited to 0.1 seconds (50 Hz). The measured impedance and resistance are tabulated in Table 5-2. The reference did not provide any information as to the condition of the skin, wet or dry, at the contact areas.

Table 5-2 Human Body Resistances for Low Contact Voltages (V_{cc})- Switzerland and Austrian Investigations

Contact Voltage Volts	Initial (Instantaneous) Body Resistance Ω		Overall Body Impedance Ω	
	Range	Average	Range	Average
15∗	375 - 875	637 ± 98	2020 - 7193	3717 ± 1181
25♦	530 - 1101	781 ± 114	1547 - 9118	3517 ± 1397

∗ Thirty males and 20 females were tested. No significant difference in male and female body resistances was found.

♦ Eighty males and 20 females were tested. These males and females were weighing 53 kg to 102 kg and ranging in age from 15 to 68 years old. No significant difference in male and female body resistances was found.

For most of the statistical population and for a wide range of contact voltage levels, IEC[48] provides the data for human body resistances as shown in Table 5-3.

Table 5-3 Human Body Resistances for Wide Range Contact Voltages (V_{cc})- IEC

Contact Voltage Volts	Body Impedance Ω		
	With 5% Probability	With 50% Probability	With 95 % Probability
25	1750	3250	6100
50	1450	2800	5100
75	1250	2550	4500
100	1200	2400	4150
125	1100	2200	3800
220	1000	1800	3000
700	750	1100	1550
1000	700	1050	1500
Asymptote	650	750	850

Whitaker, Underwriters' Laboratories[83], conducted experiments on body resistances using 47 children ranging in age from 3-15 years and 40 adult employees. The test circuit was a 12 volt battery and the test current was 1 mA for children and 5 mA for adults except where the resistance was so high to make it impossible to obtain these currents. Direct currents were used as a precautionary measure since people can tolerate higher values of direct current rather than alternating current.

Table 5-4 presents the body resistance data obtained by Whitaker. The data in Table-5-4 yield an important conclusion regarding the body resistance of the child compared to that of the adult. Regardless of the moisture content of the skin, the body resistance of the child is higher than that of the adult measured under the same conditions. A plausible explanation for this observation is that differences in various factors, such as volume, surface area, skin thickness and skin resistance may influence the body resistance magnitude.

Table 5-4 Body Resistances of Adults and Children - Whitaker

Subject	Resistance Hands-to-Feet Ω				Resistance Right Hand-to-Feet Ω			
	Dry		Wet		Dry		Wet	
	Range	Average	Range	Average	Range	Average	Range	Average
Adult∗	1500 - 13500	4838	610 - 1260	865	-	-	820 - 1950	1221
Child♦	1810 - 55000	6046	860 - 4200	1443	1900 - 35450	7800	1270 - 5700	2016

∗ Forty adults were tested.

♦ Forty-seven children were tested.

Similar to cows, the human body resistance varies significantly between the paths that the current takes in the body. The percentages of the impedance of the human body for various paths in relation to the path from hand-to-hand or hand-to-foot was measured by Sam[74]. Table 5-5 shows the resistance values calculated from these research data for various paths. Because 1000 Ω is a widely accepted resistance value for the hand-to-feet path in the United States, all the values in the table are based on this number (1000 Ω = 100 %) for convenience.

Table 5-5 Human Body Resistances for Various Paths (1000 Ω= 100%)

Path	Path Resistance Ω	% (1000 Ω = 100 %)
Hand-to-Hand	1333	133
Hand-to-Foot	1333	133
Hands-to-Foot	1000	100
Hand-to-Feet	1000	100
Hand-to-Trunk	666	67
Hands-to-Trunk	333	33
Hand-to-Head	666	67
Hands-to-Head	400	40
Hand-to-Heart	600	60
Hands-to-Heart	307	31
Hand-to-Knee	933	93
Hands-to-Knee	600	60

Permissible Body Resistance Because of the physiological variability in humans, it is difficult to establish a firm value for the body resistance to alternating current, particularly at higher contact voltage levels. This value may not be so difficult to determine, however, for the circuits with low contact voltages (<25 volts) as generally found in stray voltage cases. Presently, 1000 Ω is a widely accepted resistance value in the United States regardless of the level of contact voltage. Initially, this resistance value became an acceptable standard due to its recommendation by IEEE Std-80 for substation ground grid designs where contact voltage levels are relatively higher. As the need in other areas evolved, the 1000 Ω value started being accepted for those areas. Looking at the research data presented above, use of 1000 Ω resistance value for stray voltage cases would be on the conservative side and should be acceptable. The research data also indicates that 1000 Ω can represent the resistance value for the wet skin conditions. As to the body path, the permissible 1000 Ω value is generally assumed for the hand-to-feet path.

Human Sensitivity to Stray Voltage / Current

The earliest experiments regarding electric shock effect on the heart were made on guinea pigs to discover the effect of different voltages by comparing the percentage of fatalities[31]. A significant outcome of these experiments was the realization of the dependence of physiological effects on the magnitude of current. Experiments by a number of researchers were also done on larger animals, particularly sheep, calves, pigs, and dogs, since their body weight and heart weight are more comparable to that of a human. As a result, quantitative data is available on the amount of current needed to produce a specific physiological response. This and actual measurements on humans is used to estimate what constitutes a safe threshold to current stimulation of a few milliamperes.

In humans, the four most important measurable thresholds are perception, let-go, respiratory paralysis, and ventricular fibrillation. Each of these thresholds is discussed next.

Perception Threshold The perception threshold denotes the level at which the effect of current is first perceived. A tingling sensation is felt from the alternating current stimulus. This level has no adverse effects. Thompson[78], whose work preceded Dalziel's, investigated the smallest 60 Hz alternating current perceived for a hand contact on 70 healthy adults. He found the perception threshold for men to be between 0.4 – 1.39 mA and that for women to be between 0.27 – 0.88 mA.

Dalziel[22] plotted perception current levels (on X-axis) versus population percentile rank (on Y-axis) for 167 men. The perception current levels included 0-2 mA. The plotted data closely followed a straight line, which indicated that the response follows a normal distribution and can be analyzed using statistical methods. He determined 1.1 mA to be the mean value (50% of the test subjects had perception thresholds below this value) for the test subjects. Dalziel, on the basis of Thompson's work, assumed the mean value for women to be two-thirds of the men's mean value. For women, he then suggested the mean value of 0.7 mA. Derived from Dalziel's graph, Table 5-6 shows the three data points for men and women.

Table 5-6 Perception Current Thresholds for Men and Women

∗Population Percentile Rank %	Perception Current Threshold mA	
	Men	Women
99.5	1.8	1.15
50	1.1	0.7
0.5	0.4	0.25

∗ This percentage of test subjects has thresholds below the values shown in right two columns.

Dalziel also investigated the effect of frequency on perception current. Obviously, the perception level increased with the frequency. At 5000 Hz, the threshold of perception was approximately 7 mA. Above 100 kHz, the sensation changed from tingling to heat. The smallest current that might cause an unexpected involuntary reaction and produce a secondary effect is called the reaction current. Such an unexpected current might cause a housewife to drop a skillet of hot grease, or cause a worker to fall from a ladder.

In 1967, some 20 U.S. organizations funded the Underwriters' Laboratories to determine reaction currents under the guidance of the American National Standards Institute (ANSI). After conducting the necessary experiments at the Laboratories in New York, a standard was adopted by ANSI in November 1970. This standard established 0.5 mA as the maximum allowable leakage current for two wire portable devices and 0.75 mA for heavy movable cord-connected appliances such as freezers and air conditioners.

Let-go Current Threshold As the current is increased above the perception threshold value, the tingling sensation is transformed into one of discomfort accompanied by muscle tightening. This muscular contraction increases with current until a value of current is reached at which the subject cannot voluntarily let go of the conductor being grasped. The let-go current value represents this threshold. The let-go current is the maximum safe current a person can tolerate and still release grip of an energized object, using muscles directly affected by the current. For continuous currents (such as stray currents), the let-go values are the criteria used in establishing safe current requirements. For safety, these values must not be exceeded.

Supervised by physicians from the University of California Medical School, Dalziel[22] conducted experiments on healthy adults (134 men and 28 women) to determine safe let-go currents. When plotted, these data followed a straight line distribution similar to the perception threshold values. Table 5-7 lists the three data points for men and women from the graph.

Table 5-7 Let-Go Current Thresholds for Men and Women

∗Population Percentile Rank %	Let-Go Current Threshold mA	
	Men	Women
99.5	22.5	15
50	16	10.5
0.5	9	6

∗ This percentage of test subjects has thresholds below the values shown in right two columns.

The author suggests taking a conservative approach in selecting the permissible let-go current from Table 5-7. In the interest of safety, he recommends 0.5 percentile values, 9 mA for men and 6 mA for women, as the maximum continuous current values. In the absence of reliable experimental data on children, Dalziel assumed their let-go value to be one-half the let-go value for men, or 4.5 mA[21]. Whitaker[83] established 5 mA as the maximum uninterrupted 60 Hz current to which a two year old child may be safely exposed. Interestingly, Underwriters' Laboratories use this value as the maximum safe continuous current for the general population.

Similar to perception currents, the let-go current increases with the frequency. At 5000 Hz, the let-go current is more than three times that at 50 or 60 Hz. This alternatively means that it takes over three times the current value at 60 Hz to produce the same muscular reactions when the frequency is increased to 5000 Hz.

Threshold for Respiratory Paralysis Above the let-go current, voluntary control is relinquished and the subject is "frozen" to the circuit. The currents exceeding the let-go current are very painful, frightening, and hard to endure. In the opinion of Ferris[31], "Any currents ….. that prevent voluntary control of the skeletal muscles are dangerous because their pathway through body might include respiratory muscles and stop breathing during shock". This loss of voluntary control over respiratory muscles and cessation of breathing during shock is referred to as respiratory paralysis. Generally, if the current is interrupted, normal respiration resumes and no adverse permanent after effects are produced. Lee[58] has published data indicating 30 mA as the threshold of respiratory paralysis, which is frequently fatal. According to Murray[62], a 50 Hz alternating current of 25 mA or less can produce a slight contraction of the respiratory muscles. Experimentally Dalziel found that 60 Hz alternating current in the range of 18 mA to 22 mA could arrest breathing in adults when flowing across the chest[22].

Threshold for Ventricular Fibrillation At even higher levels of current, the heart's pumping action ceases and uncontrollable quivering of the heart results. This condition, known as ventricular fibrillation, is initiated by the stimulating effect of the current rather than physical destruction to the heart tissue. The onset of ventricular fibrillation can produce a dangerous situation, which without immediate expert help, is irreversible.

The parameters influencing fibrillation include body weight, time duration of the current, and current magnitude. Controversy exists pertaining to the shock parameters involved in the initiation of ventricular fibrillation. Dalziel and Lee[22] support the view that an electric shock hazard from 60 Hz currents is related to energy. They based the current energy relationship from their experimental data that showed the fibrillating current between 8.3 ms and 5 sec duration is proportional to $t^{-1/2}$, where t is the period of shock duration. Another viewpoint, expressed by Osypka[63], is that the total charge and not the energy that determines the hazard. Osypka found that for a period of 8 ms to 5 sec, the fibrillating current was proportional to t^{-1}. It should be emphasized that both of these investigators derived their results from studying current and duration parameters and not from a physiological basis. Geddes[33] proposes a physiological explanation by relating the responses of irritable (nervous) tissue to current density. The equation derived from the relationship is of hyperbolic form, with current density proportional to t^{-1}. Biegelmeier and Lee[10], by reevaluating Dalziel's data, provide another interpretation related to the charge rather energy concept.

While this controversy continues, the industry[6] has adopted Dalziel's interpretation of data suggesting that fibrillating current is related to $t^{-1/2}$. This relationship and the "electrocution equation" derived from this relationship are explained below. Dalziel found that the minimum 60 Hz current causing ventricular fibrillation is proportional to body weight and inversely proportional to the square root of the shock duration time. Based on this, the IEEE Std-80 (2000) provides two electrocution equations for two different body weights:

$$I = \frac{116}{\sqrt{t}} \text{ mA for 50 kg body weight} \qquad (5\text{-}1)$$

$$I = \frac{157}{\sqrt{t}} \text{ mA for 70 kg body weight} \qquad (5\text{-}2)$$

Where:
I = Ventricular Fibrillation threshold, mA (60 Hz, rms)
T = Shock duration time in seconds

Stray Voltage Threshold As seen in all the research, the shock severity is proportional to current flow through the body rather than the contact voltage at which the shock occurs. As a result, all threshold values are in terms of current and not in terms of voltage. In most stray voltage investigations, however, the only quantity measured or known is the open circuit contact voltage (V_{oc}). The process to determine voltage threshold values from the known current threshold values is not simple. The body resistance and the equivalent source resistance (Thevinin's equivalent resistance, see Section 4) must be known. 1000 Ω for human body is an acceptable resistance value for the low voltage circuits. However, in the cases involving swimmers or boaters or a person with a cut in the finger may make contact and the 1000 Ω body resistance may not be applicable. The resistance of 300 Ω would be more appropriate in such a case. To determine the equivalent source resistance for a given circuit is where the major difficulty lies. The equivalent source resistance can vary from less than a hundred ohms (for swimmers and boaters) to several thousands ohms (for soil). This resistance also varies with contact area. For example, a swimmer with half of his body in the water would have significantly less resistance compared to the same swimmer with his two feet making contact with the concrete deck.

For users' convenience, an example of determining a threshold value for stray voltage is presented in this paragraph. Assuming 1 mA as the threshold value for the current (perception level), 1000 Ω for the body resistance, and 100 Ω (swimming pool case) for the equivalent source resistance, the stray voltage threshold would compute 1.1 volts (see Section-4). This means that following the application of the mitigation means, the open circuit voltage measured between contact points should be less than 1.1 volts at the swimming pool.

SECTION 6

FIELD MEASUREMENTS

Field measurement is an integral part of any stray voltage related investigation. Both the equipment and procedures must match the measurement objective, detecting the source or sources of the problem. If carefully selected and used, standard electrical instruments are adequate for most types of measurements required for stray voltage investigations. However, more sophisticated instruments may be required for detailed investigations requiring short and long duration measurements. In this respect, both the equipment and the procedure must also match the electrical expertise of the investigator.

This section addresses various measurement techniques and associated devices. Step by step investigating procedures for specific problems are covered in Section 9.

Voltage Measurements

As shown by experience, voltage is the easiest and most convenient electrical quantity to measure in stray voltage investigation. It is also the most reliable first indicator of a possible stray voltage problem. Typically, a stray voltage investigation includes two types of voltage measurements: 1) point-to-point and 2) point-to-reference ground.

Point-to-Point Measurement

The point-to-point method measures the voltage levels which may potentially affect the animals or humans. This is the most important measurement and it simply means taking the voltage measurements between two points which may simultaneously be touched by a livestock or a human. Usually this will be between a metal structure, such as a stanchion or a faucet, and the concrete floor or soil. In a dairy farm, the cow contact locations may include water bowl to floor, water bowl to stall, parlor steel to floor, heated waterer to floor, feed bunk to floor, and facility entrances. The milking machine and associated pipeline typically are not considered the locations of concern. In the case of humans, the points of contact depend on the stray voltage location. Outside water faucets and the soil are two typical contact points in a residential area. The shower knob or showerhead and the concrete floor would normally be the contact points in a campground. Sometimes contacting the outlet panel while standing on wet soil may cause a shocking hazard at the campground. When investigating stray voltages at swimming pools, voltages between pool water and the concrete deck, between pool water and coping stone, and between pool water and handrail are typically measured. At a boat deck, for example, the contact may be made between water and the steel rope of a boatlift.

To assess the severity of the problem, two point-to-point voltage measurements are necessary. These voltage measurements include measurement of the open circuit voltage, V_{oc}, and the measurement of the closed circuit voltage, V_{cc}. Of these two measurements, the measurement of open circuit voltage is quick and easy and is invariably performed first. This measurement is obtained simply by connecting a high impedance digital voltmeter between the two contact points. It is the closed circuit voltage measurement, which demands the most attention. This is because the closed circuit voltage determines the body current (see Equation 4-9) and the equivalent source resistance (Equation 4-10) between the contacted points. It is important that these measurements are accurate such that the severity of the problem can be ascertained. The closed circuit voltage measurement is obtained by connecting a suitable resistor representing an animal or human body across the contact points and measuring the voltage across that resistor. To represent a cow, a 500 Ω (2 Watt) resistor is typically used. This resistance value includes the contact resistance at each end. Although, the closed circuit voltage is rarely measured in the cases involving humans, investigators desiring this voltage may use a 1000 Ω (2 Watt) resistor.

Figures 6-1 and 6-2 illustrate these two voltage measurements in the cases involving a cow in a barn and a human at a campground, respectively.

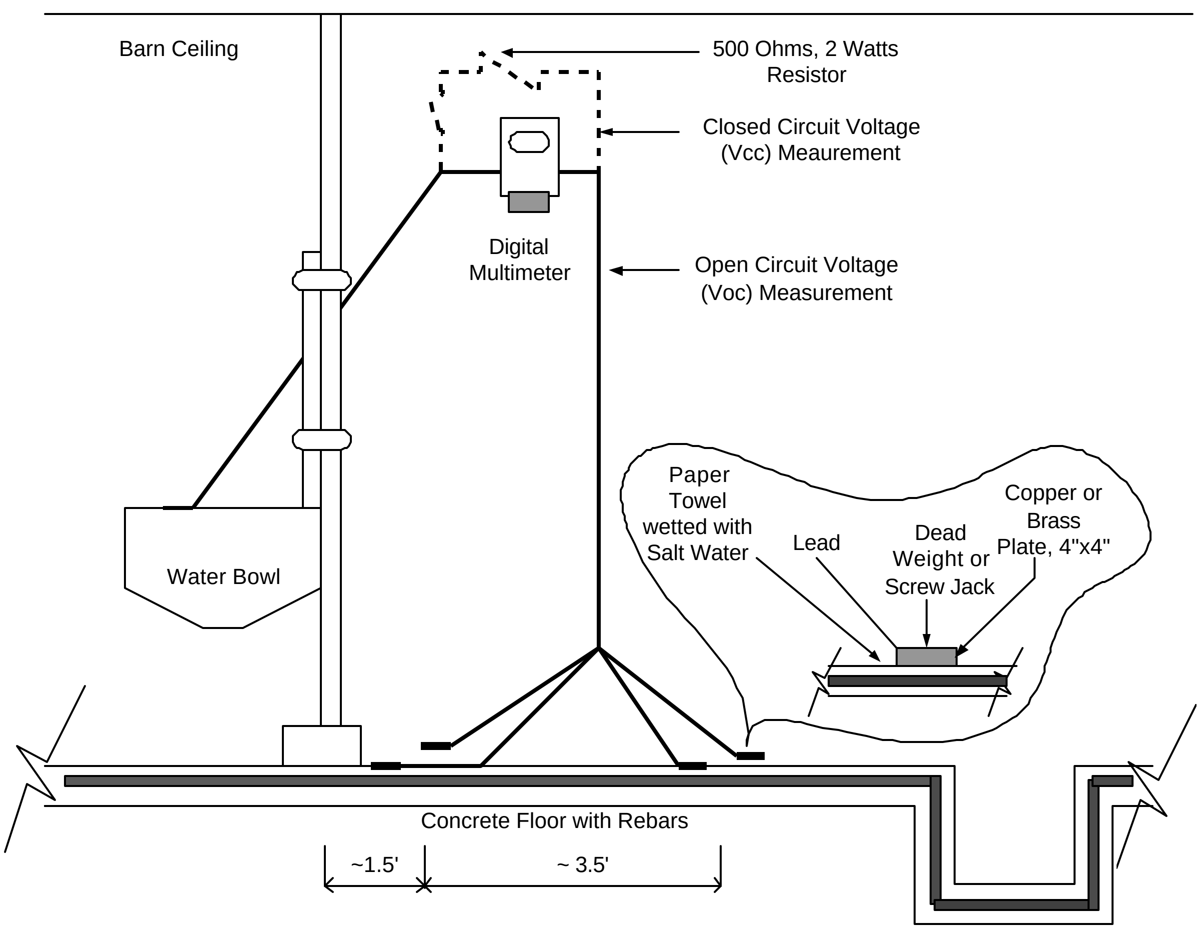


Figure 6-1 Point-to-Point Voltage Measurement in Cow Contact Area

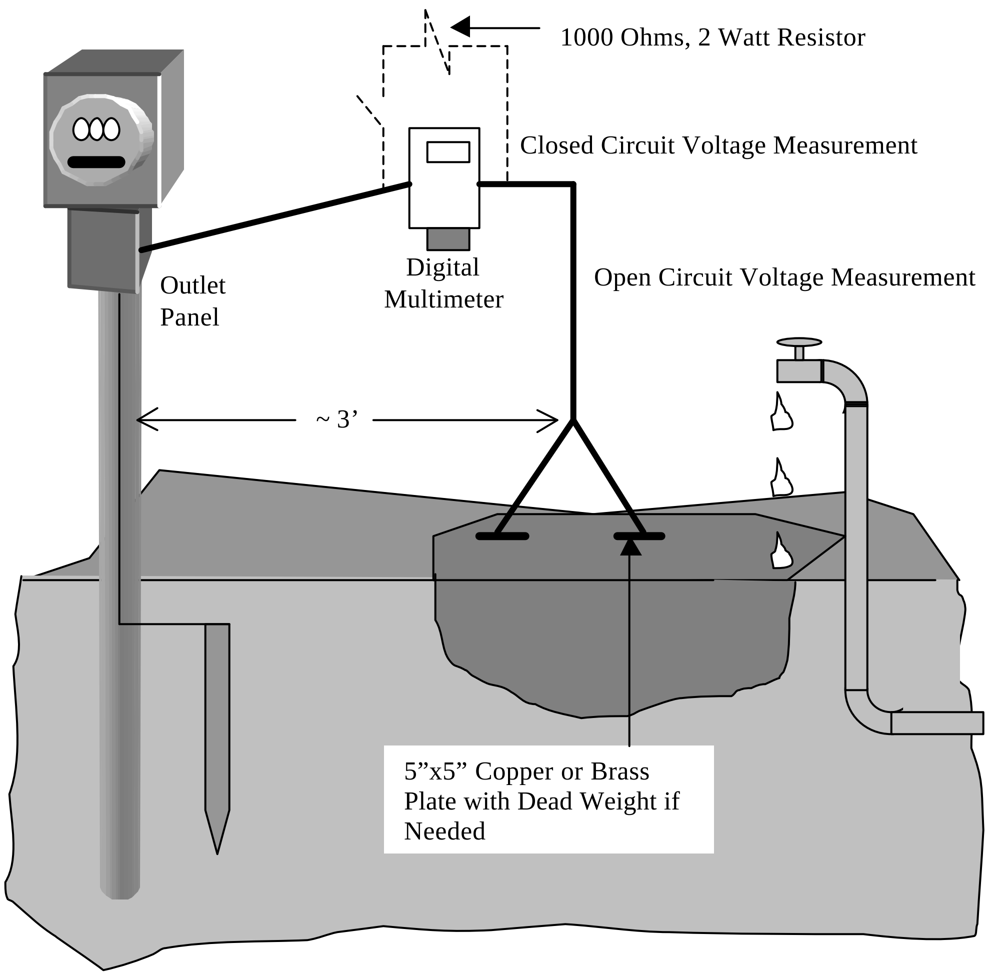


Figure 6-2 Point-to-Point Voltage Measurement in Human Contact Area (Campground)

For measuring only the open circuit voltage between the metal structure and the soil, the investigator may not require copper or brass plates as shown in Figure 6-2. Pushing a short ground rod into the soil can establish the contact point. However, for a concrete floor or for a detailed investigation requiring the measurement of V_{cc}, the plates representing the hooves or the feet as shown in Figures 6-1 and 6-2 respectively are necessary.

Good contact to the floor or soil is essential in determining the contact current, I_c, accurately. Not only good contacts but also a close representation of hooves or feet is essential for accurate measurement of shock current. The contact point at the other end such as the water bowl or the outlet panel also should not be ignored. These contact points should be scraped free of dirt and rust and the meter lead should be solidly connected, preferably with a clamping device.

The investigator should attempt to make voltage measurements under both “as found” and “worst case” conditions. There are two factors which must be considered to determine the worst stray voltage / current condition for a facility. Obviously the best time to make measurements would be when the customer load is at its peak and the neutral is carrying the maximum current. In many instances this may not be feasible because the investigation may include shutting off the load. The investigator, in such a case, may decide to make two trips to the customer’s facility. The first trip is to just measure the voltages during the peak load period and the second trip with a scheduled outage for a detailed investigation. Alternatively, as practiced often in dairy farm investigations, the investigator will make only one trip to make both types of measurements. “As found” measurements will be made first followed by the “worst case” measurements. The worst stray voltage condition for the measurements would be established using 120-volt and 240-volt load boxes.

Another factor, which must be considered for the worst-case condition, is the measurement of the highest contact current or the lowest source resistance in the contact area. If the contact point involves soil, wetting the soil may create the desired condition provided enough time is allowed for the water to penetrate. For a concrete floor, this condition may not be achieved quickly because of the time delay in water penetration. However, the animal contact areas in most dairy farms remain wet almost all of the time and special efforts may not be needed. Likewise, the human contact areas such as those at swimming pools, boat decks, and shower stalls would have similar worst case conditions. Regardless of the facility being investigated, any attempt to measure V_{cc} or I_c on a dry concrete pad or on dry and high resistivity soil would lead to a gross misinterpretation of the results as well as the customer complaint.

Once a worst case source resistance of a contact area has been determined (from Equation 4-10), its’ value can be used to estimate the animal or human contact current for future investigations at that site. For such a site, the future investigations would then include the measurements of only the open circuit contact voltages. However, if the ground electrode system is altered in the contact area following the initial measurements, the source resistance may change and the new value must be determined.

Figures 6-1 and 6-2 illustrate the methods to measure the contact voltages from mouth to feet and from hand to feet respectively. If step voltage measurements are required, the voltmeter would be connected between the copper plates representing the hooves or the feet.

Investigations involving swimming pools and boatlifts generally consist of measuring the voltages between the grounded metal structures and the water. In these investigations it is not practical to measure the closed circuit contact voltage (V_{cc}) by simulating human feet or a human body and dipping them in the water. For this reason, such investigations involve measurement of only the open circuit contact voltages (V_{oc}). Figure 6-3 shows an example of open circuit voltage measurements in a swimming pool.

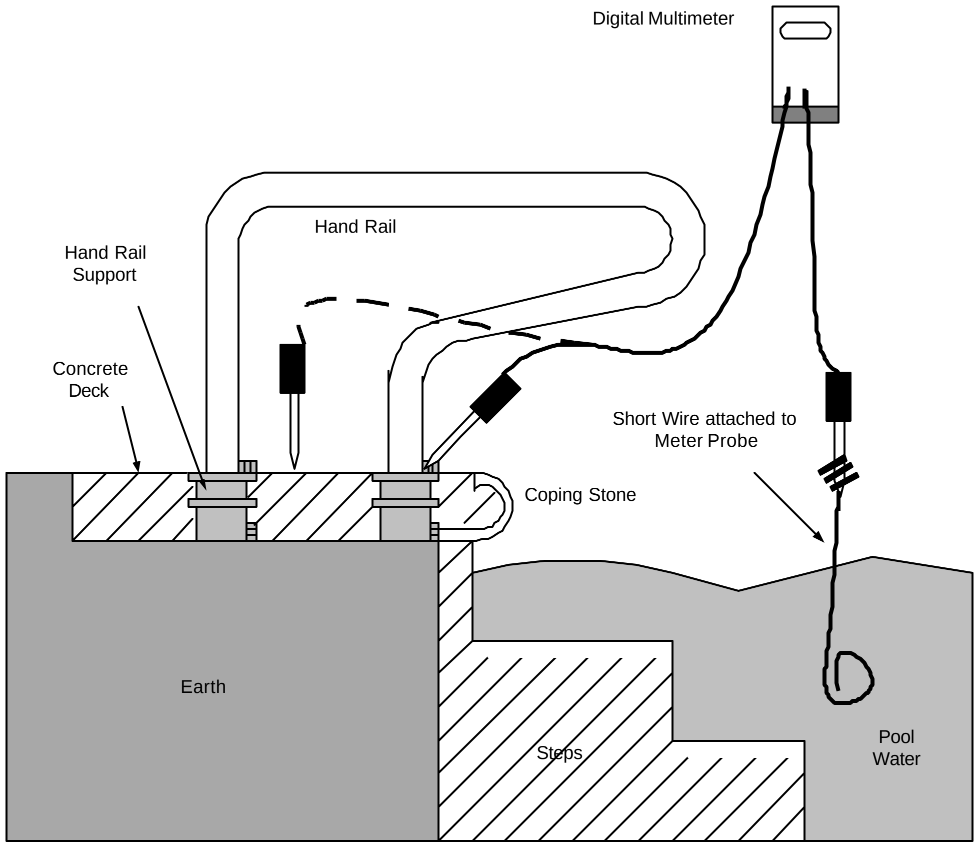


Figure 6-3 Point-to-Point Voltage Measurements in Human Contact Area (Swimming Pool)

Point-to-Reference Ground Measurement

The point-to-reference ground method basically measures N-E voltages. While point-to-point voltage measurement helps determine the severity of the problem, the point-to-reference ground measurement helps identify the stray voltage sources. If correctly measured, the point-to-reference ground voltages are of higher magnitude compared to those measured between the contact points (point-to-point method). The difference is inversely proportional to the distance between the contacted points and the nearest grounding electrode. For example, the faucet located 30 feet from a ground rod would measure approximately the same voltage as the N-E voltage of the ground rod. If the faucet were located near the ground rod, for example at a distance of three feet, the contact voltage would be a fraction of the ground rod N-E voltage.

A high impedance multimeter is connected between the intended point on the neutral or on the grounding electrode system connected to the neutral, or the contact point under investigation and a remote reference ground rod. The reference ground typically consists of a short ground rod (2’ to 4’ long) driven into the soil. Its location with respect to the facility’s grounding electrode system such as ground rods at the service panels is very critical to the measurement accuracy. As a general rule, the reference ground should be located at least at a distance of three times the depth of the buried grounding electrode system. The reference ground should also be located away from any buried power line, gas line, or metallic water line. For example, to measure the N-E voltage of a 10' ground rod connected to the service neutral bus, the reference ground should be placed at least at a distance of 30 feet from the ground rod. For a grounded well, field experience has shown that a distance of 150 feet is usually satisfactory. When the grounding electrode system is an equipotential plane, the reference ground rod should be located at a distance approximately four times the diagonal of the equipotential plane.

For accuracy, it is important that the same remote reference ground rod is used for all N-E voltage measurements. Referencing only one ground rod for all measurements eliminates the error caused by the N-E voltage, which may exist on the reference ground. In a large facility such as a dairy farm, this may require longer leads to reach distant points. Figure 6-4 illustrates typical point-to-reference ground voltage measurements in a dairy farm.

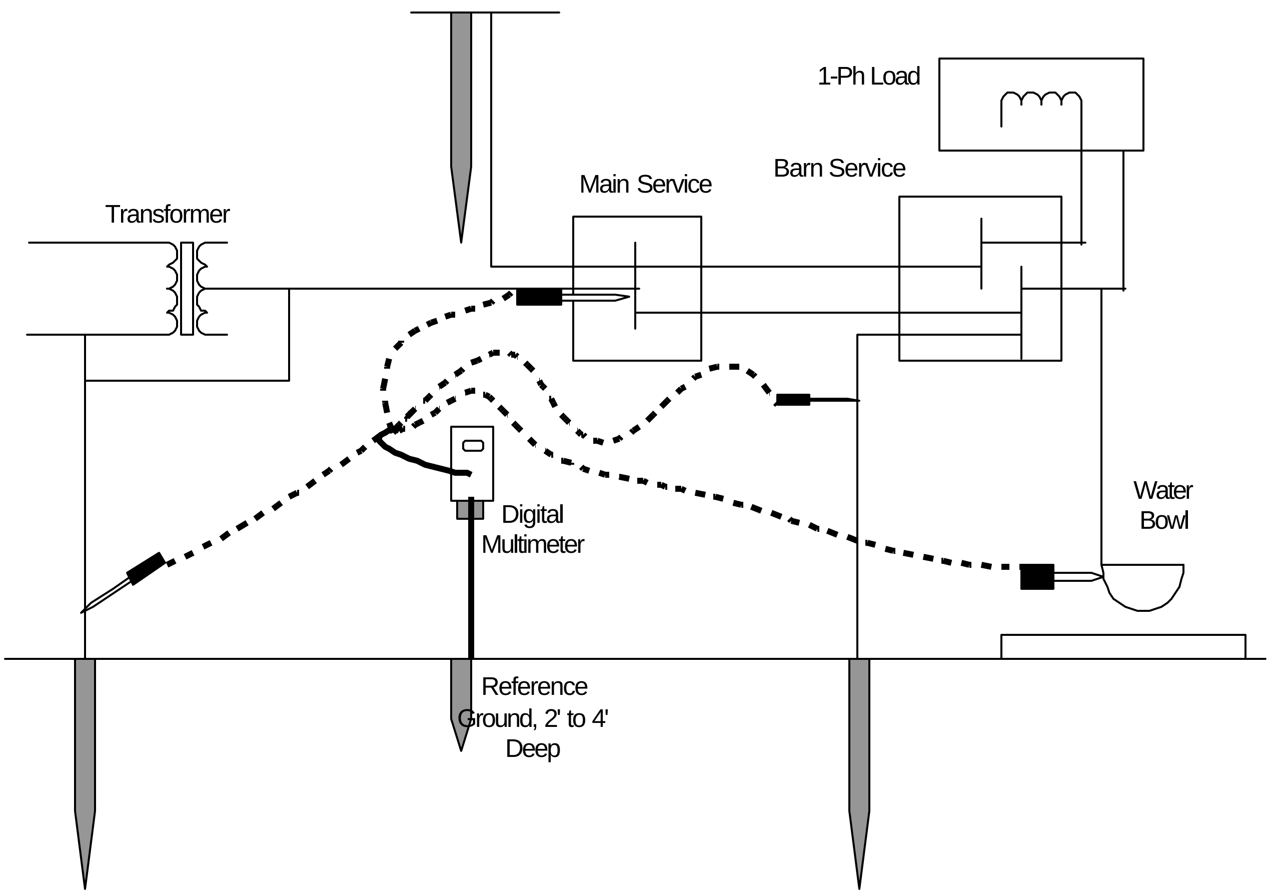


Figure 6-4 Point-to-Reference Ground Measurements in a Dairy Farm

While investigating the N-E voltages on the primary side, it is not practical to use a common reference ground for distant pole grounds or padmount transformer grounds. For this type of investigation, different reference grounds are often used. Using different reference grounds should be acceptable provided the constraint of keeping the reference ground away from the subject ground electrode(s) and other buried metallic structures, as stated above, is adhered to.

Sometimes, the investigation requires measuring the voltage differential across a secondary neutral span. For example, the investigation in the dairy farm of Figure 6-4 requires determining the voltage differential (drop) between the transformer ground and the ground bus in the main service panel. There are two ways to determine this voltage differential. One way is to calculate the difference in the N-E voltages measured at the transformer ground and that measured at the main service panel (see Figure 6-4). The more direct way is to measure the voltage between the two grounds.

Current Measurements

In stray voltage investigations, it may be necessary to make several current measurements. These measurements may include the stray current or contact current (I_c), load current, neutral current (I_n), and grounding electrode current (I_g). Sometimes, in the course of investigation, a low current fault might turn out to be a source of stray voltage. The current measurement in the equipment grounding circuit will be necessary in such a case.

Among the current measurements, the stray current (I_c) magnitudes are typically in the low milliampere range and are difficult to measure with a clamp-on meter or even with the meter inserted into the circuit. As a result, this current is usually determined by measuring the closed circuit voltage (V_{cc}) across the resistor representing an animal or a human. User should refer to the previous section for the details of this measurement.

Another current which is typically too small to accurately measure using a clamp-on current meter is the current flowing in a grounding electrode system, such as a pole ground (I_g). One way to estimate this current is to measure the resistance of the ground electrode alone in addition to measuring its N-E voltage (using point-to-reference ground method). A ratio of the N-E voltage to the resistance will yield an estimate of ground electrode current, I_g. The stand alone grounding electrode resistance can be conveniently measured using a clamp-on resistance meter (see Figure 6-8).

The load current and the neutral current are typically measured using clamp-on meters with a normal range of 100 A. The clamp-on digital meters in this range are not only accurate but also safe to use on energized circuits. It is a common practice to attach a clamp-on meter to the end of a hook-stick to measure the load and neutral currents on the primary side.

Figure 6-5 illustrates the various measurement methods. Although, the methods are illustrated for a dairy farm, they can be equally applied to other types of facilities or to the primary side of the distribution system.

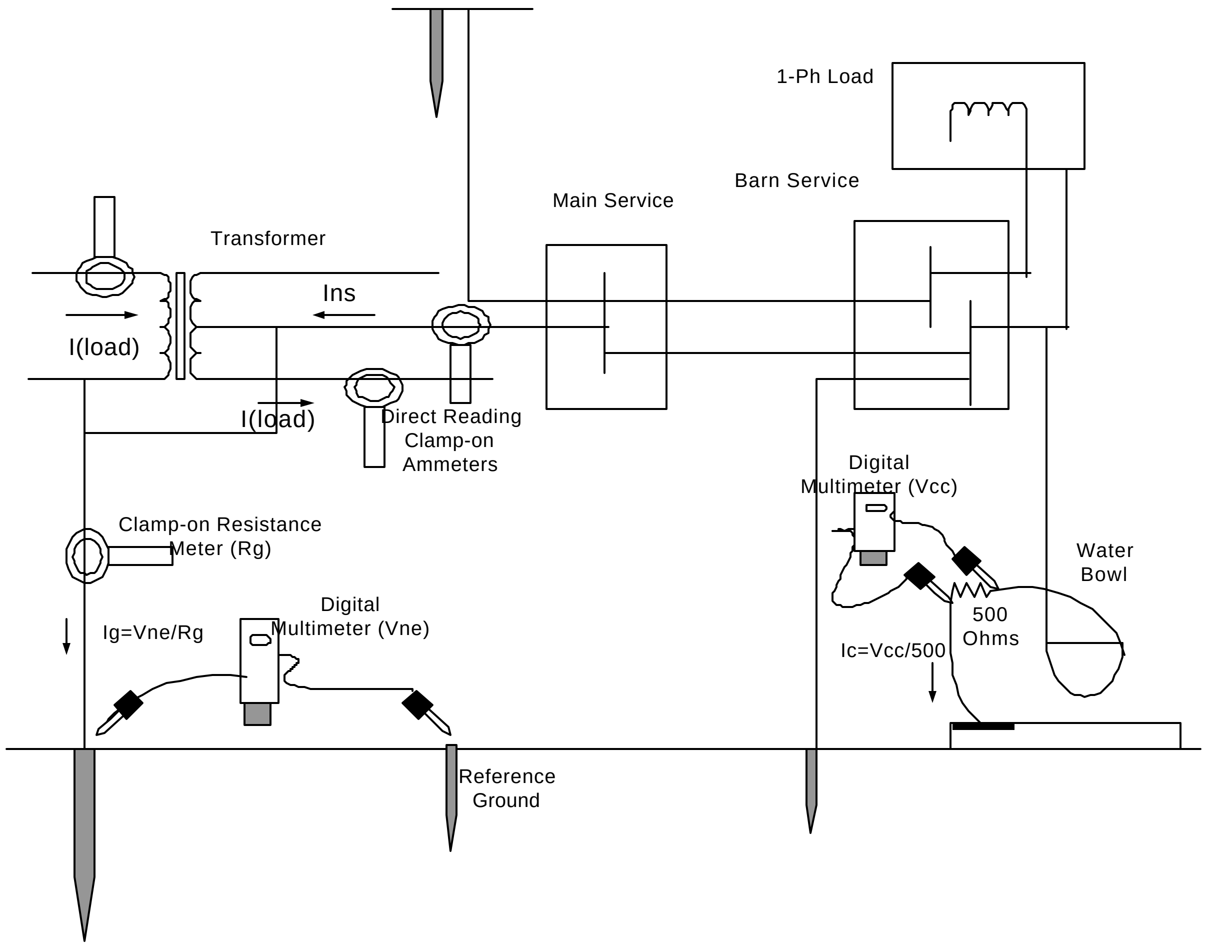


Figure 6-5 Various Measurements in a Dairy Farm

Resistance Measurements

As discussed in Section 4, the high resistance neutral path or ground return path might be the source of stray voltages at the customer location. It has also been shown that the corroded splice in the neutral path substantially elevates the N-E voltage on the load side of the splice. In an underground distribution system with bare concentric neutrals, it is not uncommon to find the neutrals which are opened due to corrosion. Measuring the resistance of neutral and ground return paths is a necessary task in many stray voltage investigations. Sometimes, the resistance data can add important information concerning the relative effectiveness of various return paths.

Leakage current due to a high impedance fault is often a source of stray voltages on secondary system. This type of fault can occur from insulated secondary cable (120-volt or 240-Volt) to grounded conduit or raceway or it can occur in electrical equipment such as in the element of a water heater. When N-E voltage measurements indicate the source to be a high impedance fault, an insulation test is performed to verify the source. A description of insulation test for secondary cables is also described in this section.

Measurement of Neutral / Ground Wire Resistance by Digital Multimeter

Digital volt-ohm-meters (VOM's) or digital multimeters (DMM's) are often used to measure the resistance between the two points on the neutral circuit or equipment ground circuit. Most of these instruments use dc currents and any stray dc or ac current flowing in the wire may make the measurement task difficult or cause significant error. As a rule of thumb, this resistance measurement can be made if the extraneous signal is 0.5 volts or less. Typically two measurements are obtained; one with the test leads in one position and the second with the test leads reversed. The true resistance value is then the average of the two readings.

Figure 6-6 shows testing for continuity between the meter ground and the pool pump ground in a swimming pool.

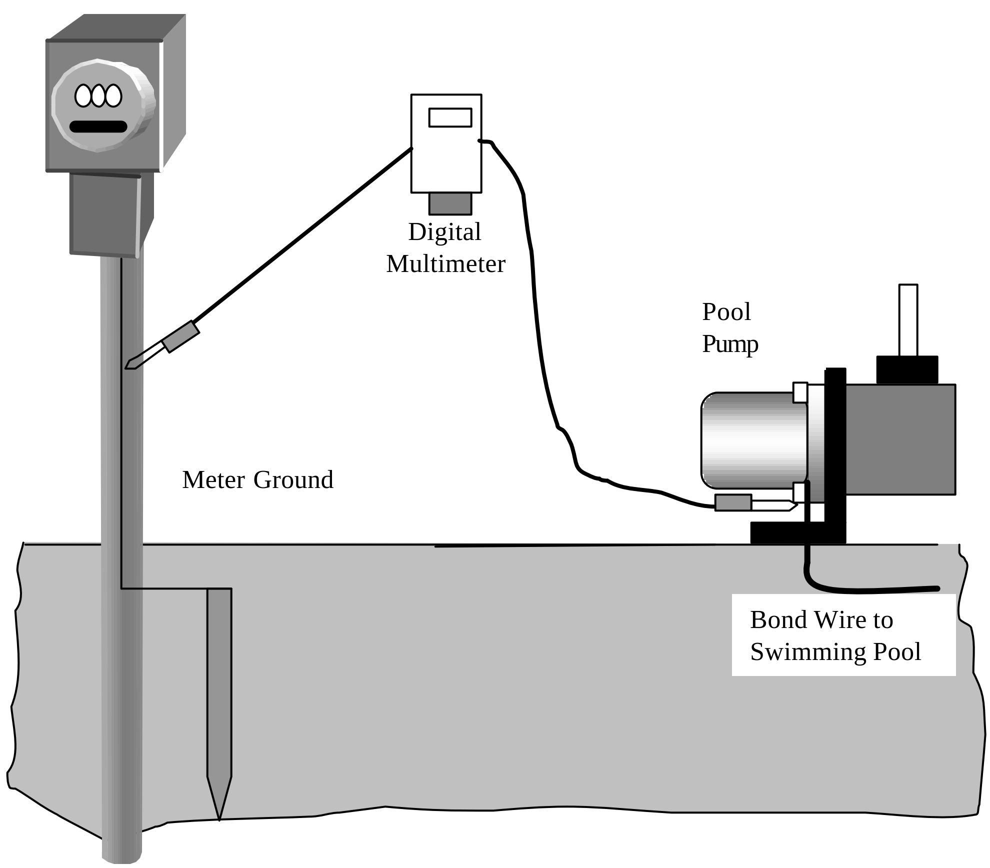


Figure 6-6 Ground Conductor Continuity Test between Meter Ground and Pump Ground in Swimming Pool

Measurement of Neutral Wire Resistance by Neutral Tester

This test method involves accurately measuring the resistance of a neutral path without isolating it from the service[64]. The condition of the neutral under test is determined by comparing the measured resistance to the resistance of a new neutral (calculated) of the same type. All of these functions are incorporated in a single device.

The schematic in Figure 6-7 shows an application of this method. In this application, a bare concentric neutral between two padmount transformers is tested. However the test method is equally applicable to overhead neutral or shield wire. The test system injects a 60 Hz current (0-30 Amperes) through the neutral system between the two padmounts. A portion of injected current returns through the neutral that is being tested and the balance returns through other parallel paths. The device measures the current flowing in the neutral under test, the voltage drop across the neutral, and the phase angle between them and calculates the resistance of the neutral using following equation.

$$R_n = \frac{V \cos\theta}{I} \qquad (6\text{-}1)$$

Where:

R_n = Resistance of the neutral
V = Voltage across the neutral
I = Current in the neutral
θ = Phase angle between V and I

The unbalanced current may be flowing in the neutral during the test. This current will add to the test current, vectorially. The clamp-on current probe with the device would measure the net current both in magnitude and in phase with respect to the voltage drop across the neutral.

The resistance of a new neutral is calculated as follows.

$$R_{ref} = \frac{R_s K_1 L}{n} \qquad (6\text{-}2)$$

Where:

R_{ref} = Resistance of a new neutral
R_s = Resistance of one neutral strand
L = Length of the cable
n = Number of strands in the neutral
K_1 = Lay factor accounting for additional length of spiral neutral strand

The resistance ratio, R_n / R_{ref}, determines the condition of the neutral being tested. Once the condition of the neutral is determined, a decision to replace the cable can be made on the basis of pre-determined replacement criteria. Although the cable replacement criteria can vary from one utility to another, it is generally based on short circuit and / or steady-state performance of corroded neutrals.

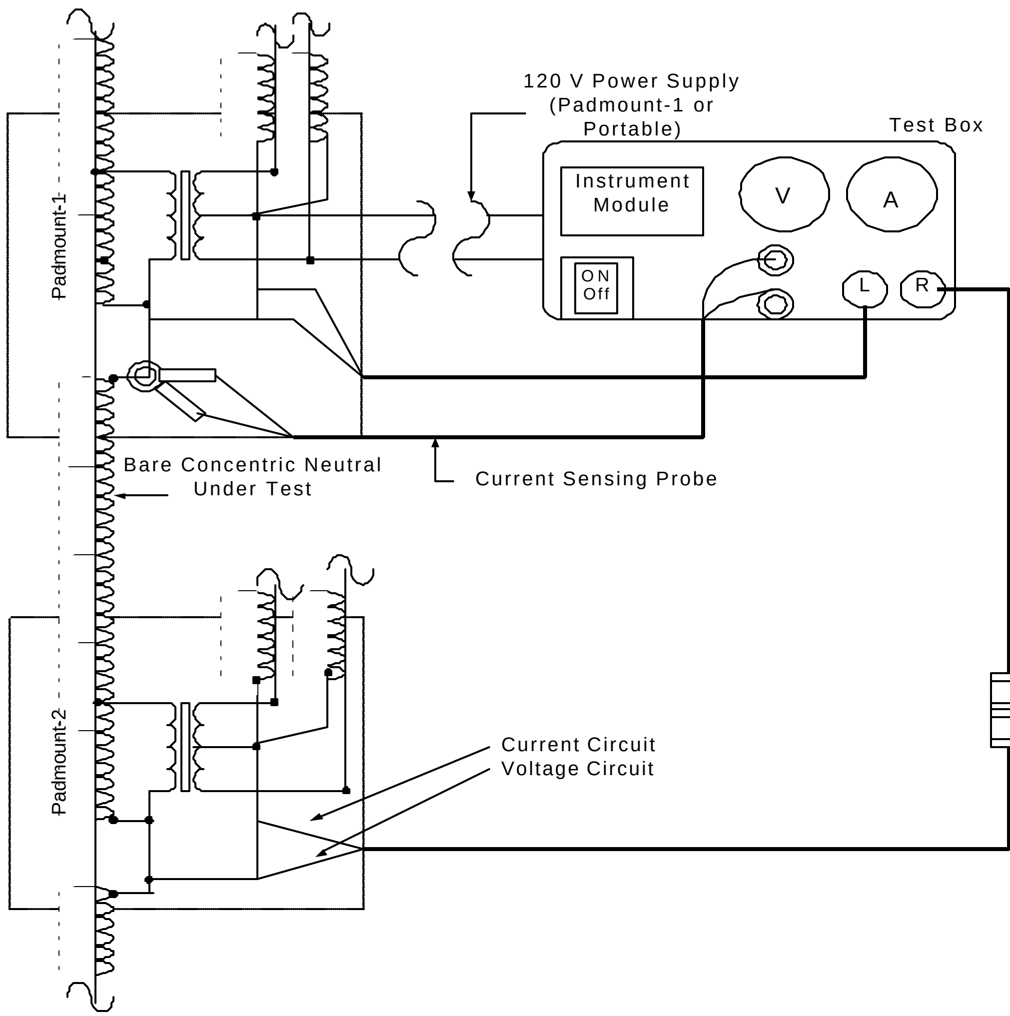


Figure 6-7 Neutral / Shield Wire Integrity Test by Resistance Method

Measurement of Grounding Electrode Resistance

Measurement by Clamp-on Meter The clamp-on meter measures the resistance of a grounding electrode by clamping on to the down lead wire, as illustrated in Figure 6-8. When turned on, it induces a high frequency voltage into the integrated ground system, including the grounding electrode under measurement. The induced voltage causes a current to flow in the multigrounded system, which is measured by the meter. The voltage-to-current ratio (impedance) is then determined and displayed in digital format by the meter. The method is based on an assumption that the impedance of the multigrounded neutral (or shield wire) system, excluding the grounding electrode under test, is so small that it can be assumed to be approximately zero. With this assumption, the indicated reading represents the resistance of the tested grounding electrode.

Although this method is the most practical and widely used method today to measure pole grounds, its theory lends itself to some application limitations, as listed below.

- The application is limited to a grounding electrode connected to a relatively low impedance multigrounded system.
- Corroded splices or connections on the neutral (or shield wire) system may influence the reading.
- The method is not applicable to a multiple connected grounding electrode system, such as a substation ground grid or multi-connected pole grounds (for example, four-legged towers).
- The high frequency noise in the system may influence the reading.

Fall of Potential Method for an Isolated Grounding Electrode System This method has been in use since the early days of the original AIEE grounding guide of 1961. The method determines the resistance of an isolated grounding electrode or the impedance of an interconnected grounding system. Its application to measure the resistance of an isolated grounding electrode system is described in this section.

The method involves passing a current between a ground electrode (G) and a current electrode (C) and measuring the voltage with the help of a voltage electrode (P), as shown in Figure 6-9. To minimize inter-electrode influences, the current electrode is generally placed at a substantial distance from the electrode under test. Typically, this distance is at least five times the largest dimension of the ground electrode under test. In the case of a pole grounded with a single ground rod, this distance should be five times the depth of the rod. The voltage electrode is typically placed in the same direction as the current electrode, but can be placed in the opposite direction. In practice, the distance "d" for a voltage electrode is often chosen to be 62 percent of the distance of the current electrode when voltage and current electrodes are in the same direction. This distance is based on the theoretically correct position to measure the exact electrode resistance for uniform soil resistivity. For a two-layer or multilayer soil, the 62% rule may yield erroneous value.

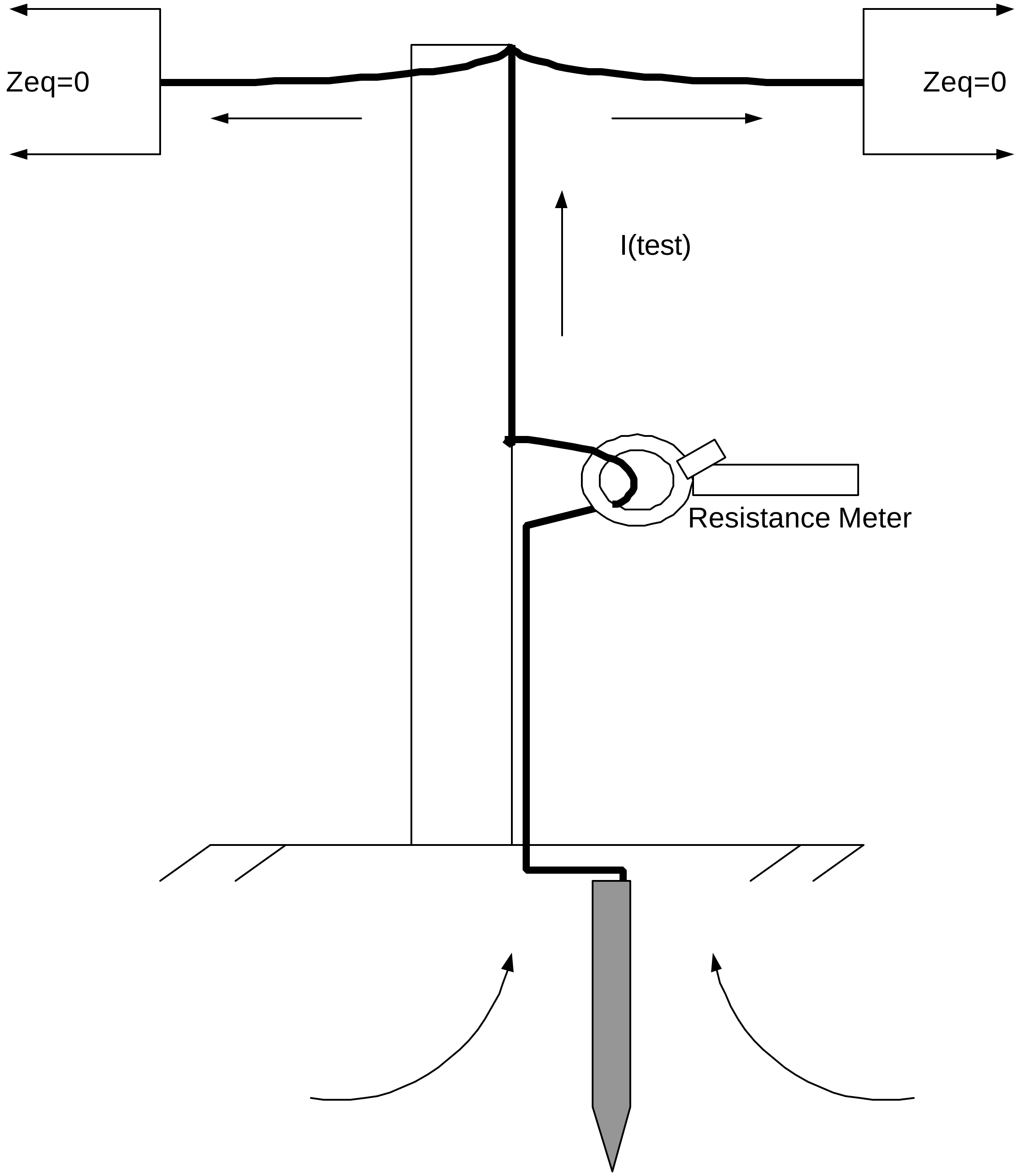


Figure 6-8 Pole Ground Resistance Measurement with Clamp-on Resistance Meter

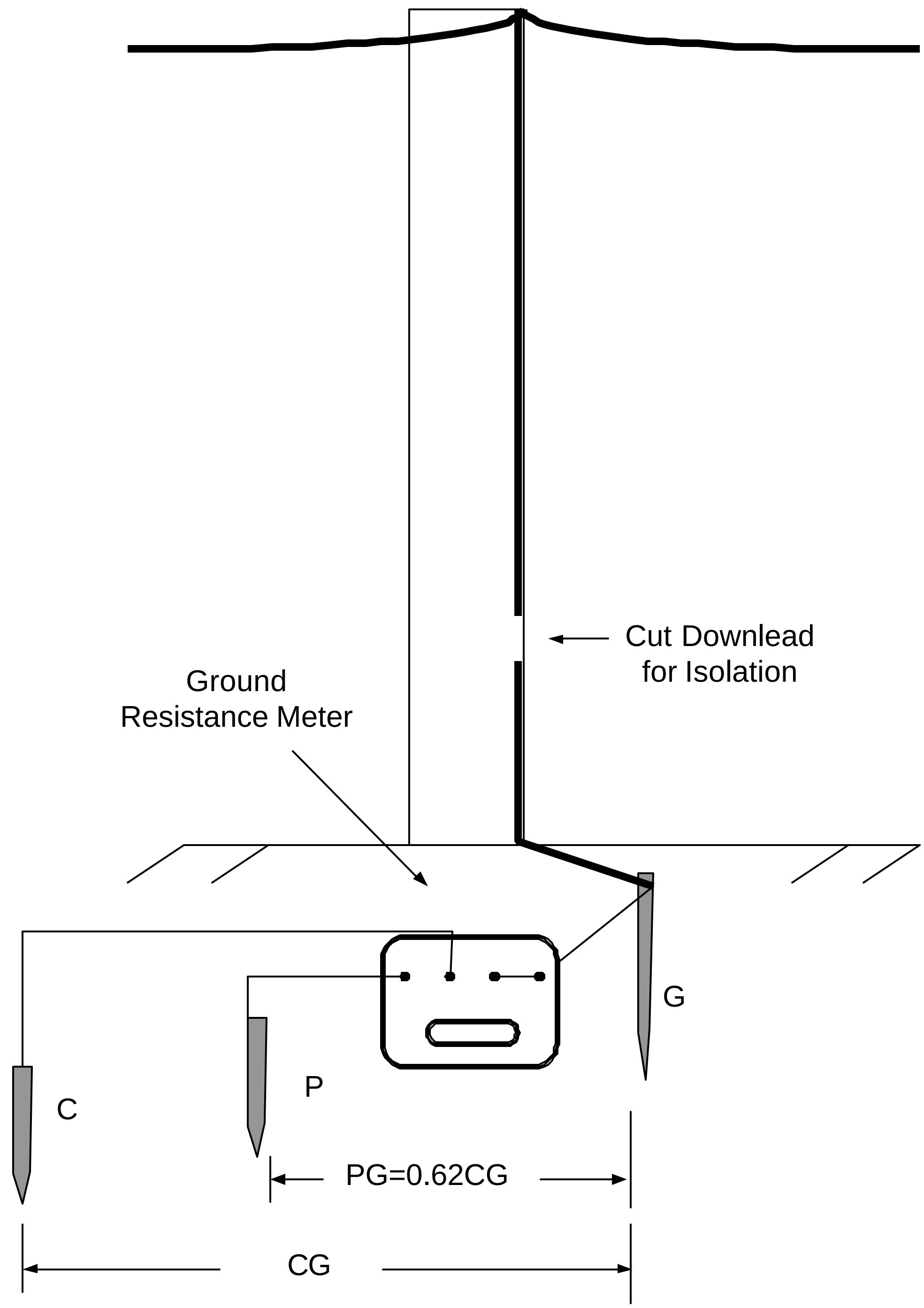


Figure 6-9 Fall-of-Potential Method to Measure Resistance of Isolated Pole Ground

Insulation Test to Detect Fault on the Secondary Side

Insulation failures or broken conductors or connections may cause a circuit conductor to contact a grounded surface. A grounded surface may include a metal conduit, a metal raceway, a bare conductor, or simply an equipment casing. The insulation failure in these circumstances would normally cause a ground fault. A low impedance fault, most likely, would produce enough current to operate the breaker. Sometimes, however, a low impedance fault will not produce enough current to operate the breaker. For example, a fault near the neutral connection in a 120-volt load or a fault in the middle of a 240-volt load may not produce sufficient current to open the breaker. These undetected faults may continue to exist on the system affecting the N-E voltages in the area. Similarly, regardless of its location, a high impedance fault would always result in a small current also known as leakage current. These high impedance faults are the sources of stray voltages in many cases.

Initial voltage measurements may identify the circuit that should be tested for insulation failure. Performing an insulation test then can verify the faulty circuit. It should be noted that the insulation test is always performed on de-energized circuits. Initially, a digital multimeter can be used to detect the fault. However, the multimeter being low voltage equipment can only identify circuits with low impedance faults or shorts. To identify a high impedance fault in a circuit, a battery powered Megger Tester is typically used. This instrument is capable of applying voltages of 0.5, 1.0, 2.5, or 5kV to determine the dc resistance of the fault. The testing generally starts at the lowest available test voltage of 500 volts. If there were a low impedance fault or a short, the tester would show the resistance being less than 100 kΩ, which is the lowest marked reading on the instrument. To detect a high impedance fault, the applied voltage is increased in steps until the voltage collapses.

Figure 6-10 shows an insulation test setup using a digital multimeter. The figure illustrates detection of a low impedance, low current fault in a water heater element supplied by 240 volts. As shown, the low impedance fault occurs near the electrical center of the heating element.

Figure 6-11 illustrates the insulation test set-up using the high voltage dc tester (Megger Tester) to detect a high impedance fault from a line wire L1 to a metal conduit.

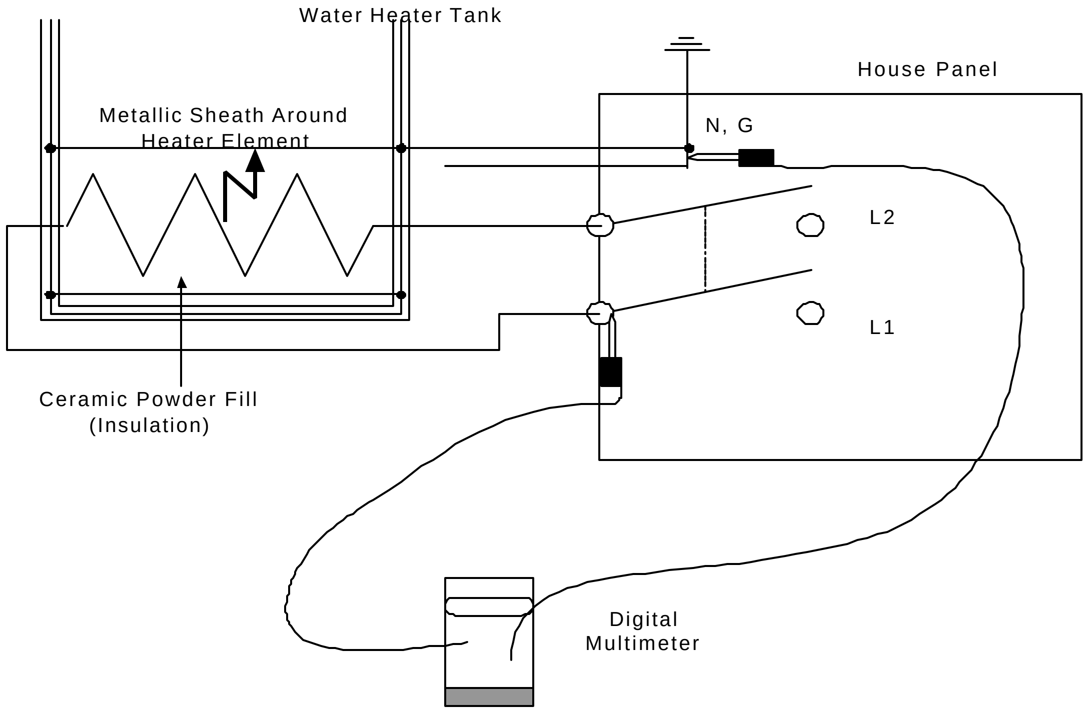


Figure 6-10 Insulation Test Using Digital Multimeter to Detect Low Impedance, Low Current Fault in a Water Heater Element

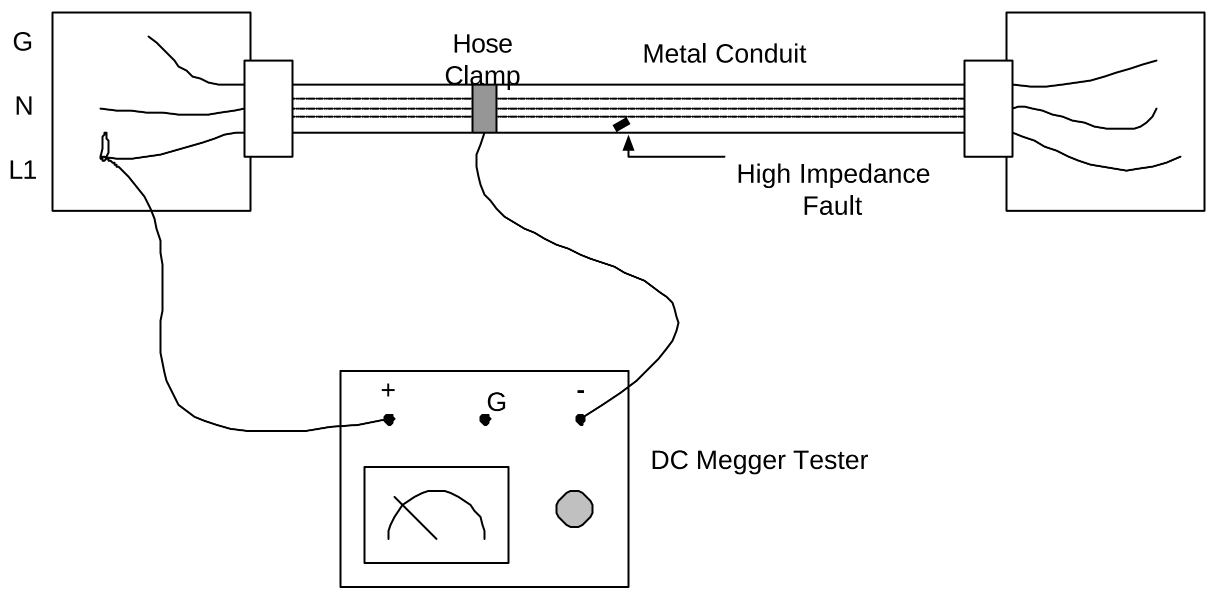


Figure 6-11 Insulation Test HV Megger Tester (DC) to Detect High Impedance, Low Current Fault in a Metal Conduit

Special Tests

Load Box Tests for Dairy Farms

As stated in Section 2 of this handbook, the Public Service Commission of Wisconsin (PSCW), in its 1989 docket 05-E1-106, proposes the load box test to determine the various stray voltage sources in dairy farms. For detailed analysis, their proposal includes several other tests such as primary profiling tests, voltage drop tests, and the signature test, which determines the impact of major equipment on the contact voltage[72]. Another researcher suggests a test procedure to determine the contributions made by off-farm and on-farm sources[16]. In this procedure, N-E voltages at selected locations are measured with and without the load boxes. The test procedure described in this section is developed from the above two references.

The test procedure uses 240-volts and 120-volts load boxes as proxy loads to methodically analyze the stray voltage contributions made by the primary and secondary neutrals. Knowing the contributions made by the primary and secondary neutrals has several advantages. The task of selecting effective mitigation means becomes easier. Also, the analysis provides the utility personnel and the customer a clear picture concerning the stray voltage magnitudes that each is responsible for.

The 240-volts load box typically consists of a non-inductive resistor element (such as used for stove elements) with either a 18 kW or 25 kW rating. These load boxes are also available with dual capacities, 9/18 kW or 12.5/25 kW. For all practical purposes, two 9/18 kW load boxes serve the testing needs well. This load box can deliver the maximum of 75 A and 37.5 A loads at 240 volts and 120 volts, respectively. Note that the 240-volts load box can be used for 120-volt applications with reduced capacities. Use of a hair dryer, however, is more common to represent a 120-volt load.

Traditionally, the load box tests are performed in dairy farms where detailed analysis of stray voltage sources is required. However, these tests can also be performed for other large facilities such as RV parks, campsites, or residential estates. Here, the test procedure is illustrated using a dairy farm for an example.

Figure 6-12 shows various measurements involved in typical load box tests.

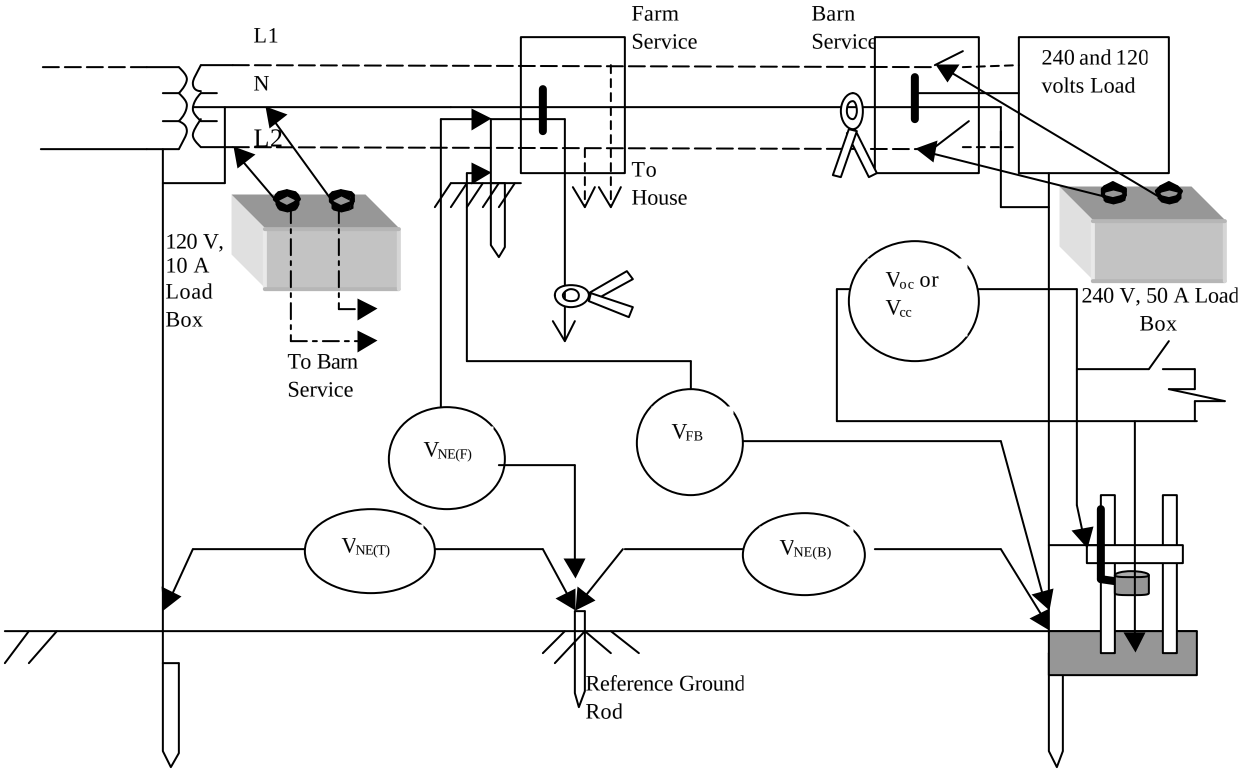


Figure 6-12 Various Measurements Involved in Load Box Tests

Detection of High Impedance Fault or High Impedance Connection Before analyzing the on-farm and off-farm stray voltage contributions, it is necessary to rule out the sources due to a high impedance fault on the secondary lines (L_1 or L_2) and high impedance connections on the secondary neutrals. If any of these two sources is detected, it may have to be addressed before proceeding with a detailed stray voltage analysis.

Existence of a high impedance fault on the secondary side can be detected by turning off all the farm loads and observing the energy meter. The meter movement would indicate a possible fault on the secondary side. In some cases, utility personnel may be required to assist the customer to identify the faulty circuit. In such a case, it would be necessary to measure the line currents (using a clamp-on probe) on individual circuits including the branches. In all probability, the circuit indicating the current would be the stray voltage contributor. After identifying the circuit, it is customary to perform an insulation test to validate the initial conclusion.

A high impedance connection in the secondary neutral can be detected using a 120-volts (10 A) load box or an equivalent portable load such as the hair dryer. With all farm loads off, the load is applied at each service panel, one at a time. Referring to Figure 6-12, for example, the 10 A load is applied at the barn service panel to check the neutral path between the barn service and farm service ground rods. The measurements include the neutral current, $I_{n(FB)}$, at the barn service panel and the voltage difference (V_{FB}) between the ground rods at the barn service and the farm service. If the load current is a fixed value and is known, its measurement may not be necessary. The ratio, $V_{FB} / I_{n(FB)}$, represents the impedance of the neutral circuit. Knowing the size and type of the conductor, the expected impedance can be determined from the wire tables provided in NEC or the cable manufacturer's catalog. The impedance value determined from the wire table should be close to that determined from the measurements if the connections and conductor are both in satisfactory condition.

Analysis of Off-farm and On-farm Sources In general, the stray voltage contribution from off-farm loads is determined first. After turning all farm loads off, the N-E voltages at selected locations are measured. Typically for a dairy farm, these locations include the transformer ground, the farm service ground, and the barn service ground (see $V_{NE(T)}$, $V_{NE(F)}$, and $V_{NE(B)}$ in Figure 6-12). For more detailed analysis, contact voltages (V_{oc} and V_{cc}) in the animal confinement area may be measured in addition to the N-E voltages. Because there is no load in the farm, these measured voltages are solely due to off-farm loads. Note that the primary to secondary neutral connection is responsible for bringing these voltages into the farm.

The stray voltage contribution due to on-farm loads consists of two parts; one part is due to the current flowing in the primary of the transformer (farm loads / turns ratio) and the other part is due to the current flowing in the secondary neutrals. The following paragraphs describe the steps which may be followed to determine these components.

To determine the stray voltage contribution due to the transformer primary, the following steps should be taken (Refer to Figure 6-12):

1) Turn all farm loads off.
2) Connect the 240-volts (50 A) load at the barn service panel (on the source side).
3) Connect the 120-volts (10A) load at the transformer secondary.
4) Measure $V_{NE(T)}$, $V_{NE(F)}$, $V_{NE(B)}$, V_{oc} and V_{cc}.
5) Subtract the voltages due to off-farm sources from 4) to determine the contribution made by the transformer primary.

To determine the stray voltage contribution due to secondary neutrals, the following steps should be taken (Refer to Figure 6-12):

6) Turn all farm loads off (same as step-1) .
7) Connect the 240-volts (50 A) load at the barn service panel (same as step-2).
8) Connect the 120-volts (10A) load at the barn service panel.
9) Measure $V_{NE(T)}$, $V_{NE(F)}$, $V_{NE(B)}$, V_{oc} and V_{cc}.
10) Subtract the voltages measured in 4) from 9) to determine the contribution made by secondary neutrals.

To determine the total stray voltage contribution due to on-farm loads, add voltages measured in 5) and in 10).

Off-farm and On-farm Source Analysis – An Example A computer model can best illustrate the off-farm and on-farm stray voltage analysis described in the previous paragraphs. For the illustration, the same dairy farm system as modeled in Section 8 (see Figures 8-1 and 8-2) was selected. With the exception of farm loads, all the parameters remained the same. The modeled farm loads, for this illustration, consisted of a 12+j0 kW load across L_1 and L_2 and a 1.2+j0 kW load between L_1 and the neutral. The first load represented the 240-volts load box and the second load simulated the 120-volts load box. Note that the selection of 50 A, 240-volts load and 10 A, 120-volts load is arbitrary. In reality, these loads would be selected based on the maximum 240-volts and 120-volts loads in the investigated farm.

The computed voltages due to off-farm sources are the same as listed in Tables 8-1, 8-2, and 8-3 of Section 8. For comparison purpose, some of the data are repeated in Table 6-1 and Table 6-2. Table 6-1 shows the contributions made by various sources to the farm N-E voltages. Table 6-2 shows the contributions made by various sources to the contact voltage and current in the animal confinement area.

Table 6-1 Contributions Made by Various Sources to the Farm N-E Voltages

Ground Location	N-E Voltages, Volts			
	Contribution due to Off-farm Loads	Contribution due to On-farm Loads		Total of all Contributions
		Contribution due to Transformer Primary	Contribution due to Secondary Neutrals	
BUS6 (TFM)	3.64	1.70	-0.02	5.32
FARM SERVICE	3.63	1.71	0.1	5.44
BARN SERVICE	3.63	1.71	0.3	5.64

Table 6-2 Contributions Made by Various Sources to the Contact Voltages and Contact Current in the Animal Confinement Area

Contact Voltages and Contact Current	Contribution due to Off-farm Loads	Contribution due to On-farm Loads		Total of all Contributions
		Contribution due to Transformer Primary	Contribution due to Secondary Neutrals	
OPEN CIRCUIT CONTACT VOLTAGE (V_{oc})	3.4 Volts	1.6 Volts	0.3 Volts	5.3 Volts
CLOSED CIRCUIT CONTACT VOLTAGE (V_{cc})	1.32 Volts	0.62 Volts	0.11 Volts	2.05 Volts
CONTACT CURRENT	2.64 mA	1.236 mA	0.218 mA	4.1 mA

Knowing contributions from various sources as shown in Tables 6-1 and 6-2 has several advantages. In the example, the off-farm loads contributed 3.63 volts towards the 5.64 volts total N-E voltage at the barn. The on-farm loads contributed the rest (see Table 6-1). Similarly, the data contained in Table 6-2 provide the contribution analysis for the contact voltages and the contact current. The data presented in Tables 6-1 and 6-2 also helps in determining the effectiveness of certain mitigation means. For example, if a neutral isolator were provided (at the transformer) in the dairy farm, the N-E voltage at the barn would reduce to 0.3 volts (see Table 6-1) and the contact current would reduce to 0.218 mA (see Table 6-2).

Long Duration Tests

Conventional analog meters / recorders which respond too slowly, or digital multimeters which are unlikely to sample at the precise peak of interest, seldom, if ever, detect the true magnitudes of voltages which occur when motors are started. Also, the peak load and resulting N-E voltages may not exist when the measurements with the indicating meters are performed. To understand the true nature of stray voltage problem including its severity, long duration measurements with recorders are essential. Measuring N-E and contact voltages continuously for 24 to 48 hours provides an assurance that the highest levels of these voltages and their duration are captured. In fact, for this reason, Public Service Commission of Wisconsin requires electric utilities to test for a minimum period of 24 hours covering at least two milking periods.

For long duration measurements, it is necessary to use a computer based Data Acquisition System (DAS). A description of an example system[23] is provided here. The intent is to familiarize the users with the basic components and characteristics associated with the system and not to promote the product. The system described here was developed prior to 1987 and, as a result, might be construed as an old technology. More efficient and sophisticated DAS's may be available in the market presently.

The DAS consists of the following components:

- An IBM compatible portable or laptop computer.
- An analog to digital signal converter card.
- A clock/calendar card.
- An IBM compatible printer with graphic capability.
- A data processor (Wave Rider).

The system has following capabilities:

- Eight independent input channels for monitoring time-varying analog signals at power frequencies and their harmonics.
- Sequential sampling of the enabled channels (maximum eight channels).
- Sampling rate of 14,285 samples/second/channel.
- Visual display of sampled data in real time.

- Storage on magnetic disk for subsequent processing of peak voltage-versus-time data for every 1/60-second interval.
- Unattended and extended duration data acquisition.
- Visual display of stored peak voltages-versus-time plots with controllable time scale (0.02 seconds resolution).
- Printed copy of displayed data.

Typically, the measurements acquired by a DAS include:

- N-E voltage at the transformer ($V_{NE\ (P)}$).
- N-E voltage at the barn service panel ($V_{NE\ (S)}$).
- Voltage difference across the secondary neutral, from the transformer to the barn service panel (V_{TB}).
- Animal closed circuit contact voltage (V_{cc}).

Measurements of Short Duration Voltages

Normally occurring electrical events in a dairy farm or in a residential house have been classified in three categories[4]. Transients are events which last for less than 1/60th of a second (less than one 60 Hz cycle). The transient can also be a "non-repetitive" voltage or current of a short duration (less than one-half cycle), and possibly of larger magnitude than that of the steady-state supply voltage or current. Momentary events are typically from 1/60th of a second to one second in duration. Steady-state events are events, which are constant for more than one second duration. These definitions allow the classification of most events in a dairy farm or in a residential house. For example, to start a motor in a dairy farm, the switch or the contactor must close and in the process may arc. The arcing switch would produce the transients. Once the switch closes firmly, a continuous current is delivered to the motor. Generally, more current (4 to 5 times the normal load) is required to start the motor. The motor starting current may last for a few cycles. This event is then classified as a momentary event. Finally, the event with the motor running at its operating speed and drawing a normal current can be classified as a steady-state event. Depending on the application, the motor may operate for a few hours two or three times a day.

The electrical measurements of transient and momentary events are sometimes performed to determine the impact of starting and stopping of individual pieces of major current drawing electrical equipment on customer's electrical system. In dairy farm investigations, this test is known as a signature test [72]. A minimum of two persons are generally involved in this test; one person records the waveforms and the other person operates the loading device such as the vacuum pump or milk pump. The person controlling the loading device must have a watch or a timing device to synchronize the "on" and "off" timings with the recorder. A digital recorder is typically used during this test with the sample interval set to one second. Like long duration measurements, the recorder is set to measure a minimum of four data points: voltages from transformer neutral to reference ground ($V_{NE\ (P)}$), neutral to reference ground voltages at the barn ($V_{NE\ (S)}$), transformer neutral to barn neutral voltage drops (V_{TB}), and the closed circuit contact voltages (V_{cc}). For each piece of electrical equipment for which a signature is desired, the type and location are noted along with the start and stop times, usually separated by 15 or 20 seconds. If a piece of equipment is found in running condition, a stop and then restart is performed.

The signature test can be extended to determine the actual load profiling of momentary events during a typical day in a dairy farm. For example, the impact of “on” and “off” operations of feeding, milking and environmental equipment during a 24 hours period can be determined by automatically capturing the events on portable oscilloscopes[4]. The number of scopes required would depend on the number of voltages measured and the number of channels available on each scope. One channel in each scope is selected for triggering. Typically, the current measured off of the line triggers each scope synchronizing the voltage measurements. The waveforms stored on the scopes are downloaded to the PC through a serial link. The software then resets the scopes so that it is ready to collect the next triggered event.

Primary Profiling

The “primary profile” test may be performed either during a morning milking or evening milking or when the electrical activity on the primary distribution system is likely to be at maximum. Human related stray voltage investigations mostly involve primary profiling. These may include stray voltage investigations in residential subdivisions, RV parks or campground facilities.

This test involves measuring load currents, neutral currents and pole ground N-E voltages of the primary distribution system. While these measurements for the overhead system are performed at taps, transformer poles, and poles with capacitors and switches, padmount transformers typically are the target locations in the case of an underground system. For an inline dairy farm, approximately 3/4 mile of the distribution system on each side of the farm may be included in primary profiling. For a dairy farm located on a single-phase tap, the line length on each side of the tap may be reduced but the tap would be included in the measurements.

In “primary profiling” tests, the clamp-on probe typically measures the load and neutral currents. On the other hand, there are two alternate methods which may be used to measure the N-E voltages. Usually, the pole-ground N-E voltages are directly measured by connecting a digital multimeter between the pole ground and a reference ground (see Figure 6-4). Note that the reference ground locations, most likely, would be different for different pole grounds in this type of testing. An alternate method of determining the N-E voltages consists of measuring the current in the downlead using a clamp-on current probe and measuring the ground electrode resistance using the clamp-on resistance meter (see Figure 6-8). In accordance with Ohm’s law, the product $I_g x R_g$ yields the N-E voltage.

An actual primary profiling performed in a residential investigation is presented in Figure 6-13. The investigated residential area had been experiencing a high stray voltage problem during the winter season due to heat pump and strip heater loads. Also, due to expected load growth in the area, there was a concern that the stray voltage problem would become worse.

The first step in the investigation was to conduct the "primary profile" test from the substation to the end of the tap. The load and neutral currents were measured with the clamp-on meter. Each N-E voltage was measured directly between the pole ground and a reference ground in the proximity of the pole. Although, computed data are not a part of the test, they are shown in the figure for the purpose of validating the computer program used in this handbook.

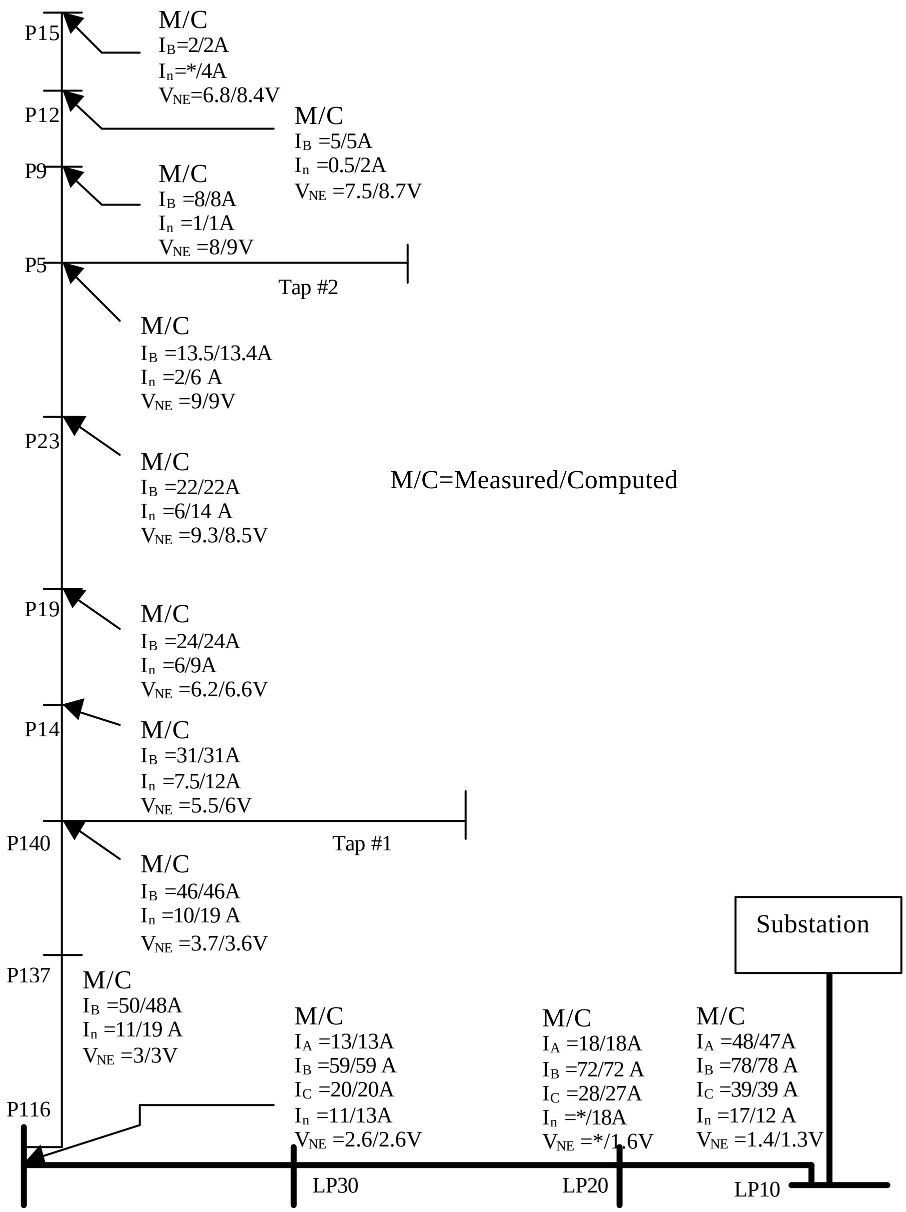


Figure 6-13 Primary Profiling of a Residential Area with a Stray Voltage Problem

Instruments

Several types of measurements as described in previous sections may be necessary to identify the presence of stray voltages and their sources. Measuring instruments may include an indicating portable voltmeter, clamp-on ammeter, recording voltmeter or ammeter, oscilloscope, ground resistance tester, and insulation tester. Some commonly used instruments and their applications are discussed in this section.

When making measurements, instrument characteristics and monitoring points are significant considerations. The instrument used should be able to separate ac and dc current or voltage. Harmonics of 60 Hz are present at many stray voltage locations. For accuracy, true rms reading meters would be required for these locations. To be able to read small voltages accurately, the instruments should have a minimum resolution of 0.1 volt (100 mV). If the instrument is to be operated over extended periods, it must be able to withstand the harsh physical environment of customer's facility or protection must be provided. The instrument for this application must also be protected from electrical extremes, such as faults or lightning.

Voltage Measuring Instruments

One of the most common variables measured in stray voltage investigations is voltage. Usually, voltage is measured with an analog volt-ohm meter (VOM), a digital multimeter (DMM), a recorder, or an oscilloscope. For use in stray voltage investigations, a voltmeter should meet three basic requirements: 1) it should be able to separate ac and dc voltages, 2) it should have minimum voltage resolution of 0.1 volts, and 3) it should have an impedance of at least 5,000 Ω/V.

If the meter reads on the ac scale when connected to a flashlight battery, it does not separate ac and dc. A capacitor of at least 5 μF with a voltage rating of 50 volts (use 200 volts capacitor if measuring across 120 volts circuit) may be placed in series with one of the leads to block the dc voltage. A meter with an input impedance of less than 5,000 Ω/V may unduly load the circuit with a significant voltage drop across the source impedance. Such instruments would read the open circuit voltages (V_{NE} or V_{oc}) lower than the actual values. If accurate open circuit voltage measurements are desired, the measured voltages should be corrected using Equation 6-1. To be able to apply Equation 6-1, the open circuit voltage (V_{NE} or V_{oc}) is measured first. The closed circuit voltage (V_{cc}) is read next by connecting a known resistance (500 Ω or 1000 Ω) across the meter.

$$V_{oc(t)} = \left[\frac{R_b (V_{oc} - V_{cc})}{Z_m V_{cc} - V_{oc} R_b} + 1 \right] V_{oc} \qquad (6\text{-}1)$$

Where:
$V_{oc(t)}$= Corrected open circuit voltage, volts
V_{oc} = Measured open circuit voltage (no resistor across the meter), volts
V_{cc} = Measured closed circuit voltage (with 500 Ω or 1000 Ω resistor across the meter), volts

R_b = 500 Ω or 1000 Ω resistor across the meter
Z_m = Meter impedance (>>R_b), Ω

Analog Meters It is important to use an analog meter with a voltage scale sensitive enough to measure in the millivolts range. A typical analog meter would have 0-2.5 volts minimum scale. The internal resistance of such instrument would also be 5000 Ω/V range on the ac scale. With multiscale instruments some scales are non-linear. Accurate readings are difficult to make and it is easy to make an error by reading the wrong scale.

One of the advantages of analog meters is the ability to respond to momentary events such as motor starting overvoltages. For this reason, some stray voltage investigators prefer the needle "kick" response of an analog meter. An oscilloscope, however, is the best instrument for capturing short duration waveforms.

Digital Meters A majority of the digital multimeters meet the three basic requirements listed in the previous paragraphs. They may have either light-emitting-diode (LED) displays or liquid crystal displays (LCD). LCD's are much easier to read than LED displays except in dark areas. Most digital meters have an input impedance of 10 MΩ or greater. Also, most digital meters can read either ac or dc quantities. However, most commonly used DMM's are average reading meters and may not be suitable for measuring the voltages containing the power frequency harmonics. The Fluke 87 is an example of a true rms reading meter suitable for these measurements. A main advantage of a digital multimeter is that it provides good resolution at low voltages. Many are small and lightweight and can be read quickly and accurately.

There are some problems that are associated with high impedance digital voltmeters. Because of the high input impedance, these meters can easily measure the capacitively coupled or leakage voltages associated with high source impedances. Most of these voltages are not the stray voltage of concern and will have to be distinguished from the stray voltage resulting from a low resistance source. One way to detect the low resistance source is to obtain the reading by shunting the meter with a 1000 Ω to 10000 Ω resistor. If the latter voltage changes substantially from the open circuit voltage, a low resistance source should be concluded and vise a versa.

Another disadvantage of some digital voltmeters is their sampling rates. Typically, the instrument samples the input voltage over a short interval and displays the rms value. If the input voltage waveform is changing in value, the digital meter may not respond quickly to accurately register the change or may display continuously changing readings.

Recording Meters A recording voltmeter should have the same characteristics as an indicating meter discussed above. Because this type of meter is generally used for long duration measurements including capturing the momentary events, the fast response time for transients is required. In addition, it is desirable that a recording meter be able to record multiple voltages simultaneously.

Multiple-channel recorders are available in both analog and digital types. The analog recorders have a specific voltage range while the digital recorders are auto ranging. Recording voltmeters can gather voltage information for several days or weeks. This capability is especially important when problem voltages are suspected but are not found at the time of voltage measurements with indicating meters, as some problems occur infrequently. Recording voltmeters can also be used to record test results as specific loads are operated (as in equipment signature test).

Oscilloscopes A portable oscilloscope can be used to display actual waveforms including fast rising peaks. The oscilloscope allows the simultaneous measurement of both ac and dc components of a waveform. It will reveal whether a dc source is pure dc or has been rectified from ac. It will indicate whether an ac source is only 60 HZ or has other harmonic frequency components. Sometimes, such information can provide valuable clues as to where to look for the sources. The multichannel oscilloscope can also measure the phase between the current and the voltage that results from the current.

The oscilloscope should be battery operated such that it can be operated in differential mode (two inputs balanced to ground). Most line voltage operated oscilloscopes have one terminal connected to the equipment grounding conductor; thus this terminal is normally at the neutral-to-earth voltage. This connection makes it difficult to properly measure the voltage between two animal contact points.

Current Measuring Instruments

In stray voltage investigations, it may be necessary to make several current measurements. These measurements commonly include the current in circuits involving animal or human contact points, load current, and fault or leakage currents. The current in motors, lights, or other equipment can be measured to determine whether the equipment is operating properly. The current in the equipment grounding conductor can be measured to check for fault or leakage currents. To help diagnose neutral voltage drop, measuring the neutral current during periods of peak power usage is useful. Neutral current measurements also aid in determining whether or not the electric loads are balanced or where and when imbalance occurs.

For many current measurements, clamp-on-type ammeters or recording ammeters are used. Some types of ammeters require opening of the circuit to connect the ammeter in series with the circuit or to install a current transformer. In stray voltage measurements, these types of ammeters are never used.

There are many types of clamp-on ammeters that are available in the market. Some digital clamp-on ammeters or DMM accessory clamp-on probes have auto ranging from 1 to 999 A and are easily and accurately read. They may also have a locking function to measure peak amperes from rapidly changing loads such as motor starting current. Clamp-on ammeters are generally not accurate at levels below 1 A.

Detection of currents less than 1 A in grounding conductors can be of significant value in locating sources of stray voltage. Special AC clamp-on ammeters are available, which have ranges from 1 mA to 20 A full scale. These ammeters can be used for quick measurements of low currents. However, the most practical method to measure the low current value such as the contact current (I_c) value is to measure the voltage drop across a known resistor as described in previous sections.

SECTION 7

MITIGATION METHODS

N-E voltages associated with distribution systems arise from various sources as described in Section 4. These sources can be separated into following categories:

1. Primary neutral current due to primary loads
2. Primary neutral current due to customer loads
3. Secondary neutral current due to customer load
4. High resistance connection (due to corrosion) in neutral path
5. High impedance secondary line to ground fault
6. Low voltage fault inside customer equipment
7. Neutral current on equipment grounding conductor due to improper interconnection
8. Induced voltage / current

Both the elimination of existing stray voltage problems and the prevention of future problems require careful consideration of sources, human or animal sensitivity thresholds, and characteristics of the mitigation methods or devices. With a clear understanding of these factors, one or more of the mitigation methods described in this section can be applied to the problem.

A basic approach to stray voltage mitigation is to reduce N-E voltages in contact areas. Because stray voltages in contact areas are proportional to N-E voltages of nearby grounding electrodes, reducing these voltages reduce the stray voltages. Extending the grounding system to the contact area or installing an extensive grounding system in and around the contact area is another effective approach to stray voltage mitigation. With this approach, the N-E voltage is reduced somewhat but the reductions in stray voltages are substantial. For this mitigation method to be economical, the contact areas need to be well defined and limited in size. Installing an equipotential plane in a dairy farm is a good example of this type of mitigation method.

Reduction in N-E voltage around contact areas can be effected by either modifying the source or by active voltage suppression on the secondary neutral / ground system. Source modifications may include removing bad neutral connections, faulty loads, or low current ground faults. Reducing impedance of neutral / ground paths or decreasing current in these paths by balancing the loads also reduces the N-E voltages. Isolation of a portion of the grounding or grounded neutral system accessed by the humans or animals is yet another technique which can be applied to reduce N-E voltages in customer premises. In fact, isolation of the primary neutral from the secondary neutral with an approved isolation device is a well accepted mitigation method in the electric utility industry.

Depending on the severity of stray voltage problem, one or more mitigation methods may be applied. The most suitable approach in any given situation, however, should be based on the investigation results, constraints as related to site and economics, and the conformance of applicable local or national codes. This section describes the concepts involved in various mitigation methods. Where applicable, the associated devices are also described and discussed. In addition, relative effectiveness of several mitigation methods, where they can be clearly determined, is also stated.

Restoration of Faulty or Corroded Neutral

The investigation may show a high level of N-E voltage due to presence of one or more of the following conditions:

- High resistance connection either on primary or secondary neutral wire,
- Open neutral strands (such as bare concentric neutral strands) due to corrosion,
- High impedance fault from the secondary line wire (L_1 or L_2) to either soil or neutral,
- Low current fault in the equipment, or
- Connection of equipment ground and neutral at the equipment.

In general, the above conditions are corrected first when detected. Following the necessary repairs, the voltages are rechecked to determine their acceptance. If unacceptable N-E voltages still exist, the investigation continues to identify additional sources.

Grounding Improvement

Improvement of Primary Pole Grounds

For multigrounded systems, NESC requires grounding of poles (minimum of 8' deep ground rod) at a minimum of four locations per mile in addition to providing grounds at each service pole. The intent of this requirement is to provide an additional current return path in the case of a phase to ground fault on the system. In addition, during steady state operation, these ground rods help reduce the N-E voltages along the line. Reducing the pole ground resistance at the transformer and nearby poles is a well accepted mitigation practice in the utility industry.

Driving additional ground rods at selected poles is typically considered first to mitigate stray voltage problem. This may be because ground rods can be easily installed without interrupting the service. However, the ground return path being a high impedance path, requires a significant reduction in the pole round resistances to effectively reduce the N-E voltages. More reduction in ground electrode resistance requires more ground rods either driven in parallel or on top of each other. As an example, the analysis of the dairy farm case of Section 8 (see Corrective Measure Scenario-1) can be restated here. Reducing the transformer pole ground resistance from 42 Ω to 8.6 Ω reduced the N-E voltages in the farm by only 17%. Also, no significant additional reduction in the N-E voltages was accomplished when ground resistances on the entire tap line were reduced from 50 Ω to 25 Ω.

A field investigation[66] undertaken by Wisconsin Electric Power Company could be sited as another example. The measurements on 2.6 miles long system (two phase, three wire) with six dairy farms showed little improvement in N-E voltages when ground locations from nine locations per mile were increased to that on every pole on the system. Adding multiple parallel grounding systems with a counterpoise at each dairy farm transformer pole and at two nearby poles, however, showed a relatively higher reduction in N-E voltages. There are two additional groups of investigators[23][77] who have shown that improving primary pole grounding systems reduce the N-E voltages a small amount.

The above results suggest that:

- Improving grounding at the transformer pole would be more effective than improving ground resistances along primary poles.
- The mitigation method of improving primary pole grounding can be economically applied when small reduction in N-E voltages is required (<20%) or there are number of customers along the distribution line who are affected.

Voltage Gradient Control

In the electrical industry, the concept of voltage gradient control is recognized as a means of minimizing the risk of hazardous step and touch (contact) voltages under fault conditions in substations and around electrical equipment[6]. The same concept applies for stray voltage cases during steady state operations of distribution systems. Installing a mesh type of ground grid system in the stall area, for example, accomplishes a very effective voltage gradient control. A ground ring around the electrical equipment typically accomplishes this voltage gradient control. The contact voltage is minimized because the feet or the hooves are almost at the same potential as the hands (human) or the body (animal), respectively. The step voltage is minimized because the surface voltage gradients between two feet (human) or between the hooves (animal) are minimized. In addition to minimizing the stray voltage between the contact points, the additional grounding system also lowers the N-E voltages by lowering its resistance to remote ground.

Equipotential Planes in Dairy Farms Depending on the mesh size, the equipotential plane can be one of the most effective mitigating methods especially for animal farms. Smaller meshes obviously provide better protection. In addition, equipotential planes improve the electrical safety with regard to lightning protection and clearing of faults without harm to animals. Corrective Measure Scenario-4 in Section 8 demonstrates the excellent mitigation effectiveness of the equipotential plane in the example dairy farm. Referring to the study case results, the equipotential plane reduced the N-E voltage at the barn service panel by 24 % and the open circuit contact voltage (or stray voltage) in the stall area by 97 %. Note that the stated reductions are in comparison with the base case results of Analysis Scenario-3 in Section 8.

Figures 7-1 and 7-2 graphically illustrate the stray voltage gradients for the base case with just a ground rod at the barn service panel (Analysis Scenario–3) and for the case with equipotential plane added (Mitigation Scenario-4), respectively. These illustrations provide more insight into the effectiveness of the equipotential plane as a mitigation means.

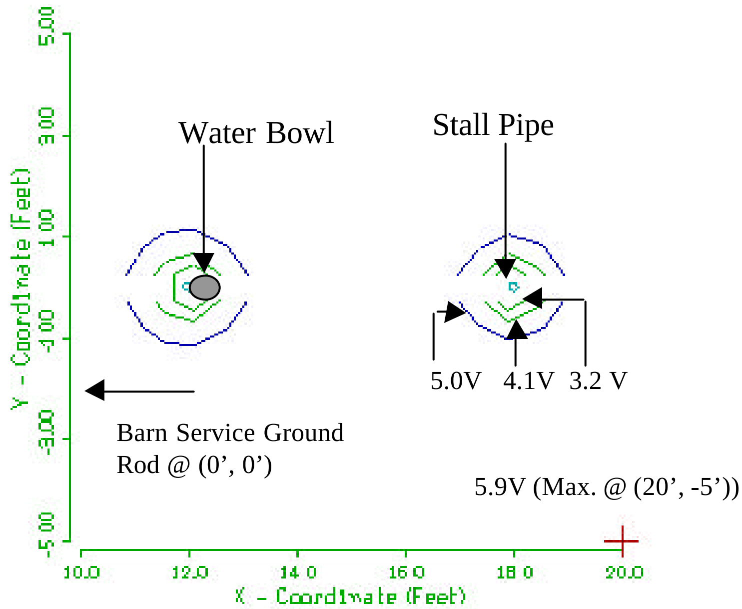


Figure 7-1 Stray Voltage Profile Around Stall Pipes - Base Case with an 8' Ground Rod at Barn Service Panel (See Analysis Scenario-3, Section 8)

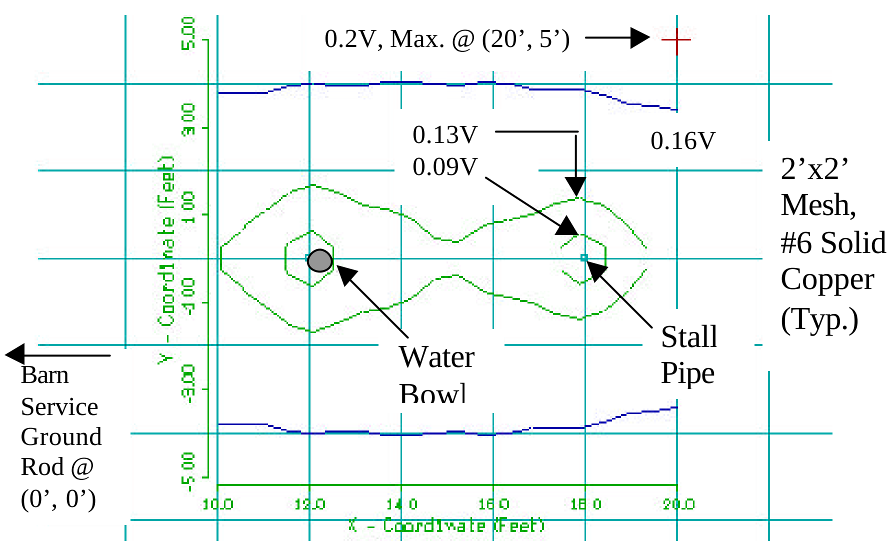


Figure 7-2 Stray Voltage Profile Around Stall Pipes – 30'x16' Equipotential Plane in the Barn Area (See Corrective Measure Scenario-4, Section 8)

If the equipotential plane is properly installed, the only other concern is that the animals may experience an undesirable step voltage between the front hooves and the rear hooves when they move on or off the plane. This is due to the fact that the front and rear hooves are on two different surfaces such as the concrete and the soil. Figure 7-3 illustrates the concerning step voltage in the dairy farm example of Section 8.

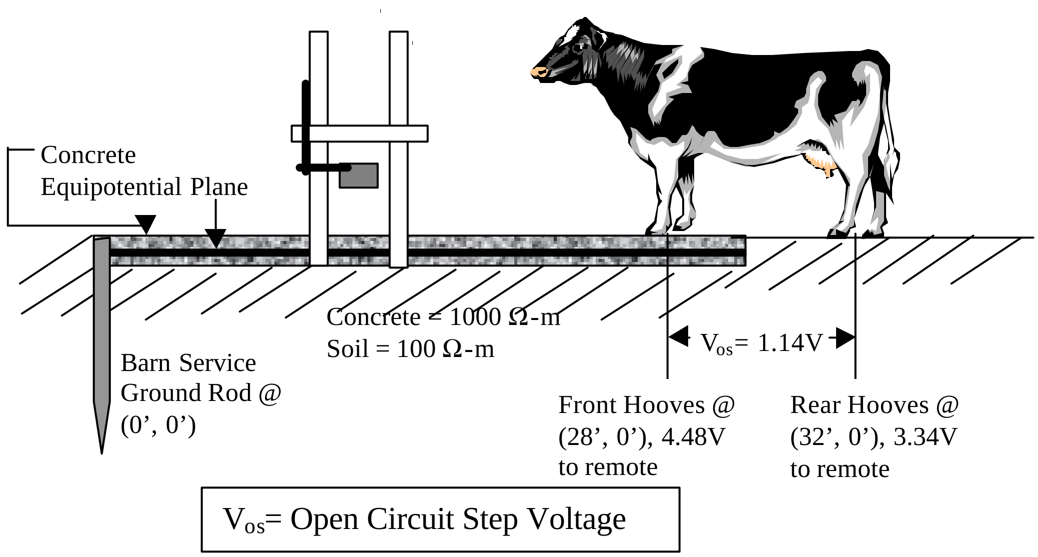


Figure 7-3 Open Circuit Step Voltage for the Animal Approaching the Equipotential Plane (see Corrective Measure Scenario-4, Section 8)

The open circuit step voltage may be high enough to force an unacceptable current through the animal's body from the front to rear hooves. In this case the animal may refuse or be reluctant to move on or off the equipotential plane. To reduce this step voltage, it is customary to install the voltage gradient ramp as illustrated in Figure 7-4.

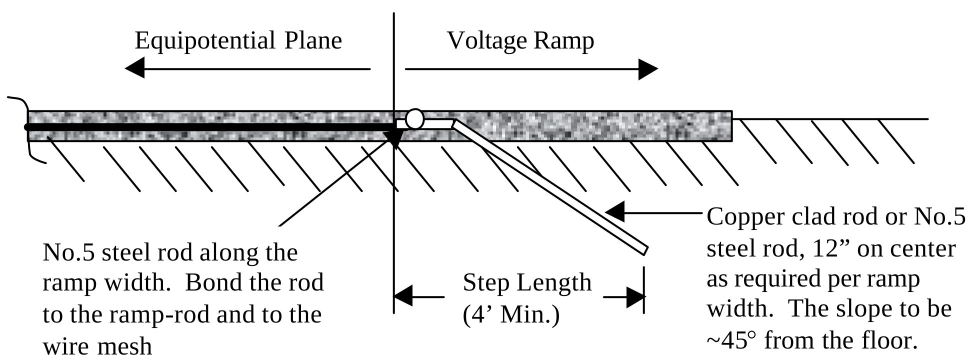


Figure 7-4 Illustration of a Voltage Gradient Ramp in Dairy Farm

Design and Construction of Equipotential Plane NEC Article 547-8(b), requires installation of wire mesh or other conductive elements in the concrete floor of livestock confinement areas. It further requires bonding this wire mesh to the building grounding system to provide an equipotential plane that has controlled voltage gradients at entrances and at exits. Article 547-8(b) specifies the bonding conductor to be insulated, covered, or bare copper not smaller than No. 8 AWG. The means of bonding to the wire mesh must be by pressure connectors or clamps of brass, copper, or copper alloy. An equivalent approved bonding means is also allowed by the code.

Though the wire mesh material recommended by NEC is copper, there are several other materials, such as steel rebars and steel wire that can be used. The following is a list of typical materials that are used for the wire mesh system.

- Heavy welded-steel wire mesh – No. 10 AWG or larger
- Bare copper wire – No. 8 or larger
- Reinforcing steel – 3/8" diameter or larger

Welded steel wire mesh generally is available in 6" x 6" patterns. Copper or steel wire and reinforcing rods placed in a grid pattern may also be used. A typically recommended mesh spacing is 12" x 12" or smaller. It is also recommended to bond every cross point in the pattern. To protect the wire mesh from corrosion, it should be covered with a concrete layer at least 1½" thick.

A properly installed equipotential plane involves more than just a wire mesh embedded in the concrete floor. It should include proper equipment grounding, metalwork bonding, a conductive network in the floor, and a properly voltage graded transition area. In a dairy stall barn, the cow contact surfaces are the metal stanchions or tie stalls, the water line or bowl, and the concrete stall floor. Typically, the wire mesh or reinforcing steel in the concrete floor is bonded to the metal equipment in the barn and to the grounding / neutral bus in the service entrance panel. The entrances and exits of the concrete area may require voltage gradient ramps to reduce the step voltages.

As mentioned before, the NEC requires that an equipotential plane be installed in all newly constructed or remodeled livestock confinement facilities. In new construction, there is a perfect opportunity to install an equipotential plane and bond to reinforcing steel or wire mesh typically used for controlling cracking. In new construction, it is also easy to bond the wire mesh to all equipment, stalls and partitions that will be finally embedded in the concrete. The equipment that will not be embedded in the concrete are also bonded to the wire mesh before the concrete is poured.

Installation of retrofit equipotential plane in existing facility can be difficult and as a result its cost should be weighed against the benefits in mitigating the stray voltage problem. Other means of mitigation should also be reviewed before making the decision in favor of retrofitting the facility with the equipotential plane.

There are several ways to install an equipotential plane in an existing barn. One alternative is to remove the entire floor and install a new concrete floor with wire mesh and reinforcing steel and provide the bonding similar to new construction. This installation option would, most likely, be very expensive one. The livestock may be greatly inconvenienced if they were to remain in the area under construction.

Another alternative is to lay the wire mesh on the existing concrete floor and bond it to the metal components in the barn. A 5 cm (2 inch) cap or layer of concrete is placed over the mesh and the existing concrete floor. The cost of materials and labor for this method may range from \$ 8.00 to \$ 16.00 per square meter (or \$ 0.75 to \$ 1.5 per square foot) in 1990 dollars. As to the inconvenience to the livestock during construction, this alternative is similar to the first alternative [55].

In an effort to reduce the time of installation and, in turn, the amount of disruption in the dairy farm operation, a third alternative has been developed. This method consists of cutting 1½" deep by ¼" wide grooves at selected locations on the barn floor, inserting copper wires in the grooves, and grouting over the wires. The installed wires are bonded together at several points and to the metallic structures in the facility and finally to the service entrance neutral. Typical groove locations in the barn stall include [55]:

- One groove in the feed manger approximately 7-12 inches from the curb,
- Two grooves in front hoof area approximately 7-12 inches from the curb and 12 inches apart, and
- Two grooves in the rear hoof area approximately 7-12 inches from the gutter and 12 inches apart.

Milking parlors and holding areas can also be retrofitted in the manner described above. In this case, the wires are placed in the areas where cows stand when milked and also under the worker area of the pit floor and the livestock walk aisles. To ensure all contact areas are bonded together, plane wires should be bonded to the milk line (if metal), steel partitions and the feeders.

Voltage information was collected from 17 different installations that have been retrofitted with equipotential planes in the state of Wisconsin over a two-year period [54]. These retrofits were made by cutting grooves in existing concrete with an average cost of \$ 2.66 / grooved foot in 1987 dollars. The voltages were measured before and after the equipotential plane installation to determine the effectiveness of this mitigating method. The measured voltages included N-E voltages at transformers, N-E voltages at barn service panels, and open circuit voltages (stray voltages) in cow contact areas. Because the voltages in the dairy farms varied continuously, the authors measured the voltages at each location several times. Table 7-1 present the maximum and minimum values of these voltages at 17 farms.

Table 7-1 Measured NE and Stray Voltages in 17 Farms Retrofitted with Equipotential Planes in State of Wisconsin

Dairy Farm Number	Range	N-E Voltage at Transformer, Volts		N-E Voltage at Barn Ground, Volts		Stray Voltage in Cow Contact Area, Volts	
		Before	After	Before	After	Before	After
1	Maximum	1.0	1.2	0.8	0.7	0.8	<0.1
	Minimum	0.1	0.3	0.1	0.3	0.1	<0.1
2	Maximum	3.0	1.1	2.8	0.5	1.2	<0.1
	Minimum	0.5	0.3	0.3	0.1	0.2	<0.1
3	Maximum	0.9	1.8	2.0	2.3	0.5	<0.1
	Minimum	0.2	0.3	0.2	0.8	0.1	<0.1
4	Maximum	3.2	1.8	3.2	2.1	0.6	0.4
	Minimum	0.7	0.1	0.7	0.1	<0.1	<0.1
5	Maximum	4.0	2.5	4.0	4.0	2.0	<0.1
	Minimum	0.4	0.1	0.3	0.1	0.2	<0.1
6	Maximum	0.2	0.3	0.4	0.3	0.2	<0.1
	Minimum	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
7	Maximum	N/A	N/A	N/A	N/A	0.4	0.1
	Minimum	N/A	N/A	N/A	N/A	<0.1	<0.1
8	Maximum	N/A	N/A	N/A	N/A	1.5	0.1
	Minimum	N/A	N/A	N/A	N/A	0.3	<0.1
9	Maximum	N/A	N/A	1.5	0.9	1.2	0.2
	Minimum	N/A	N/A	0.2	0.2	0.1	<0.1
10	Maximum	N/A	N/A	N/A	N/A	0.3	<0.1
	Minimum	N/A	N/A	N/A	N/A	<0.1	<0.1
11	Maximum	N/A	N/A	N/A	N/A	N/A	N/A
	Minimum	N/A	N/A	N/A	N/A	N/A	N/A
12	Maximum	1.3	1.3	1.0	1.3	1.1	<0.2
	Minimum	0.3	0.3	0.2	0.3	0.1	<0.1
13	Maximum	1.5	0.7	1.4	0.7	0.7	<0.1
	Minimum	N/A	N/A	N/A	N/A	N/A	N/A
14	Maximum	0.5	0.5	0.7	0.5	0.4	<0.1
	Minimum	N/A	N/A	N/A	N/A	N/A	N/A
15	Maximum	N/A	N/A	N/A	N/A	0.6	<0.1
	Minimum	N/A	N/A	N/A	N/A	N/A	N/A
16	Maximum	N/A	N/A	N/A	N/A	<0.1	<0.1
	Minimum	N/A	N/A	N/A	N/A	N/A	N/A
17	Maximum	N/A	N/A	N/A	N/A	0.8	0.2
	Minimum	N/A	N/A	N/A	N/A	N/A	N/A

N/A = Not Available

Ground Ring or Mesh in Human Contact Areas Unlike animal farms where the contact areas are well defined, installing a wire mesh or even a ground ring is rarely applied for stray voltage cases involving humans. However, where human contact areas are well defined, this method can be an effective and economical mitigating method. Figure 4-1 in Section 4 illustrates the advantage of installing a ground mesh around a distribution pole. Referring to the figure, the square mesh ground system around the pole fares significantly better than the single ground rod or the counterpoise. Compared to a 20' deep ground rod, the square mesh reduced the stray voltage around the pole by an average of 34%.

Installation of ground rings or meshes around electrical equipment and facilities for safety is an accepted practice in the electrical industry. Similar grounding systems can effectively mitigate the stray voltage problems in residential areas, boat docks, and campgrounds. Referring to the boat dock study case in Section 8 (Figure 8-16) as an example, installing a ground ring around the dock reduced the N-E voltage from 4.6 volts to 1.4 volts.

Increasing Neutral Wire Size

For a fixed length, a smaller size neutral wire offers higher impedance to the return current. This obviously results in higher N-E voltages along the neutral length, the highest voltage being at the starting point of the return current (customer transformer location on the primary side and the farthest load point inside customer facility). One way to reduce the N-E voltages is then to replace the smaller size neutral wire with a larger diameter wire or to add another wire in close proximity to the existing wire.

The extent of N-E voltage reduction by increasing neutral wire size will depend on three factors; the amount of increase in the wire size, the length of the replaced neutral, and the amount of load current flowing in the replaced neutral. Obviously, replacing the existing neutral with the largest available neutral size would be ideal. The mechanical loading and the replacement cost, however, will ultimately dictate the replacement neutral size. On a primary system where the stray voltage problem is widely spread along the feeder, replacing the entire feeder neutral will effectively reduce the N-E voltages. This is illustrated in the residential study case in Section 8. Referring to Figure 8-7, replacing the entire feeder neutral with a 4/0 ACSR neutral reduced the N-E voltages in the subdivision by 25%. Note that the partial replacement would have yielded a smaller reduction.

In general, secondary neutrals (in customer facilities) are shorter in length compared to primary neutrals. However, facilities such as animal farms or boat docks may have longer neutrals and may carry significantly higher load current. Replacing them with larger size neutrals may effectively reduce the N-E voltages in the contact areas. In the example dairy farm case, replacing 1/0 AWG neutrals with 4/0 AWG neutrals, however, reduced N-E voltages only by 8% (see Corrective Measure Scenario-7, Section 8). Customer facilities with longer neutrals and higher currents can benefit more by upgrading their neutrals.

Load Balancing

Load Balancing – Primary Side

N-E voltages are directly proportional to the current flowing in the neutral. Reducing this current can effectively reduce the N-E voltages. In a three-phase four wire primary system, the neutral current results from unbalanced phase loads. Distributing these loads as evenly as practical among the three phases can reduce the neutral current and in turn reduce the N-E voltages. Because this requires changing connections for transformers, lightning arresters and fuse links on the primary side, a planned customer outage may be necessary.

Rarely does a three-phase feeder have a stray voltage problem. This is because utilities generally keep the loads on three-phase feeders balanced for improved voltage regulation. Customers on single-phase feeders, on the other hand, are more likely to have stray voltage problems due to the neutral current of nearly the same magnitude as the load current. Unlike three-phase feeders, single-phase feeders require the addition of one or two additional phases before switching the loads for balancing. This may be an expensive solution especially to mitigate stray voltage problem of a single customer on the feeder. However, for a stray voltage case involving several customers, adding additional phases for load balancing may be justified.

To illustrate the effectiveness of load balancing, Section 8 presents two study cases. One study case illustrates reduction of N-E voltages in the dairy farm (see Corrective Measure Scenario-2) and the second example illustrates the reduction at three houses in residential subdivision (see Corrective Measures, Figure 8-9). In the dairy farm scenario, one additional phase was installed on the tap line up to BUS5 (See Figure 8-1) to transfer all but the farm load onto the new phase. This solution reduced the N-E and contact voltages in the barn by almost 61%. In the example involving the residential subdivision, the N-E voltages at the three houses were reduced by 75% when load balancing was carried out following the extension of three phases to the end of the feeder and the installation of one additional phase in the subdivision.

Load Balancing – Secondary Side

The grounded secondary neutral carries current under the normal operation of the customer's electrical system. Although the impedance of a typical secondary neutral is very low, there may be a measurable voltage drop developed due to high current flow. For the dairy farm example of Section 8, 125 feet of 1/0 neutral developed 0.82 volts with 35 ampere current flow (Z_n=0.023 Ω). If the current were to reduce in the neutral, the N-E voltage on the load side would reduce proportionately.

Although load balancing is an effective mitigation method, it is difficult to implement, particularly for a facility such as a dairy farm which normally has more than one building. For effective load balancing, the knowledge of load types and their times of use are essential. Once this is known, the loads can be re-connected between L_1 and L_2.

Load balancing in a facility such as a dairy farm can be achieved by balancing the 120-volt loads between L_1 and L_2 or by converting 120-volts motor loads to 240-volts loads. Operation of motors at 240-volts has the additional advantage of reduced starting and running currents. Using the dairy farm example of Section 8, the effectiveness of each balancing method is demonstrated in Table 7-2. With the exception of various loads in the farm, the system parameters remain the same as shown in Figures 8-1 and 8-2.

Table 7-2 Secondary Load Balancing as a Means of Mitigation - Illustration Using the Dairy Farm Example of Section 8

Farm Load, KVA		Various Neutral Currents, Amps		
At House	At Barn	TFM to Farm Service	Farm Service to House	Farm Service to Barn
(1) 240 V= 1+j0.2 120V(L_1)=2+j0.3 120V(L_2)=0+j0	240 V= 2+j0.5 120V(L_1)=4+j2 120V(L_2)=0+j0	50.8∠-172°	16.1∠-159°	35.3∠-177°
(2) 240 V= 1+j0.2 120V(L_1)=2+j0.3 120V(L_2)=0+j0	240 V= 2+j0.5 120V(L_1)=0+j0 120V(L_2)=4+j2	20.8∠-11°	16.5∠-159°	35.8∠-177°
(3) 240 V= 1+j0.2 120V(L_1)=2+j0.3 120V(L_2)=0+j0	240 V= 2+j0.5 120V(L_1)=2+j1 120V(L_2)=2+j1	15.9∠-159°	16.3∠-159°	0.29∠26°
(4) 240 V= 1+j0.2 120V(L_1)=2+j0.3 120V(L_2)=0+j0	240 V= 3.5+j1.25 120V(L_1)=1+j0.5 120V(L_2)=0+j0	24.6∠-166°	16.3∠-159°	8.8∠-178°
Farm Load, KVA		N-E Voltages at Various Farm Locations		
At House	At Barn	At TFM	At House	At Barn
(1) 240 V= 1+j0.2 120V(L_1)=2+j0.3 120V(L_2)=0+j0	240 V= 2+j0.5 120V(L_1)=4+j2 120V(L_2)=0+j0	4.79∠25°	5.7∠27°	6.31∠26°
(2) 240 V= 1+j0.2 120V(L_1)=2+j0.3 120V(L_2)=0+j0	240 V= 2+j0.5 120V(L_1)=0+j0 120V(L_2)=4+j2	5.03∠27°	4.96∠28°	3.91∠27°
(3) 240 V= 1+j0.2 120V(L_1)=2+j0.3 120V(L_2)=0+j0	240 V= 2+j0.5 120V(L_1)=2+j1 120V(L_2)=2+j1	4.92∠26°	5.34∠27°	5.12∠27°
(4) 240 V= 1+j0.2 120V(L_1)=2+j0.3 120V(L_2)=0+j0	240 V= 3.5+j1.25 120V(L_1)=1+j0.5 120V(L_2)=0+j0	4.66∠26°	5.2∠27°	5.2∠27°

(1) Base Case, All 120-Volts Farm Loads are Connected to L_1. See Analysis Scenario-3, Section 8
(2) Same as Base Case except 120-Volts Barn Load Transferred to L_2 from L_1, See Corrective Measure Scenario-5, Section 8
(3) Same as Base Case except 120-Volts Barn Load Distributed Equally between L_1 and L_2.
(4) Same as Base Case except 3+j1.5 KVA of 120-Volts Barn Load Converted to 24-Volts Load.

Increase in Primary System Voltage

Many times stray voltage problems exist in low voltage primary distribution systems. The 2,400 volts primary distribution system is an example of such a system. At lower primary voltage, the neutral current is obviously higher for the same kVA load. Upgrading the existing distribution system to a higher voltage level thus reduces the neutral current in approximately the same proportion. The reduced neutral current in turn reduces the N-E voltages along the feeder.

Although increasing primary system voltage is an effective stray voltage mitigation means, it is hardly a cost justifiable method. It not only requires upgrading the line, but also requires changing out the customer transformers with associated protective equipment. However, if other more justifiable reasons (load growth, voltage regulation problems) exist and the line has to be converted, the reduced N-E voltages can be a welcome side benefit. Sometimes a distribution system with a higher voltage level runs either on the same poles or in the vicinity of the customer having a stray voltage problem. In such a case, it may be feasible to mitigate the problem by changing out and connecting the transformer to the higher voltage line.

The mitigation effectiveness of upgrading the distribution is illustrated in the dairy farm case of Section 4. See Figure 4-10 for the modeled system. Referring to Figure 4-18, the dairy farm N-E voltage is 5.5 volts with a 12 kV primary side voltage. When the line was converted to 23 kV, the dairy farm voltage reduced to 2.0 volts as shown in Figure 4-11.

Neutral Isolation

Isolation of part of the grounded neutral or grounding systems can eliminate access to N-E voltages by humans or animals in contact with the isolated system. If isolation is selected on a conventional single-phase grounded neutral system, two points lend themselves to isolation:

1. Isolating the entire customer facility from the primary distribution system, and
2. Isolating the grounding or grounded neutral system at a single building service for a customer with multiple building facilities, such as a dairy farm.

Regardless of the isolation method selected, careful consideration must be given to the safety of humans or animals and the operational effects on the primary and secondary systems.

Neutral Isolation – Primary to Secondary

Isolation can be accomplished by removal of all bonds between the primary and secondary neutrals at the distribution transformer as shown in Figure 7-5 for an overhead system. For an underground system, the device can either be mounted inside the secondary cabinet of the padmount or in a separate enclosure as shown in Figures 7-6 and 7-7, respectively.

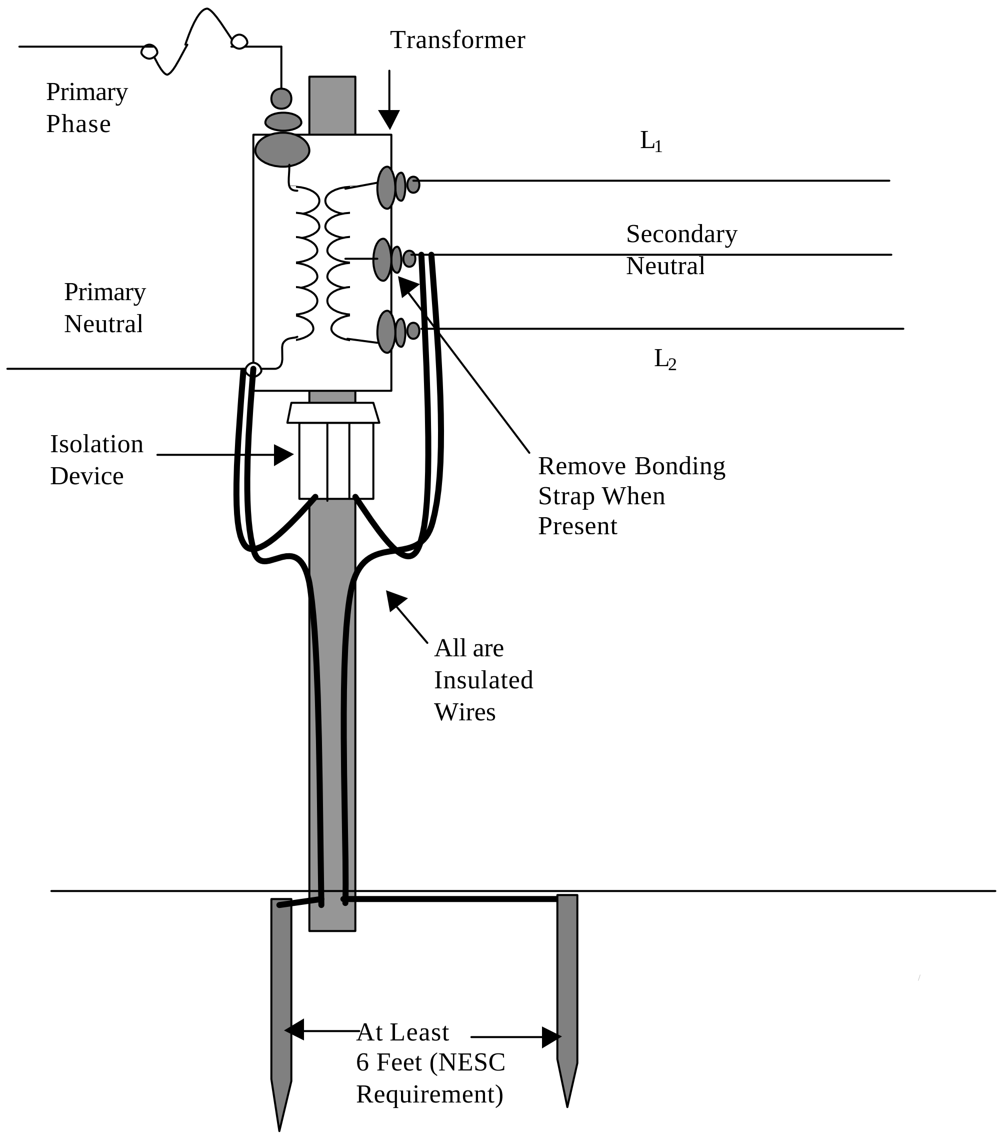


Figure 7-5 Installation of Neutral Isolation Device – Pole Mounted Installation

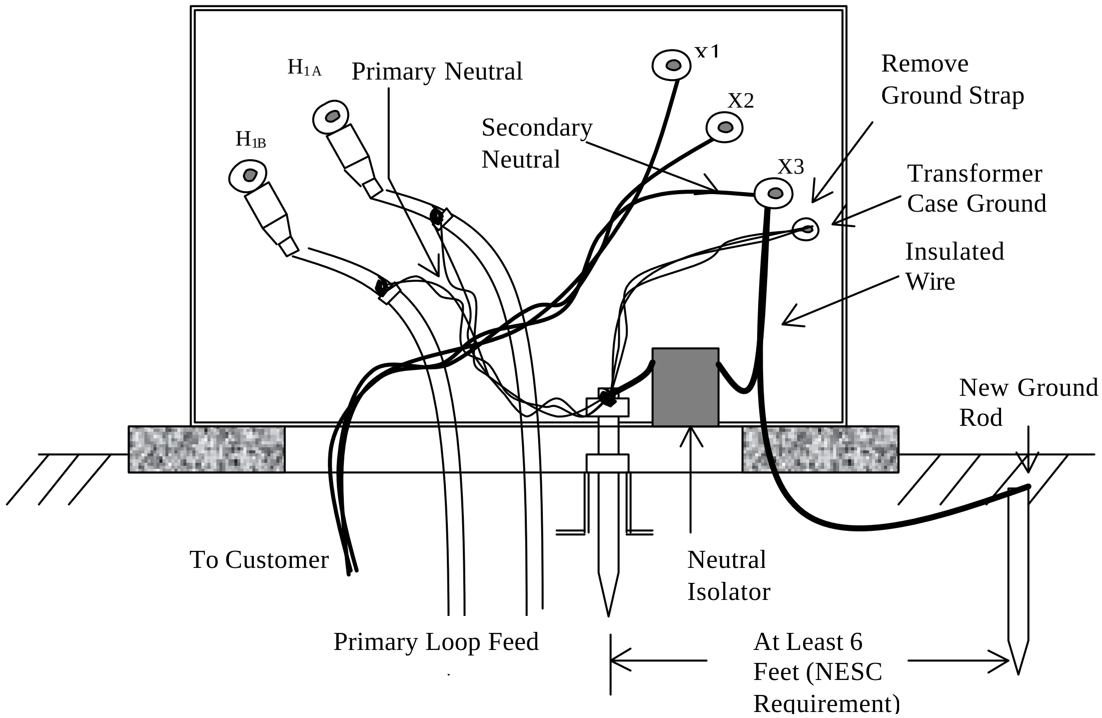


Figure 7-6 Installation of Neutral Isolation Device – Inside Padmount Transformer

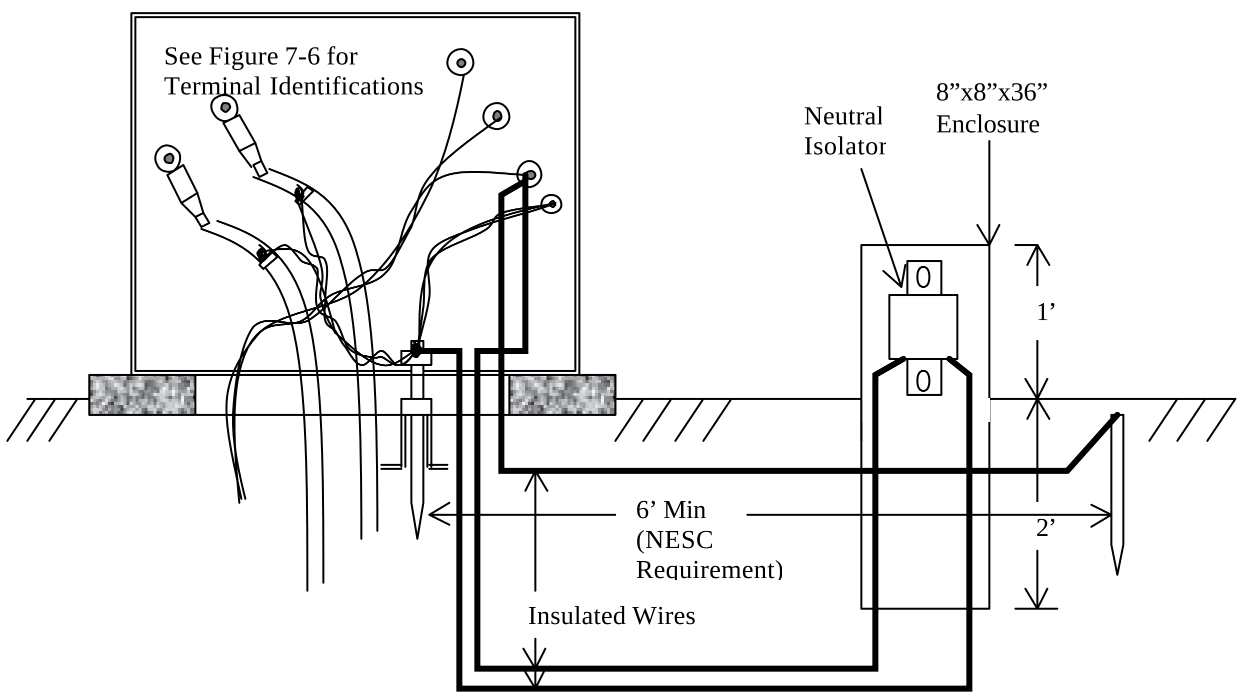


Figure 7-7 Installation of Neutral Isolation Device – Outside Padmount Transformer

Devices are now available to provide primary to secondary neutral isolation in conformance with Section 97 D of the National Safety Electric Code, 1997 edition. Depending on the type of device, three methods are currently used for primary to secondary isolation:

1. Neutral isolation by conventional spark gap or surge arrester,
2. Neutral isolation by saturable reactor,
3. Neutral isolation by a switching / reconnect device for fault conditions

Earlier editions of the NESC allowed isolation by use of a spark gap with a rating of 10 kV or greater. This provision was developed early in the history of electrical distribution systems, primarily for the protection of the transformer winding during transient situations. Later on, the neutral isolation was reviewed with respect to protection of customer and customer facilities. The major safety concern considered was for the prompt interruption of service to the customer in the event of a winding-to-winding fault in the transformer or the primary conductor shorting to the secondary conductor external to the transformer. Sufficient fault current must pass from the customer service to the primary system to assure timely operation of protective devices. The concerns were also for the fault current returning to the primary neutral through high impedance paths such as the customer ground, water pipes, or telephone or cable shield wires and high N-E voltages in customer's facilities. As a result of these concerns, NESC modified the earlier code to require isolating devices to have 3 kV or less 60 Hz breakdown voltages. This requirement allows the device to short the primary and secondary neutrals in the case of a primary-to-secondary fault. In the case of a saturable reactor or electronic switch isolating device, a parallel spark gap or surge arrester is typically installed to let through the lightning or switching surge from the primary side.

Regarding neutral isolation, a different viewpoint exists in some States where many customers are served with primary neutrals isolated from the secondary neutrals without the use of shorting devices. The main reason for this practice is to guard the customers against phase to ground faults on the primary side.

To aid the users in understanding the two different viewpoints regarding permanent neutral isolation at the transformer, the dairy farm example of Section 8 is revisited. The intent here is to show influences of various fault conditions in the customer (dairy farm) facilities with and without neutral isolation. Modeling the system as shown in Figures 8-1 and 8-2, the following faults are simulated: 1) phase to ground fault on the primary of the transformer, 2) primary to secondary (L_1) fault, and 3) Line (L_1) to ground fault in the barn. Table 7-3 shows the fault currents and N-E voltages at the transformer as well as in dairy farm. When the secondary neutral is isolated, the N-E voltages increase in proportion to the dairy farm's ground resistance value. To illustrate the influence of this variable, Table 7-3 presents the data for two different resistance values.

Table 7-3 Influence of Neutral Isolation on N-E Voltage in the Dairy Farm (See Example in Section 8 for System Model) for Various Primary and Secondary Faults

Type of Fault	Neutral Isolated Or Connected	Combined Ground Resistance of Dairy Farm (Ω)	Fault Current (Amps)				¶N-E Voltages (Volts)		
			Pri. Neu.	Sec. Neu.	Pri. Ph.	Sec. Ph. (L_1)	At TFM Primary Neutral	At TFM Secondary Neutral	At Barn
Ph. to Gr. at TFM Primary	*Connect.	10.375	1496	233	1785	2.6	3387	3387	3382
	Isolated	10.375	1637	10	1719	0.12	3794	184	184
	Isolated	51.45	1681	2	1697	0.02	3917	189	189
Prim to L_1 in TFM	Connect.	10.375	1494	225	1783	12	3382	3382	3378
	$Isolated	10.375	43	**&**590	850	55	801	9107	9094
	$Isolated	51.45	10	**&**124	#228	62	223	12174	12172
L_1 to Gr. at Barn	Connect.	10.375	9	1422	13	1442	24	24	77
	Isolated	10.375	12	1423	13	1440	33	21	31
	Isolated	51.45	13	1423	13	1440	35	21	31

* Data for a fault from primary to L_1 and transformer casing would be similar to these data.
$ Data for a fault from primary to secondary neutral would be similar to these data.
# Primary protection may not operate for this fault condition.
¶ These N-E voltages are short duration voltages and cannot be compared with N-E voltages resulting from steady state operations of distribution systems. In general, the short duration permissible voltage levels are significantly higher than that resulting from the steady state operations of the distribution systems.
& Most of these currents return to the primary neutral via customer grounds.

Referring to Table 7-3, the primary to secondary (L_1) fault causes extremely high N-E voltages in the customer's facilities when neutrals are isolated. The collateral damages due to fault currents flowing in unintended paths should also not be ignored. Depending on the resistance of the customer's grounding system, the primary phase current may not be of sufficient magnitude to operate the protective devices. On the other hand, the advantages of neutral isolation are obvious for close-in primary to ground faults. The dairy farm is minimally affected by these faults. Whether the neutrals are connected or isolated, the faults on the secondary side produce relatively lower N-E voltages.

In addition to 60 Hz fault analysis, lightning surges on the primary or secondary system should also be analyzed to assess the risk of damage to customer equipment. Neutral isolation will significantly increase this risk for lightning strokes landing directly on customer facilities. As to the lightning surges developed on the primary side, neutral connection may increase the risk if customer ground resistance is high.

Utilities should consider permanent neutral isolation in the context of total risk assessment. This not only includes the probability of a fault or lightning but also includes its consequences in terms of safety and associated damages. For example, the probability of permanent primary-to-secondary faults may be significantly lower than that of close-in phase-to-ground faults on the primary side. However, the risk associated with primary-to-secondary faults in terms of N-E voltages and the collateral damages may be significantly higher.

Effectiveness of Neutral Isolation Isolating the primary neutral from the secondary neutral with a proper isolating device is one of the most effective methods to mitigate a stray voltage problem. The reason for its superior effectiveness lies in the fact that it eliminates two main stray voltage sources: unbalanced load current on the primary side and customer load current appearing on the primary side. To show the effectiveness of this method, the dairy farm example of Section 8 (See Corrective Measure Scenario-3) can be sited. Stray voltages in the barn area were reduced by 88% when the primary neutral was isolated from the secondary neutral at the transformer pole.

Neutral isolation would be less effective if on-farm sources were to dominate. These sources may include voltage drops in secondary neutrals, a corroded splice in the neutral, or a line-to-earth fault in the customer premises. The effectiveness of neutral isolation would also be compromised if other neutral / ground paths such as shields of cable TV or telephone circuits were connected to the customer grounding system. In fact, these extraneous ground connections may increase N-E voltages in customer facilities following the neutral isolation.

Effects of Neutral Isolation on Primary System Isolation of the primary neutral from the secondary neutral removes the customer grounding system from the transformer pole ground system. This raises the ground resistance at the transformer pole and consequently increases the N-E voltage. In the dairy farm example of Section 8 (See Corrective Measure Scenario-3), the N-E voltage increased almost by 21% compared to the base case. This increase in N-E voltage was attributed to the increase in the transformer pole ground resistance from 10.375 Ω (four 41.5 Ω ground rods in parallel) to 41.5 Ω (one ground rod with 41.5 Ω resistance).

Obviously, the increase in N-E voltage at the transformer pole would be dependent on the ratio of the integrated pole ground resistance before the isolation and its resistance after the isolation. The higher the ratio, the larger would be the increase in the N-E voltage. Sometimes, there is more than one customer on the same feeder with isolated neutrals. In such a case, the primary N-E voltages will superimpose and may reach to levels of concern at several points along the feeder. Two investigators have performed an interesting study of this influence by modeling ten dairy farms along a 12-kV single-phase distribution line[38]. In this study, the authors have shown that when farms 6, 7, and 8 are isolated, the N-E voltage at farm 7 transformer rises from 1.75 volts to 4.5 volts, a 57% increase. This and other studies[67] suggest that before deciding in favor of neutral isolation as a mitigation method, it is prudent to assess its impact on the feeder and particularly on the neighboring customers.

Effects of Neutral Isolation on Secondary System As discussed in previous paragraphs, the effects of neutral isolation on the primary system is to increase the N-E voltages. Its influence on the secondary system is not as simple. Depending on the N-E voltage source, isolation may complement the existing source and may actually increase the N-E voltage in the customer facility. This section illustrates the influence of isolation on three different secondary sources: voltage drop across the neutral, line to earth fault, and corroded neutral splice.

Once again, the dairy farm system of Section 8 was used for the illustration. To focus only on dairy farm N-E sources, the single-phase load on BUS5 was removed from the modeled system (see Figure 8-1). As a result of this deletion, the only current allowed in the primary neutral was due to secondary load. All other parameters of the system remained the same as described in Figures 8-1 and 8-2. Because the influence of neutral isolation depends on the phase angle of the current, the analysis includes putting 120-volts loads on L_1 first and then repeating the same scenario with the 120-volts loads on L_2. Table 7-4 illustrates the influence of neutral isolation on dairy farm N-E voltages due to on-farm loads.

Table 7-4 Influence of Neutral Isolation on N-E Voltages Due to On-farm Loads

Neutral Connected Or Isolated	Dairy Farm Load (KVA)		N-E Voltage (Volts) / Ground Current (Amps)				
	House	Barn	TFM. Prim.	TFM. Sec.	Farm Service	House	Barn
Connected	L_1-L_2= 1+j0.2 L_1=2+j0.3	L_1-L_2= 2+j0.5 L_1=4+j2	$1.23\angle 27°$ $0.03\angle 27°$	$1.23\angle 27°$ $0.03\angle 27°$	$1.9\angle 29°$ $0.04\angle 29°$	$2.2\angle 31°$ $0.05\angle 31°$	$2.8\angle 29°$ $0.09\angle 29°$
Isolated	L_1-L_2= 1+j0.2 L_1=2+j0.3	L_1-L_2= 2+j0.5 L_1=4+j2	$1.7\angle 41°$ $0.04\angle 41°$	$0.9\angle -151°$ $0.02\angle -151°$	$0.2\angle -167°$ $0.0\angle -167°$	$0.1\angle 124°$ $0.0\angle 121°$	$0.8\angle 19°$ $0.02\angle 19°$
Connected	L_1-L_2= 1+j0.2 L_2=2+j0.3	L_1-L_2= 2+j0.5 L_2=4+j2	$1.61\angle 38°$ $0.03\angle 38°$	$1.61\angle 38°$ $0.03\angle 38°$	$0.9\angle 41°$ $0.02\angle 41°$	$0.7\angle 39°$ $0.01\angle 39°$	$0.2\angle 104°$ $0.0\angle 107°$
Isolated	L_1-L_2= 1+j0.2 L_2=2+j0.3	L_1-L_2= 2+j0.5 L_2=4+j2	$1.68\angle 41°$ $0.04\angle 41°$	$0.9\angle 29°$ $0.02\angle 29°$	$0.23\angle 13°$ $0.00\angle 41°$	$0.1\angle -56°$ $0.0\angle -58°$	$0.8\angle -160°$ $0.02\angle -160°$

Table 7-4 shows that the neutral isolation re-distributes the N-E voltages in the dairy farm. This redistribution is due to increases in the ground resistance at the transformer pole following the isolation. Isolating the neutral, as expected, reduced the N-E voltages everywhere in the farm with the exception of the barn service panel when L_2 was carrying all 120-volts loads. In this exception, the N-E voltage actually increased from 0.2 volts with the neutral connected to 0.8 volts with the neutral isolated.

The neutral isolation also influenced N-E voltages resulting from the corroded neutral splice at the barn service panel (see Analysis Scenario-4 in Section 8) as shown in Table 7-5.

Table 7-5 Influence of Neutral Isolation on N-E Voltages Due to Corroded Splice (0.2 Ω resistor) at the Barn Service Panel

Neutral Connected Or Isolated	Dairy Farm Load (KVA)		N-E Voltage (Volts) / Ground Current (Amps)				
	House	Barn	TFM. Prim.	TFM. Sec.	Farm Service	House	Barn
Connected	L_1-L_2= 1+j0.2 L_1=2+j0.3	L_1-L_2= 2+j0.5 L_1=4+j2	0.7∠19° 0.01∠19°	0.7∠19° 0.01∠19°	1.3∠27° 0.02∠29°	1.5∠30° 0.03∠31°	8.7∠10° 0.28∠10°
Isolated	L_1-L_2= 1+j0.2 L_1=2+j0.3	L_1-L_2= 2+j0.5 L_1=4+j2	1.6∠42° 0.04∠42°	2.89∠-168° 0.06∠-167°	2.3∠-174° 0.05∠-174°	2.1∠-178° 0.05∠-178°	5.2∠7° 0.2∠7°
Connected	L_1-L_2= 1+j0.2 L_2=2+j0.3	L_1-L_2= 2+j0.5 L_2=4+j2	2.1∠39° 0.05∠39°	2.1∠39° 0.05∠39°	1.5∠40° 0.03∠38°	1.2∠39° 0.03∠37°	6.3∠179° 0.2∠180°
Isolated	L_1-L_2= 1+j0.2 L_2=2+j0.3	L_1-L_2= 2+j0.5 L_2=4+j2	1.65∠42° 0.04∠42°	2.9∠12° 0.06∠12°	2.3∠6° 0.05∠6°	2.1∠2° 0.05∠2°	5.2∠-173° 0.2∠-173°

Referring to Table 7-5, the neutral isolation reduced the N-E voltage at the barn but increased the voltages at the house and at the farm-service panel. Note that the increases in the house and farm-service N-E voltages were significant.

As discussed in Section 8 (see Analysis Scenario-5), the faults from L_1 or L_2 to earth cause significantly higher N-E voltages in the dairy farm. Table 7-6 through Table 7-9 show that the neutral isolation increases these voltages even more. Tables 7-6 and 7-7 show N-E voltage data for lower amperes fault current (approximately 0.57 amperes) and Tables 7-8 and 7-9 show the data corresponding to high magnitude fault current (approximately 2.8 amperes). Tables 7-6 and 7-8 show the data for L_1-to-earth fault while Tables 7-7 and 7-9 represent the N-E voltage data for L_2-to-earth fault. Referring to Analysis Scenario-5 of Section 8, the line-to-earth fault location is 25 feet from the barn service panel, in each case.

Table 7-6 Influence of Neutral Isolation on N-E Voltages Due to L_1-to-Earth Fault- Low Fault Current (~ 0.57Amperes)

Neutral Connected Or Isolated	Dairy Farm Load (KVA)		N-E Voltage (Volts) / Ground Current (Amps)				
	House	Barn	TFM. Prim.	TFM. Sec.	Farm Service	House	Barn
Connected	L_1-L_2= 1+j0.2 L_1=2+j0.3	L_1-L_2= 2+j0.5 L_1=4+j2	0.8∠-51° 0.02∠19°	0.8∠-51° 0.02∠19°	1.1∠-12° 0.02∠-25°	1.3∠-4° 0.02∠-10°	2.1∠4° 0.02∠-21°
Isolated	L_1-L_2= 1+j0.2 L_1=2+j0.3	L_1-L_2= 2+j0.5 L_1=4+j2	1.7∠41° 0.04∠41°	5.9∠-150° 0.14∠-150°	5.2∠-151° 0.12∠-151°	4.9∠-152° 0.11∠-152°	4.1∠-149° 0.2∠-149°
Connected	L_1-L_2= 1+j0.2 L_2=2+j0.3	L_1-L_2= 2+j0.5 L_2=4+j2	0.7∠-23° 0.01∠-23°	0.7∠-23° 0.01∠-23°	0.7∠-83° 0.01∠-101°	0.9∠-95° 0.02∠-105°	1.4∠-128° 0.6∠-138°
Isolated	L_1-L_2= 1+j0.2 L_2=2+j0.3	L_1-L_2= 2+j0.5 L_2=4+j2	1.69∠41° 0.04∠41°	4.2∠-151° 0.1∠-151°	4.9∠-150° 0.1∠-150°	5.1∠-149° 0.12∠-149°	5.9∠-151° 0.2∠-151°

Table 7-7 Influence of Neutral Isolation on N-E Voltages Due to L_2-to-Earth Fault- Low Fault Current (~ 0.57Amperes)

Neutral Connected Or Isolated	Dairy Farm Load (KVA)		N-E Voltage (Volts) / Ground Current (Amps)				
	House	Barn	TFM. Prim.	TFM. Sec.	Farm Service	House	Barn
Connected	L_1-L_2= 1+j0.2 L_1=2+j0.3	L_1-L_2= 2+j0.5 L_1=4+j2	2.6∠48° 0.06∠48°	2.6∠48° 0.06∠48°	3.3∠45° 0.07∠52°	3.5∠45° 0.08∠44°	4.2∠40° 0.12∠37°
Isolated	L_1-L_2= 1+j0.2 L_1=2+j0.3	L_1-L_2= 2+j0.5 L_1=4+j2	1.7∠41° 0.04∠41°	4.2∠29° 0.9∠29°	4.9∠30° 0.1∠30°	5.1∠31° 0.12∠31°	5.9∠29° 0.22∠29°
Connected	L_1-L_2= 1+j0.2 L_2=2+j0.3	L_1-L_2= 2+j0.5 L_2=4+j2	2.9∠50° 0.07∠50°	2.9∠50° 0.07∠50°	2.3∠55° 0.05∠52°	2.0∠56° 0.05∠54°	1.5∠77° 0.05∠57°
Isolated	L_1-L_2= 1+j0.2 L_2=2+j0.3	L_1-L_2= 2+j0.5 L_2=4+j2	1.69∠41° 0.04∠41°	5.9∠30° 0.14∠30°	5.2∠29° 0.12∠29°	4.9∠28° 0.11∠28°	4.1∠31° 0.2∠31°

Table 7-8 Influence of Neutral Isolation on N-E Voltages Due to L_1-to-Earth Fault- High Fault Current (~ 2.8Amperes)

Neutral Connected Or Isolated	Dairy Farm Load (KVA)		N-E Voltage (Volts) / Ground Current (Amps)				
	House	Barn	TFM. Prim.	TFM. Sec.	Farm Service	House	Barn
Connected	L_1-L_2= 1+j0.2 L_1=2+j0.3	L_1-L_2= 2+j0.5 L_1=4+j2	5.8∠-109° 0.1∠-109°	5.8∠-109° 0.1∠-109°	5.2∠-105° 0.14∠-114°	5.0∠-103° 0.13∠-112°	4.7∠-94° 0.2∠-126°
Isolated	L_1-L_2= 1+j0.2 L_1=2+j0.3	L_1-L_2= 2+j0.5 L_1=4+j2	1.7∠42° 0.04∠42°	22∠-150° 0.5∠-150°	22∠-151° 0.5∠-151°	22∠-151° 0.5∠-151°	21∠-150° 0.8∠-150°
Connected	L_1-L_2= 1+j0.2 L_2=2+j0.3	L_1-L_2= 2+j0.5 L_2=4+j2	5.5∠-109° 0.1∠-109°	5.5∠-109° 0.1∠-109°	6.1∠-113° 0.2∠-120°	6.3∠-114° 0.2∠-119°	6.9∠-119° 0.3∠-134°
Isolated	L_1-L_2= 1+j0.2 L_2=2+j0.3	L_1-L_2= 2+j0.5 L_2=4+j2	1.7∠42° 0.04∠42°	21∠-150° 0.5∠30°	22∠-150° 0.5∠-150°	22∠-150° 0.5∠-150°	23∠-150° 0.9∠-150°

Table 7-9 Influence of Neutral Isolation on N-E Voltages Due to L_2-to-Earth Fault- High Fault Current (~ 2.8Amperes)

Neutral Connected Or Isolated	Dairy Farm Load (KVA)		N-E Voltage (Volts)/Ground Current (Amps)				
	House	Barn	TFM. Prim.	TFM. Sec.	Farm Service	House	Barn
Connected	L_1-L_2= 1+j0.2 L_1=2+j0.3	L_1-L_2= 2+j0.5 L_1=4+j2	7.9∠58° 0.2∠58°	7.9∠58° 0.2∠58°	8.6∠56° 0.22∠52°	8.8∠56° 0.2∠53°	9.5∠53° 0.34∠44°
Isolated	L_1-L_2= 1+j0.2 L_1=2+j0.3	L_1-L_2= 2+j0.5 L_1=4+j2	1.7∠42° 0.04∠42°	21∠30° 0.5∠30°	22∠30° 0.5∠30°	22∠30° 0.5∠30°	23∠29° 0.9∠29°
Connected	L_1-L_2= 1+j0.2 L_2=2+j0.3	L_1-L_2= 2+j0.5 L_2=4+j2	8.2∠58° 0.2∠58°	8.2∠58° 0.2∠58°	7.6∠61° 0.2∠56°	7.4∠61° 0.2∠57°	6.8∠66° 0.3∠49°
Isolated	L_1-L_2= 1+j0.2 L_2=2+j0.3	L_1-L_2= 2+j0.5 L_2=4+j2	1.7∠42° 0.04∠42°	22∠29° 0.5∠30°	22∠29° 0.5∠29°	21∠29° 0.5∠29°	21∠30° 0.8∠30°

Isolation Devices

Earlier editions of the NESC allowed isolation by use of a spark gap with a rating of 10 kV or greater. This provision was developed early in the history of electrical distribution systems, primarily for the protection of the transformer winding during abnormal operation (60 Hz fault or lightning) of the power system. Later, the isolation issue was reviewed with respect to protection of the customer in the event of a primary to secondary fault or lightning striking the customer premises directly. In the case of a primary to secondary fault, sufficient current must pass from the secondary to the primary for proper operation of protection devices. In the case of a lightning strike, connection to the primary neutral provides a low impedance path. As a result of these concerns, the NESC grounding committee revised the code requiring isolating devices to have a 3 kV or less breakdown voltage.

There are three types of devices currently being used for primary to secondary isolation. These include:

1. Spark Gap or Surge Arrester
2. Switching or reconnect devices during fault conditions, Saturable Reactor or Electronic Switch
3. Isolation Transformer.

Devices listed in 1) and 2) above provide mitigation by isolating the primary neutral from the secondary neutral during normal operation of the distribution system. During 60 Hz fault or lightning, these devices by themselves or in combination connect the neutrals providing safer environment for the customer and his/her premises. The device listed in 3), the isolating transformer, typically connects in series with the secondary system isolating all three conductors: two line conductors and one neutral conductor.

Spark Gap or Surge Arrester A spark gap in stand-alone applications is rarely used for stray voltage mitigation due to its unreliable shorting characteristics during a lightning surge or 60 Hz fault. Instead, utilities prefer the use of MOV arresters which have superior operating reliability. However, using these devices in conjunction with other blocking devices to let through lightning surges or faults is widely accepted practice.

In Michigan primary to secondary neutral isolation is permitted on a long-term basis. Approximately 60% of animal farms in that state are now isolated, mostly with just MOV arresters.

Saturating Reactor The saturating reactor is a device which operates directly on the principle of magnetic saturation. Primary to secondary neutral voltages seldom exceed several volts in normal operation. At these voltage levels the saturable reactor has a very high impedance value, effectively blocking the primary neutral voltage and current from entering the secondary neutral system. On the other hand, the device has a very low impedance value for voltages above 12 volts. This characteristic provides the fault current path in the event of a primary to ground or a primary to secondary fault. Typical

costs for this device range from $300 to $500. Devices are available with ratings between 12-volts and 27-volts with different saturation characteristics.
Electrical ratings of a typical 12 volts saturable reactor is shown below[24]:

- Series impedance of 2000 Ω for 6 volts or less
- Saturation impedance is 0.5 Ω or less for 12 volts and higher voltages
- 60 Hz fault current capacity exceeds 5000 amperes
- Surge protection is provided by MOV rated at 60,000 amperes (peak) and 1500 joules

The researchers[39] have tested reactors from two different manufacturers for 60Hz fault current capacity and for lightning surge performance. One manufacturer's reactor limited the voltage across itself to 2 ms spikes of 190 volts and 290 volts for 20 amperes and 2,000 amperes fault current values, respectively. Surge tests were performed with currents of approximately 15.5 kA-crest. No physical damage to the device was apparent. The second reactor was tested with currents ranging from 100 to 3,000 amperes. The inductance, internal resistance and saturation level of the device remained unchanged. The second reactor passed the lightning surge tests conducted with 8x20 μsec waveforms of crest magnitudes ranging from 2 kA 80 kA.

Solid-State Switch Another isolating device typically used for mitigating a stray voltage problem is a solid-state switch. The switch consists of oppositely directed thyristors connected in parallel, which are fired when the voltage across them reaches a preset value. This effectively reconnects the neutrals during fault conditions while blocking the N-E voltage with high impedance below the triggering threshold. In contrast to the saturable reactor which cannot block dc currents, the solid-state switch can block both ac and dc currents below the triggering threshold.

The same researchers[39] as mentioned in "Saturable Reactor Section" performed the tests on couple of solid-state switches. The switches survived the fault currents ranging from 20 amperes to 2,400 amperes with no apparent changes in their characteristics. However, an additional test at 3,000 amperes for 6 ms failed the device. The failure mode consisted of the thyristors short-circuiting across the terminals (a desirable failure mode). Note that the device rating was 1,800 amperes.

Isolating Transformer Isolating transformers, Figure 7-8, are used extensively to create a separate grounded neutral system on animal farms. In this system, a primary-to-secondary fault is carried by the distribution system neutral, an advantage that other isolation systems do not have. Such systems, however, represent quite an investment plus the cost of operating losses of the transformer. These units normally have ratings from 20 to 25 kVA. For proper installation of this system, conformance to prevailing codes and recommendations, particularly for over-current protection and bonding may be required[42]. According to one estimate, the cost of this device ranges from $1500 to $5000[24].

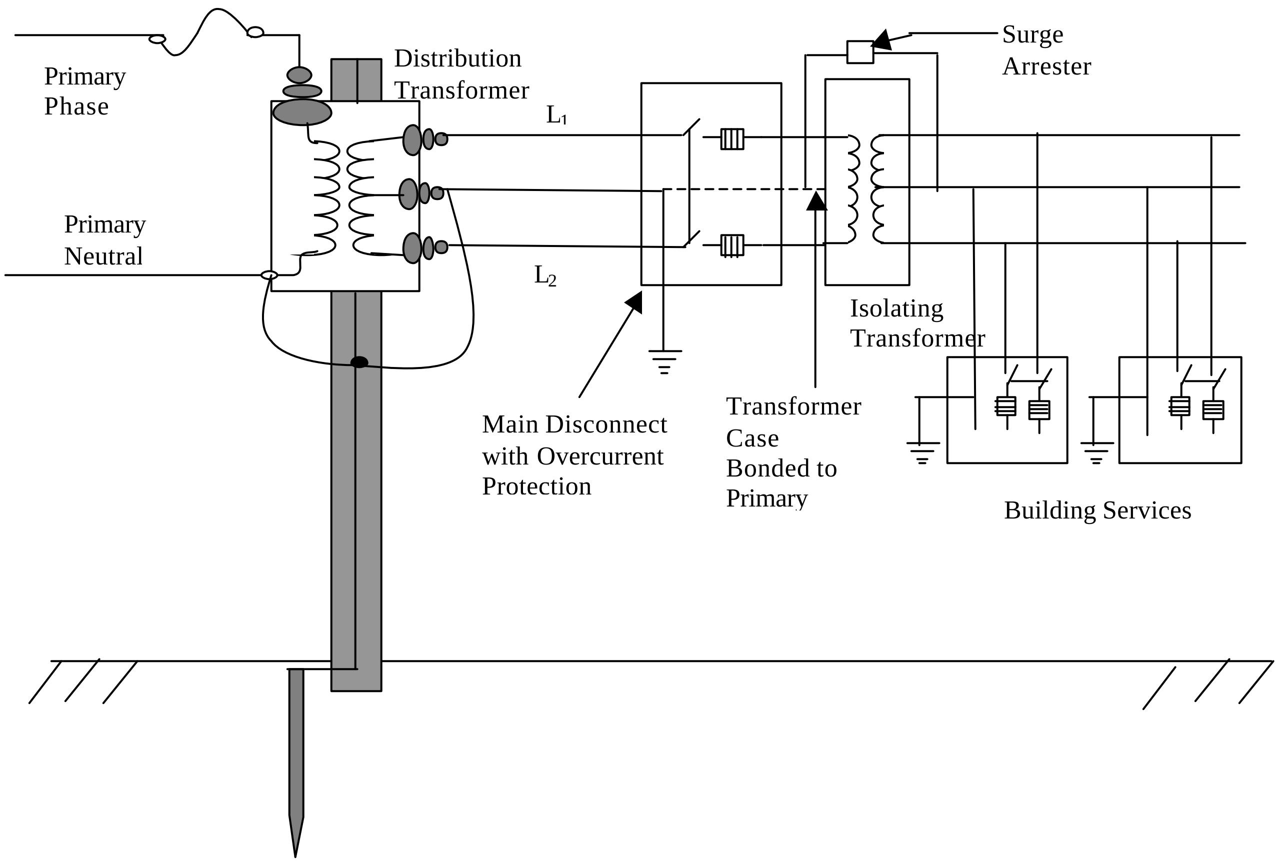


Figure 7-8 Application of Isolating Transformer at the Main Service Panel in a Dairy Farm

Isolation at a Single Building Service

Building Service Isolation

If the investigation indicates that a satisfactory mitigation can be obtained by providing isolation at the individual building service, an isolating device such as an isolating transformer can be installed at the building service panel. Figure 7-8 shows the application of the isolating transformer for the main entrance to a dairy farm. In the same manner, an isolating transformer can be used downstream for a building service. The transformer required for an individual building service will have less kVA rating and would therefore be more economical.

When the isolating transformer is installed at a single building service such as at a barn service panel, assurance is necessary that no conductive interconnection is bypassing the transformer. Some of the common interconnections in a barn includes metallic gas or water pipes, metal feeders, fences, and connected metal buildings. Any conductive interconnection will negate the isolation.

Neutral / Grounding Isolation at Service Entrance

An approach approved by the Canadian Standards Association under Rules of the Canadian Electrical Code, Part-I and II, makes use of what is termed a "tingle voltage" filter. The "tingle voltage" filter is a special name for the saturable reactor devices discussed previously. Ontario Hydro developed this approach in cooperation with Hammond Electrical Industries. Figure 7-9 shows its application at the barn service entrance of Section 8 dairy farm example (see Figure 8-2).

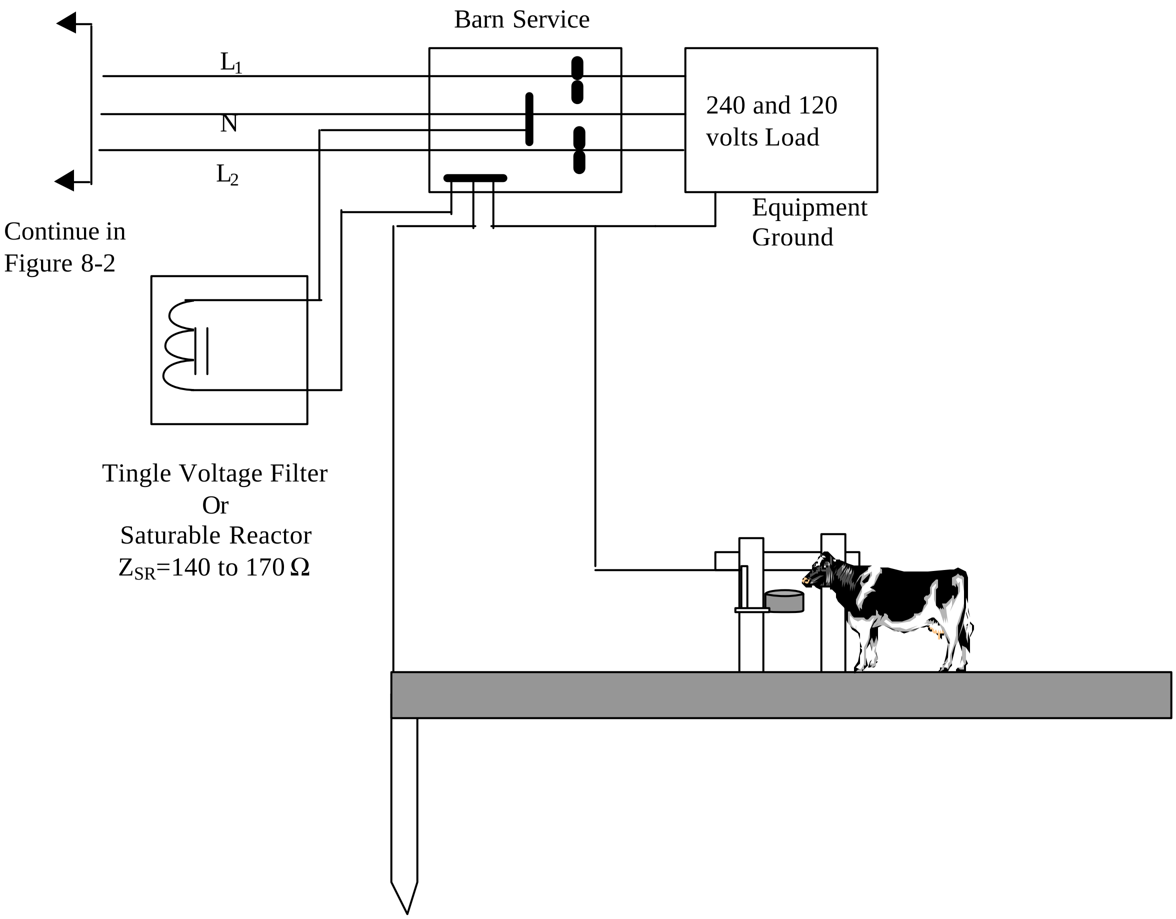


Figure 7-9 Saturable Reactor Application to Isolate the Neutral from the Grounding System at the Barn Service Entrance

As shown in Figure 7-9, the saturable reactor separates the neutral conductors (grounded at other buildings) from equipment ground and the grounding electrode at the barn service. Under normal conditions, the reactor represents a high impedance (140 Ω to 170 Ω) in the neutral to ground circuit. Introduction of this impedance forces the neutral current to return via the neutral circuit and not via the grounded equipment or the ground electrode system. Under fault conditions (above 27 volts), the reactor saturates and the impedance drops to 0.14 Ω or less. In a phase-to-ground fault on a 240/120 volts system, the impedance is 0.018 Ω. Under fault conditions, the device adds up to 15% impedance in the neutral ground path.

Effectiveness of this mitigation system can be estimated from the equivalent circuit of Figure 7-10. Neglecting any increase in N-E voltage on the source side, this isolation system would reduce the N-E voltage in the contact area to $\left(\frac{R_{eq(CAN)}}{R_{eq(CAN)} + Z_{SR}} \right) x V_{NE}$ Volts. The lower the ratio $\left(\frac{R_{eq(CAN)}}{R_{eq(CAN)} + Z_{SR}} \right)$ is, the more effective this method becomes. Since the value of equivalent resistance $R_{eq(CAN)}$ is dictated by the value of R_g, the barn grounding system resistance is typically low for a dairy farm. As a result, using a saturable reactor with moderate impedance values (Z_{SR}=j140 Ω to j170 Ω) can still help reduce the N-E voltages in animal contact areas effectively.

The effectiveness of this mitigation approach can be estimated in the field. To achieve this objective, the unsaturated impedance value for the device must be known (j150 Ω for Z_{SR} can be used). To estimate the effectiveness, the value of the equivalent resistance $R_{eq(CAN)}$ is then required. This variable can be measured at the site using a clamp-on resistance meter as shown in Field Measurements Section, Section 6.

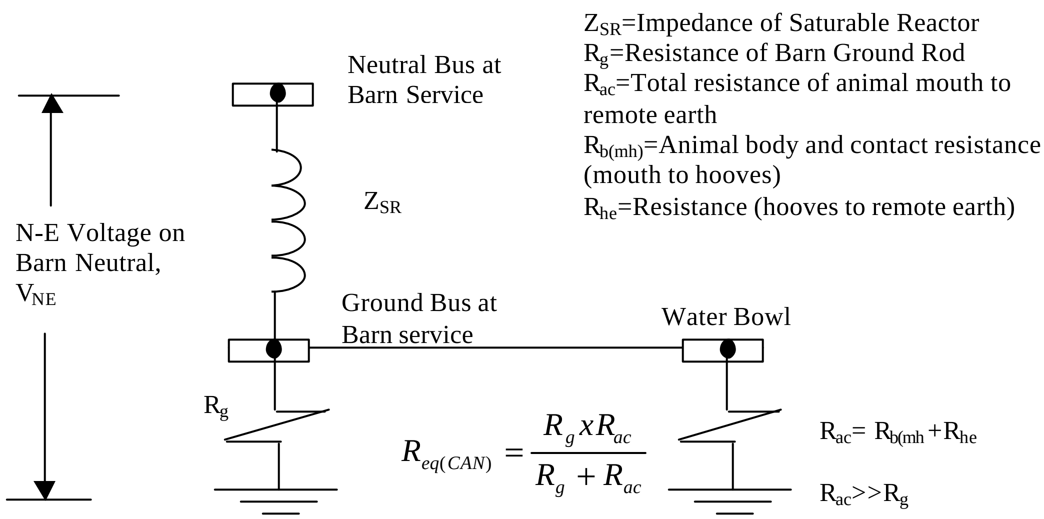


Figure 7-10 Equivalent Circuit with Saturable Reactor Applied between the Neutral and the Barn Grounding System

The computer model can also determine the effectiveness of this mitigation method accurately. After modifying the dairy farm model of Section 8 (see Figure 8-1 and Figure 8-2) to include the saturable reactor as shown in Figure 7-9, the NE and stray voltages were computed using the computer program. Table 7-10 presents these data. For comparison, the table also provides corresponding data for the base case (Analysis Scenario-3, Section 8) and for primary-to-secondary isolation case (Corrective Measure Scenario-3).

Table 7-10 Comparison of Effectiveness Between Neutral-to-Ground Isolation at Barn Service (Canadian Practice) and Primary-to-Secondary Neutral Isolation (Dairy Farm Example of Section 8)

Mitigation Type	N-E Voltage At Barn Neutral / Ground Volts	Open Circuit Contact Voltage (V_{oc}), Volts	Closed Circuit Contact Voltage (V_{cc}), Volts	Animal Current (I_c), mA	Reduction in V_{oc} or V_{cc} from Base Case
No Mitigation (Base case)	6.31/6.31	5.9	2.293	4.586	--
Primary-to-Secondary Neutral Isolation	0.74/0.74	0.7	0.268	0.536	88 %
Neutral-to-Ground Isolation at Barn	6.55/1.7	1.75	0.62	1.24	70 % (V_{oc}) and 73% (V_{cc})

This approach has the advantage of low cost. Also, unlike primary-to-secondary neutral isolation, the entire facility may not be isolated. However, because its' performance depends on complete separation of grounding from the neutral within the service and separation of grounding systems between the services, installation may be difficult in some existing facilities.

Saturable reactors have not received listing by Underwriter's Laboratory for this application. Also, the National Electric Code has not accepted the concept yet. As a result, its use in the US cannot be recommended unless approved by appropriate electrical inspection authorities on an experimental basis.

Isolation of Non-Electrified Metallic System

An addition was made in NEC article 547-8 (Agricultural Buildings) to allow isolation of any non-electrified metallic system from the building service neutral / ground through an approved high impedance device. According to NEC, the non-electrified metallic system includes any metallic piping or structure to which electrical equipment requiring grounding is not attached or in contact with. As an example, the non-electrified metallic system may include interior water pipes, stanchion pipes, and / or stall pipes provided they are not attached to any electrical equipment directly or indirectly. NEC also specifies the fault rating for the device to be a minimum of 10,000 amperes. In addition, it specifies various system bonding requirements.

As discussed previously, the Canadian approach consists of isolating the neutral from the entire building grounding system. In contrast, this method consists of isolating a part of the grounding system from the neutral. The rest of the grounding system would still remain connected to the neutral at the service panel. The non-electrified metallic pipes or structures as defined above are the only parts of the grounding system that are allowed for isolation. Typically, the animal to remote earth circuit will be in parallel and part of the isolated grounding system. Figure 7-11 shows the application of the saturable reactor in this mitigation method. Figure 7-12 shows the corresponding equivalent circuit.

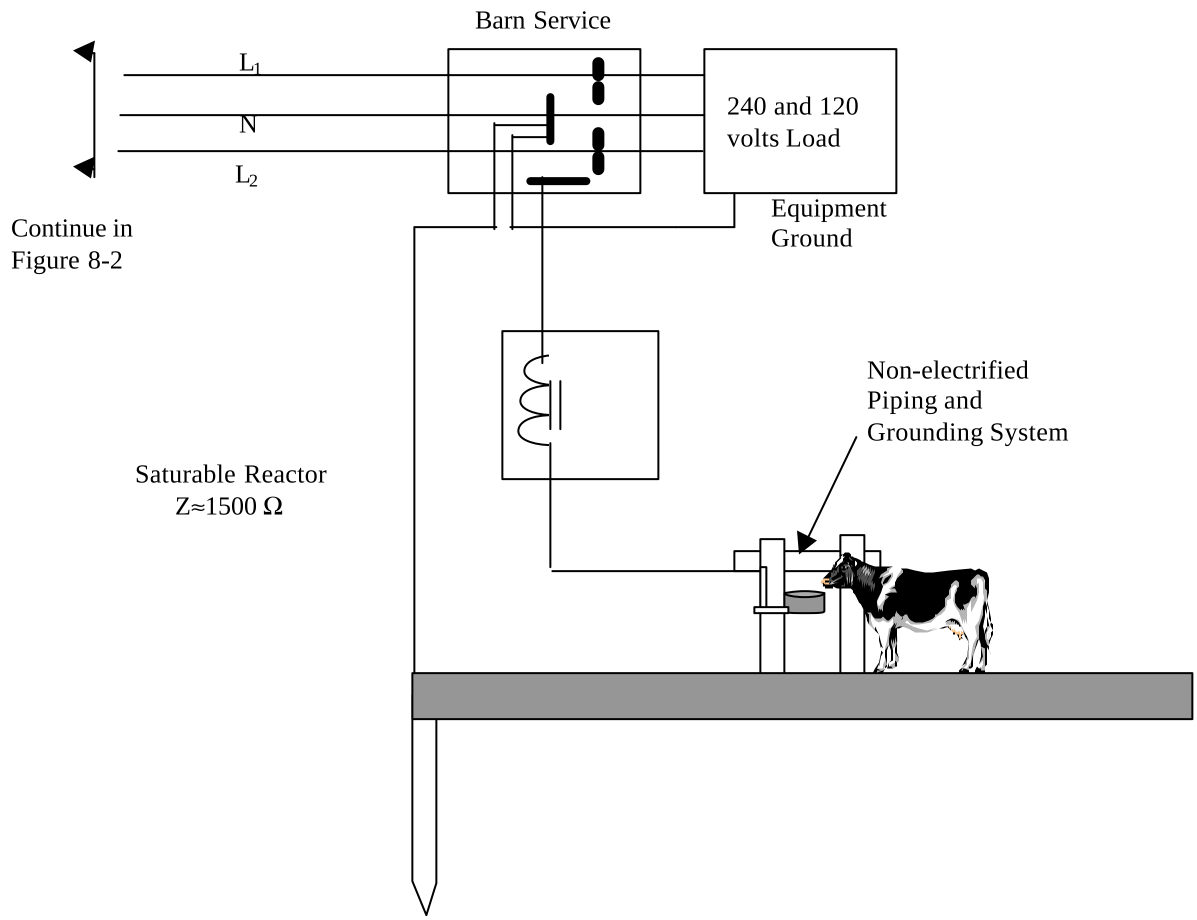


Figure 7-11 Saturable Reactor Application to Isolate the Non-Electrified Metallic System form the Building Service Neutral/Ground

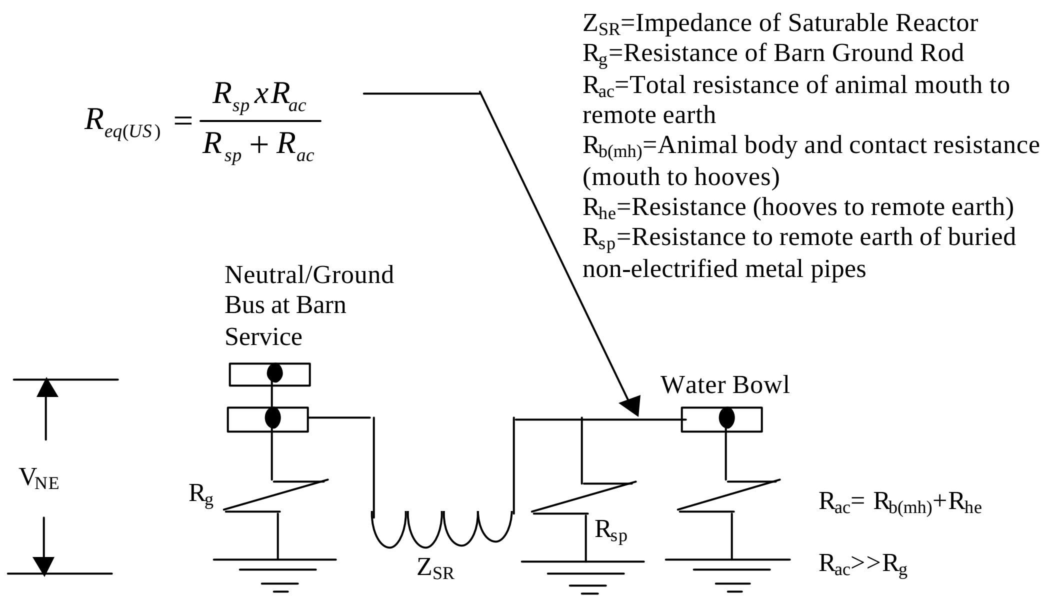


Figure 7-12 Equivalent Circuit with Saturable Reactor Applied between the Neutral / Ground and the Non-Electrified Piping System in the Barn

Similar to the Canadian approach, the effectiveness of this mitigation method depends on the ratio, $\left(\frac{R_{eq(US)}}{R_{eq(US)} + Z_{SR}}\right)$. In general, the equivalent resistance $R_{eq(US)}$ in this approach is significantly high due to its make up which consists of buried non-electrified pipes in parallel with the animal's body resistance in series with hooves' resistance to remote earth. This results in a higher $\left(\frac{R_{eq(US)}}{R_{eq(US)} + Z_{SR}}\right)$ ratio and lower effectiveness if the saturable reactor of a moderate impedance value were used for this application. To increase the effectiveness of this method, a saturable reactor with higher impedance (Z_{SR}=j1500 Ω or higher) must therefore be used[43].

The effectiveness of this method using the computer program is determined next. To illustrate the influence of various parameters on the effectiveness, the study includes application of two saturable reactors, one with Z_{SR} = j150 Ω and another with Z_{SR} = j1500 Ω. The study also includes two different values for equivalent resistance, $R_{eq(US)}$. Table 7-11 presents the data of N-E Voltages, contact voltages and animal current before and after the application of mitigation method.

Table 7-11 Influence of Reactor Impedance and Equivalent Resistance of Non-Electrified Grounding System on the Effectiveness of Partial Isolation of Grounding System as Per NEC Article 547-8 (Dairy Farm Example of Section 8)

Mitigation Type	N-E Voltage At Barn $V_{NE(Neut)}$/ $V_{NE(pipe)}$ Volts	Open Circuit Contact Voltage (V_{oc}), Volts	Closed Circuit Contact Voltage (V_{cc}), Volts	Animal Current (I_c), mA	Reduction in V_{oc} and V_{cc} from Base Case
No Mitigation (Base case)	6.31/6.31	5.9	2.293	4.586	--
NEC 547-8 Z_{SR}=j150Ω $R_{eq(US)}$=454Ω	6.3/5.9	6.14	2.16	4.33	∗V_{oc} - (4%) V_{cc} - 6%
NEC 547-8 Z_{SR}=j150Ω $R_{eq(US)}$=78Ω	6.2/3.0	3.26	1.96	3.92	V_{oc} - 45% V_{cc} - 14%
NEC 547-8 Z_{SR}=j1500Ω $R_{eq(US)}$=454Ω	6.3/1.9	2.67	0.63	1.26	V_{oc} - 55% V_{cc} - 72%
NEC 547-8 Z_{SR}=j1500Ω $R_{eq(US)}$=78Ω	6.3/0.62	0.62	0.112	0.224	V_{oc} - 89% V_{cc} - 95%

∗ 4% increase in V_{oc} compared to base case

The data in Table 7-11 suggests that for the NEC 547-8 method to be effective, the reactor with j1500Ω or more impedance must be selected regardless of the equivalent resistance ($R_{eq(US)}$) value for the non-electrified grounding system.

Four Wire System

There are times when a long secondary feeder is unavoidable. A four-wire system may be a practical mitigation method for this case. The rules for four-wire service can be found in NEC sections 547-8(a) exception-1 (Rules for Agricultural Buildings) and 250-24, exception-2 (General Grounding and Bonding Rules). The specific rules for a four-wire system from building service to the main service panel were added in 1987. These rules allow the neutral bus to be separated from the equipment ground bus in the building service panel and to carry the four-wire system (separate neutral and ground wires) from the building service panel to the main service panel. In the main service panel, the neutral bus and the ground bus must then be connected together.

To maintain the four-wire system at the building service panel, additional rules are specified.

These include:

- Each panel fed from the four-wire system must have two bus bars – one for the neutral and one for the equipment-grounding conductors.
- The grounding bus bar must be solidly connected to the panel itself and all equipment-grounding conductors (green wires).
- The isolated neutral bus bar must only connect to the neutral wires (white wires) from the equipment.
- There must be no connection between the equipment grounding and the neutral wire in the equipment or at the equipment location.

As discussed in Section 8, Corrective Measure Scenario-7, the four-wire system from the barn service to the farm service could only eliminate the N-E voltage resulting from the voltage drop on the neutral between the two service panels. In the example, the four-wire system from the barn service to main service reduced the N-E voltage at the barn by only 13%. The 1/0 ASCR neutral was 125 feet long and was carrying 35 amperes.

There are some concerns associated with the four-wire system. One concern is that since the equipment ground conductors are tied to neutral at only one point (main service panel), an open circuit or a high impedance splice in any of the ground conductors may go unnoticed until a fault occurs and then it may be too late. Another concern with the four-wire system is that it is rarely installed properly. Unsafe installation may result from poor understanding of all the rules of the NEC code. Like other isolation methods, if there are ground and neutral connections downstream, the system will not work as intended.

Mitigation of Induced Voltage / Current

In general, the magnetically coupled voltage from a nearby transmission line adds to the N-E voltages already existing on the distribution circuit due to loads. The induced voltage will be proportional to the magnitude and the direction of the transmission line load flow and the length of the parallel and will be inversely proportional to the separation distance.

By taking advantage of one or two of the above variables, the induced voltages can be minimized. For example, transferring the affected customers on an alternate feeder free from any induction is an effective solution. However, this may not be a cost effective solution. Moving the parallel section of the distribution circuit away from the transmission line also can reduce the induced voltages. If the induced voltage is on the primary side only, the isolation of the neutral at the transformer can also provide effective stray voltage mitigation for the customer facility.

Special Mitigation Methods

Current Balancing Transformer (CBT)

The Current Balancing Transformer (CBT) provides an effective tool for mitigating stray voltages and currents. For the primary side, this is the only device-based mitigation method presently available. Figure 7-13 shows its application for a customer who is receiving a single-phase service.

The CBT strongly couples the primary phase and primary neutral current, forcing the return current to travel through the neutral rather than through ground paths. Reducing the current in ground electrode paths thus reduces the N-E voltages. The magnetic field created by the return current in the neutral cancels the field created by the phase current, thereby eliminating magnetic fields in the transformer core. As shown in Figure 7-13, the CBT connects in series with the phase and neutral conductors. This connection is similar to a current transformer. However, CBT differs from a current transformer in that the transformation ratio in the case of CBT is 1:1.

Presently, single-phase units with 15 kV and 25 kV ratings are available. Technical data for 15 kV CBT as published by a manufacturer are shown below:

- Single-phase, 50 kVA, 15 kV two-wire service
- Rated to 7 amperes, 60 Hz, 55° rise
- Series impedance: 0.044 Ohms at 75° under balanced loading
- Certified to withstand 1,000 amperes rms fault current for 2.5 cycles to coordinate with a 15 amperes T-link fuse.
- Weight 180 lbs. (82 kg)

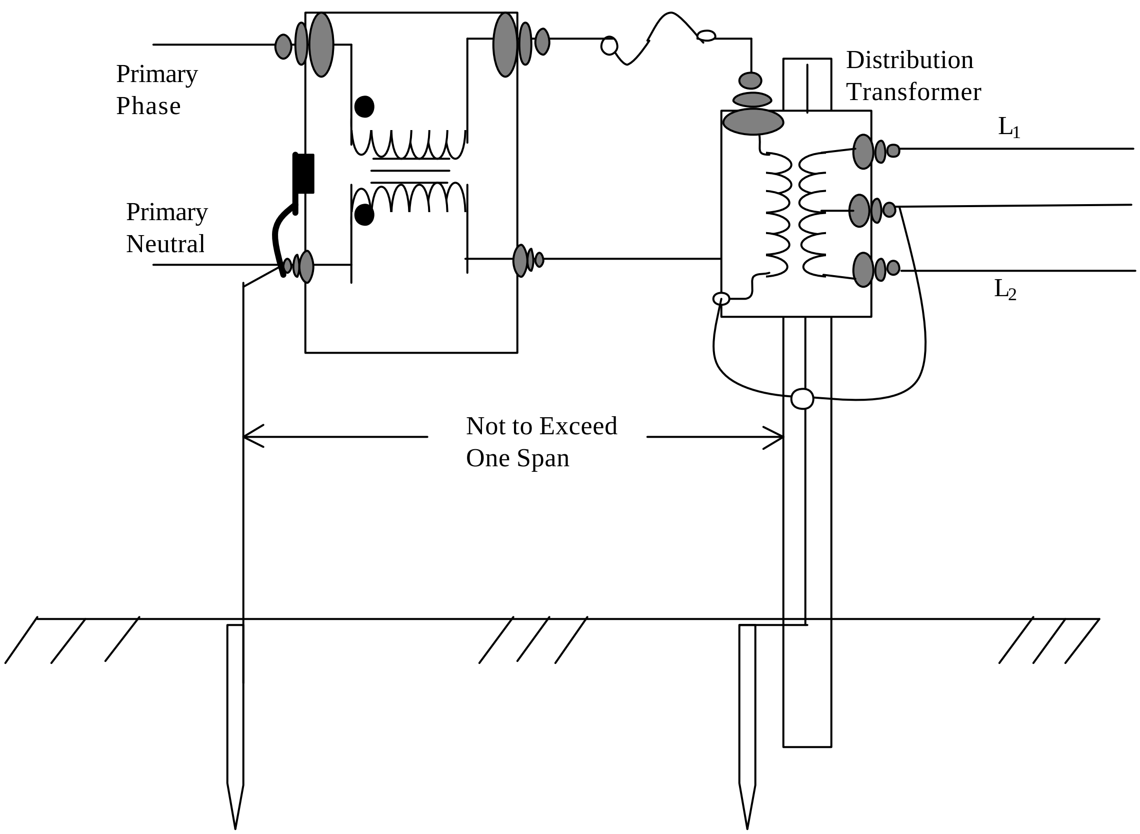


Figure 7-13 Application of Current Balancing Transformer (CBT)

The effectiveness of the CBT in reducing the N-E voltages in the customer facility depends on how balanced are the currents in the phase and neutral conductors. If the CBT is located in the proximity of the distribution transformer, these currents are mostly balanced and maximum effectiveness can be achieved. To achieve greater effectiveness, the manufacturer prefers that the device should be placed within a span length from the transformer. To illustrate the CBT's effectiveness in the dairy farm example of Section 8 (Figure 8-1 and 8-2), a 15 kV CBT was placed on the primary side of the dairy farm transformer. Keeping all other parameters the same as the base case (Analysis Scenario-3), the N-E voltages and ground currents for various farm locations were computed.

Table-12 shows N-E voltage and ground electrode current data for CBT application. For comparison purpose, the data for the base case (Analysis Scenario-3, Section 8) and that for the neutral isolation case (Corrective Scenario-3, Section 8) are also provided.

Table 7-12 N-E Voltage and Ground Electrode Currents in the Example Dairy Farm of Section 8 – Base Case, Neutral Isolation Case and CBT Application Case

Base Case (Analysis Scenario-3, Section 8)		
Ground Location	N-E Voltage, Volts	Ground Electrode Current , A
BUS6 (TFM)	4.79 ∠25°	0.115 ∠25°
FARM SERVICE	5.49 ∠26°	0.131 ∠26°
HOUSE	5.70 ∠27°	0.136 ∠27°
BARN SERVICE	6.31 ∠26°	0.149 ∠26°
Application of Current Balancing Transformer		
Ground Location	N-E Voltage, Volts	Ground Electrode Current , A
BUS6 (CBT, SOURCE SIDE) ∗	5.78 ∠34°	0.138∠34°
BUS6 (DISTRIBUTION TFM)	0.79 ∠-147°	0.019 ∠-147°
FARM SERVICE	0.08 ∠-152°	0.002 ∠-152°
HOUSE	0.153 ∠56°	0.004∠56°
BARN SERVICE	0.74 ∠28°	0.018 ∠28°
Primary to Secondary Neutral Isolation (Corrective Measure Scenario-3, Section-8)		
Ground Location	N-E Voltage, Volts	Ground Electrode Current, A
BUS6 (TFM), PRIMARY	5.78 ∠34°	0.138∠34°
BUS6 (TFM), SECONDARY♣	0.79 ∠-147°	0.019 ∠-147°
FARM SERVICE	0.08 ∠-152°	0.002 ∠-152°
HOUSE	0.153 ∠56°	0.004∠56°
BARN SERVICE	0.74 ∠28°	0.018 ∠28°

∗ 8' ground rod was added on the source side of the CBT as required by NESC Rule 97D2

♣ 8' ground rod was added to the TFM secondary neutral as required by NESC Rule 97D2

The data in Table7-12 point to an interesting conclusion regarding reduction in N-E voltages and ground electrode currents due to the application of a CBT and the neutral isolator. Their influence in reducing the N-E voltages in the dairy farm is identical. As discussed before, neutral isolation removes two main stray voltage sources, the source from off-farm load and the source due to on-farm load appearing on the primary side. The CBT performs the same task but with the neutral connected. Also, notice in the table that both methods raise the N-E voltages on the source side of their applications.

There are pros and cons of using a CBT to mitigate stray voltage concerns. The CBT is a high voltage device requiring a lightning arrester and fuse-link for protection. This protection cost should be added to the device cost of approximately $ 2000 (15 kV Class CBT). The fault current carrying capacity being only 1,500 amperes for 0.016 seconds (15 kV CBT), its application may be limited. Also, no units for underground applications are available at the present time. The units that are available include only the 15 kV and 25 kV class CBT's for single-phase applications. The 25 kV unit is tested up to 5,600 amperes of fault current. The time duration is not known. User should review the test data before purchasing the unit.

The main advantage of this device is that it can effectively mitigate a stray voltage problem without the neutral isolation. Unlike the neutral isolation method, a CBT can be installed to mitigate stray voltage problems for more than one customer. For example, a 15 kV, 50 kVA unit can be installed on the primary tap serving three to four customers, provided the fault current limitation is satisfied.

Active Voltage Suppression

Since voltage is produced by a current flow through a ground electrode system, a second source of current may be used to null or cancel the original source at a point of concern in the system. One procedure is to deliver a controlled current to earth as shown in Figure 7-14. The mitigation system shown in the figure is known as Electronic Grounding System (EGS).

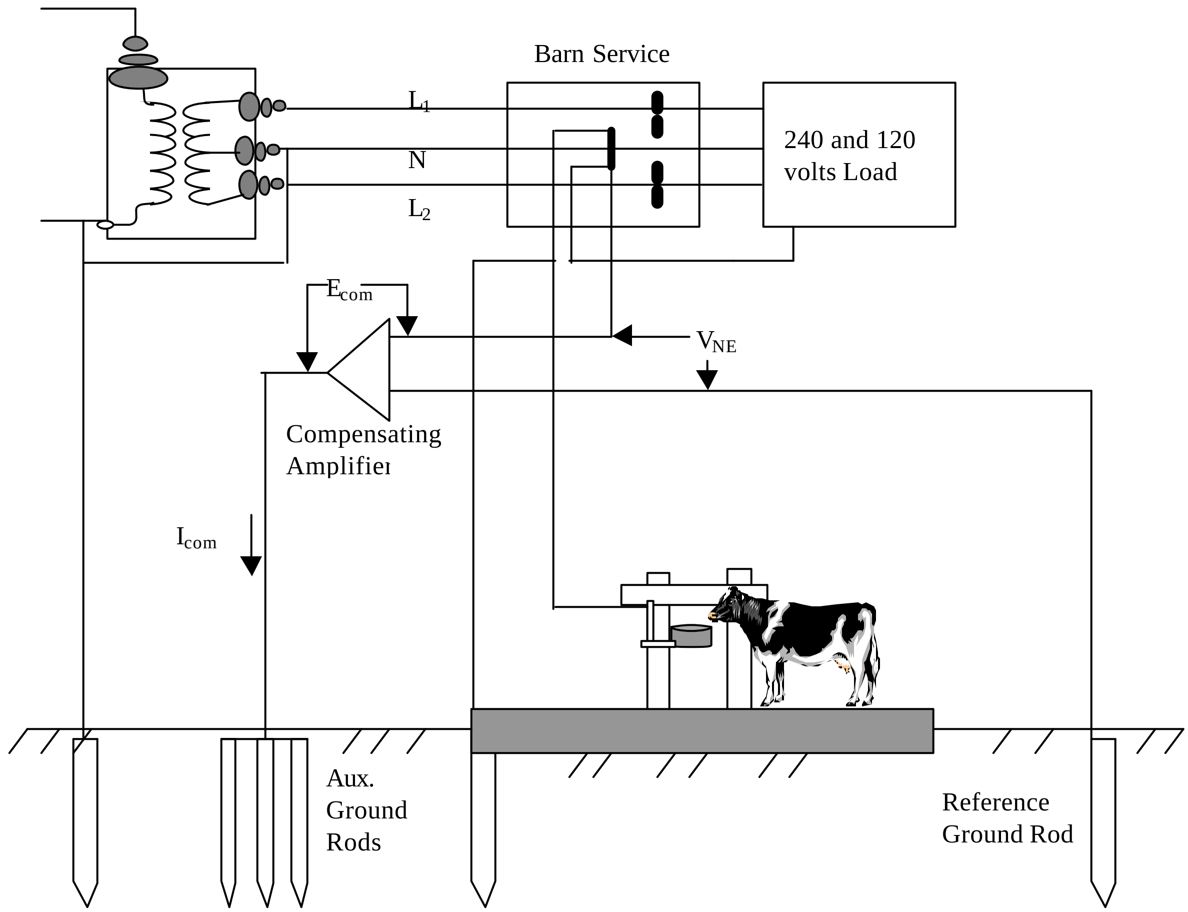


Figure 7-14 Application of Electronic Grounding System (EGS) to Reduce N-E Voltage at Barn Service

Referring to Figure 7-14, the EGS senses the barn N-E voltage, V_{NE}, and passes a proportional current, I_{com}, into earth through auxiliary ground rods, R_{ag}, which are located remote from other farm ground rods. The compensating current is drawn from the neutral / ground bus at the barn service, passed through the amplifier, and sent back to the distribution grounding system. The EGS, in effect, reduces the barn service ground resistance to 0.005 Ω or less and reduces the barn N-E voltage by factors ranging from 25:1 to 200:1 [23]. These reductions are achieved for N-E voltages at 60 Hz and at its significant harmonics. Also, the EGS is protected from transients by voltage limiting devices and fuses. Abnormal conditions such as equipment faults, earth faults, or neutral conductor problems usually cause N-E voltages higher than the compensating capability of the EGS. A monitor / alarm system in EGS activates if the resultant N-E voltage exceeds 1.0 volt.

Two advantages of this approach are:

1) Installation of this system requires no modification of the farm electrical system including the neutral isolation.
2) In addition to lowering the farm N-E voltages, this system lowers the primary N-E voltages.

Disadvantages of this system includes:

1) Possible maintenance problems inherent to active amplifier type device
2) High initial cost
3) Potential for offsetting problem sources which should be corrected by other means.

Mitigation Methods – Summaries and Surveys

So far in this section, various mitigation methods are described, analyzed, and their advantages and disadvantages listed. The users may want these mitigation methods summarized in a tabular form for easy reference. The users may also want to know about the actual field investigations that were conducted and mitigation recommendations that were made by others. Fortunately, the literature reports a few such investigations and mitigation recommendations. The remainder of these sections summarize the reported data.

Summary of Mitigation Methods Analyzed in the Handbook

Table 7-13 provides a summary of the mitigation methods analyzed in this handbook. The summary compares each method with four different categories. A brief explanation of each of these categories is provided below:

- Application – Type of customer where the method is typically applied.
- Effectiveness – Divided in to three levels: very effective, effective, and somewhat effective. Where applicable, conditions are stated.
- Advantages – Includes reliability, cost factor, ease of installation and safety.
- Disadvantages – Includes limitations, cost factor, and safety.

Table 7-13 Summary of Various Mitigation Methods Discussed in this Handbook

Mitigation Method	Application	Effectiveness	Advantages	Disadvantages
Detection and Restoration of Faulty or Corroded Neutral	Animal Farm, House, Swimming Pool, RV Campground, Boat Dock	–	–	–
Grounding Improvement – Primary Side	Animal Farm, House, Swimming Pool, RV Campground, Boat Dock	Effective if improvement is at the transformer pole	No service interruption, ease of installation, Ideal for small reduction in N-E voltage	To be effective, substantial reduction in resistance required
Equipotential Plane	Animal Farm	Very effective regardless of source(s)	New construction less expensive, provides safety for 60 Hz faults	Retrofit is expensive, inconveniency to animals during retrofit
Ground Ring or Counterpoise	Swimming Pool, Boat Dock, Residence∗	Very effective regardless of source(s)	Less expensive, ease of installation, provides safety for 60 Hz faults	Damage is likely to occur, if not properly buried and connected
♣Increasing neutral wire size	Animal Farm, House, Swimming Pool, RV Campground, Boat Dock	Effective if secondary neutrals are long	-	To be effective, substantial increase in wire size required, service interruption
Load balancing – primary side	Residential subdivision, RV Campground	Very effective for primary sources	Good voltage regulation, a side benefit	Very expensive, service interruption
Load balancing – customer side	Animal farm	Very effective for neutral voltage drop, does not help for primary sources	-	Conversion to 240-volt load is expensive, service interruption
Increase Primary Voltage Level	Entire Feeder	Very effective	Solves voltage regulation problems	Very expensive

∗ Rarely applied but can be an effective mitigation method.

♣Rarely applied on the primary side.

Table 7-13 (Continued) Summary of Various Mitigation Methods Discussed in this Handbook

Mitigation Method	Application	Effectiveness	Advantages	Disadvantages
Primary to Secondary Neutral Isolation	Animal Farm, Residence, Swimming Pool, RV Campground, Boat Dock	Very effective – with the exception of secondary neutral voltage drop, eliminates all sources	Low cost if reactors or electronic switches are used	N-E voltage on primary side of TFM increases, depending on the load or existence of faulty neutral, secondary N-E voltage may increase, ground ties of other utilities may bypass the isolation, safety during primary to secondary fault may be a concern
Isolation at single building service – Isolation Transformer	Animal Farm	Effective regardless of source	Only one building service is isolated, primary to secondary fault is no concern	Expensive, conductive interconnection with other buildings may bypass the isolation
Isolation at single building service – Isolation of neutral bus from ground bus (Canadian Practice)	Animal Farm	Effective regardless of source	Only one building service is isolated, low cost	Not approved by NEC or UL, difficult installation, interconnection with other buildings may bypass the isolation
Isolation at single building service – Isolation of Non-electrified Metallic System (US Practice)	Animal Farm	Effective regardless of source – Effective only with high impedance reactor (j1500 Ω or higher)	Only one building service is isolated, low cost	Difficult installation, interconnection with electrified metallic system may bypass the isolation

Table 7-13 (Continued) Summary of Various Mitigation Methods Discussed in this Handbook

Mitigation Method	Application	Effectiveness	Advantages	Disadvantages
Isolation at single building service – Four Wire System	Animal Farm	Somewhat effective – eliminates only the neutral voltage drop	Only one building service is isolated, low cost	Difficult installation, faulty neutral may go unnoticed until too late, unsafe installation is a possibility, interconnection with other building systems may bypass the isolation
Current Balancing Transformer on the primary side	Animal Farm, Residential subdivision, a group of customers	Very effective – with the exception of secondary neutral voltage drop, eliminates all sources	Does not require neutral isolation, single installation can help more than one customer	Expensive, N-E voltage on source side of CBT increases, applications limited to: 1000 amperes fault, 15 kV or 25 kV, single phase overhead systems
Active Voltage Suppression with Electronic Grounding System	Animal Farm	Very Effective regardless of the source	Does not require neutral isolation, lowers the primary N-E voltages	Frequent maintenance required, high cost

Wisconsin Dairy Farms Survey

Data from more than 2,900 dairy farm stray voltage investigations performed in Wisconsin between 1993 and 1997 by the Investor Owned Utilities (IOU) and the Stray Voltage Analysis Team (SVAT) have been reported in the paper presented at the American Society of Agricultural Engineers (ASAE) meeting held in Orlando, Florida in July 1998[73]. The data included dairy farm related information, which entities were contacted first by the farmers, nature of the complaints, and the types of mitigation recommended and implemented. Only the mitigation information is listed in this section. The other data are presented in Section 5.

Table 7-14 summarizes the mitigation methods found at the time of the first investigation conducted on that farm by a utility investigator. These data are reported from over 2,900 farm investigations conducted between 1993-1997.

Table 7-14 As-found Mitigation Methods During First Time Investigation by Utility Investigators

As-found On-Farm Mitigation Method	% Of Farms
Equipotential Plane	12.4
Four Wire System	6.9
Isolation Device	0.4
Active Voltage Suppression (EGS)	0.4

The on-farm mitigation methods or improvements to the farm wiring system recommended by utility investigators after the investigation was completed are reported in Table 7-15.

Table 7-15 On-Farm Mitigation Methods Recommended By Utility Investigators

On-Farm Mitigation Methods Recommended by Utility Investigators	% Of Farms
Improve Grounding	26.7
Increase Size of Secondary Neutral Wire	22.6
Balance 120–volts Load	15.2
Install Four Wire System	7.0
Install Equipotential Plane	3.8
Install Active Voltage Suppression Device (EGS)	0.3
Install On-Farm Isolation Device	0.2

The off-farm mitigation methods implemented by the utilities are reported as shown in Table 7-16.

Table 7-16 Off-Farm Mitigation Methods Implemented By Utilities

Off-Farm Mitigation Methods Implemented by Utilities	% Of Farms
Improve Grounding	16.1
Increase Size of Secondary Neutral Wire	13.9
Install Neutral Isolator	7.2
Rebuild Distribution Line	4.4
Install UG Primary Cable	1.6
Balance Primary Loads	1.0

The on-farm and off-farm mitigation methods that had been implemented by the applicants (farmers) to SVAT are listed in Table 7-17.

Table 7-17 On-Farm and Off-Farm Mitigation Methods Implemented by Farmers as Reported to SVAT

Methods Implemented	Number of Responses	% Yes
Add grounding	211	77
Rewire Barn	186	62
Add Bonding	181	43
Add Isolation Device	163	41
Add Equipotential Plane	163	30
Change Work Routines (Load Balancing)	151	27
Add Active Voltage Suppression Device (EGS)	150	17

Minnesota Dairy Farms Survey

In 1987, 394 dairy farms in west-central Minnesota were surveyed through the cooperation of four rural electric cooperatives and one investor-owned utility[8][9]. These farms were identified as having primary and secondary neutrals disconnected by use of isolation transformers before August 1986. Of 394 farms investigated, 121 farms had dairy herd improvement (DHI) data available for 24 months prior to and 12 months after the isolation.

The farms were isolated at the distribution transformer and the general criteria for isolation by utilities was a N-E voltage at the barn service entrance above 1.0 volt with an indication that the principal source was off-farm and the animals were exposed to the voltage.

Assessment of DHI rolling herd averages (RHA's) showed that the milk production per cow during the 12 months after isolation was 16,030 pounds and was significantly greater than the milk production of 15,418 pounds for the year before the isolation. Following the isolation, there was no significant change in these traits: peak milk production for first lactation, percentage of older cows leaving the herd, calving interval, conception rate, heat detection index, somatic cell count (sub-clinical mastitis), and percentage of cows having a positive somatic cell count.

Indiana Dairy Farms Survey

The researchers studied 31 Indiana dairy farms suspected of having stray voltage problems[79]. Initial voltage values at the barn service entrance averaged 0.5 volts and increased to 1.1 volts with electrical equipment turned on. Continuous 24-hour surveillance recordings on nine farms showed 1.5 volts. Following the installation of tingle voltage filters (TVF's, see Figure 7-9) in ten problem farms, the stray voltage averaged over the farms decreased by 91% (from 0.7 volts to 0.06 volts). Nine of ten herds showed improvement in individual and group behavior of cows. Milk production per cow increased by 549 pounds annually. The annual gross income increased by $4,800 in the ten TVF herds averaging 70 cows per herd.

Michigan Animal Farms Survey

In Michigan, isolation is permitted on a long-term basis. About 60% of livestock farms are now isolated from primary neutrals, most with just MOV arresters.

Poultry Farms Survey

Hens have a choice whether to lay their eggs in a nest or outside on the slats or on the ground in the chicken house. If the eggs are laid in the nest, they are kept clean and are automatically collected via belt. If they are laid on the slats or on the ground, they are likely to get broken, subject to bacterial contamination, and must be collected by hand in baskets. A significant number of birds laying eggs outside the nests is a costly problem for the farmer.

Researchers at the University of Georgia conducted an extensive study including several controlled experiments to determine the effects of stray voltages on hens laying their eggs in the nests or outside. In preparing for the experiments, the researchers obtained information from the industry on histories of stray voltage problems that had been mitigated with subsequent follow-up to see how floor egg problems were affected. The authors did not specify the area or states in which this survey was conducted. The results of this industry survey are summarized in Table 7-18[87].

The data given in Table 7-18 represents the responses that were sufficiently complete to be reported. The voltages reported are nest to ground voltages (V_{oc}s). Ranges of voltage indicate measurements at different locations in a house or variations in voltage with time. Ranges in percent nest eggs represent estimates in the absence of hard figures.

Farms 2, 3, 7, 8, 9, and 10 seemed to have a positive response to the reduction in stray voltage. Some of these farms (3, 9, and 10) had very low stray voltages before the corrections were made. Given the tendency of stray voltage to vary with time, these values could have been higher at some time other than the time of measurements. Farm 1 showed no improvement, but neither was the stray voltage problem solved. Better grounding does not solve the problem when the stray voltage is present on the primary neutral from an off-farm source unless an equipotential plane can be established. This would be very difficult to accomplish with wooden slats. That appears to be the case for Farm 1. Farm 4 obviously had other problems than stray voltage. Farms 5 and 6 did not respond to corrective measures, but did not seem to have a problem even when voltages existed. It is possible that these voltages were not present when the young birds came in to lay, and thus they were not affected.

Table 7-18 Results of Mitigation Means Applied to Poultry Farms – An Industry Survey

Farm	Stray Voltage, Volts		% Floor Eggs		Corrective Measures Taken
	Before	After	Before	After	
1	4-5	3-4	10	7-10	Improved grounding in house
2	10	0.1-0.5	10	1.5	Installed neutral isolator and other management measures
3	1.5-1.8	0	15-20	2-3	Improved grounding and recessed nests
4	0.1-0.2	?	25	17-20	Improved grounding
5	3-9	0	2.9	0.8	Installed neutral isolator and improved grounding
6	3-9	0	3.8	3.7	Installed neutral isolator and improved grounding
7	3-9	0	8.0	1.9	Installed neutral isolator and improved grounding
8	3-9	0	16.9	5.6	Installed neutral isolator and improved grounding
9	0.25	0.1	15	7	Improved grounding
10	2.7-3.2	0.25-0.5	14	6.5	Improved grounding

Mitigation Methods for Residential Shocking Incidents

A project team under EPRI sponsorship[29] collected and analyzed twelve case studies based on shocking sensations experienced by residential customers. These investigations were conducted in the months of June, July, August, and September of 1998 and included shocking voltage measurements. Measurements were taken in the early to late afternoon to reflect the maximum summertime load. The report includes the information on the shocking voltage location, the measured shocking voltage magnitude, and recommended mitigation method. Table 7-19 presents a summary of the data.

Table 7-19 Summary of Recommended Mitigation Methods for Human Shocking Incidents

Case Study #	Nature of Problem	Measured Shocking Voltages, Volts	Recommended Mitigation Method
1	RV Campground – concerns for shocks while making breaker connection standing on wet surface.	∗0.3 – 16.8	Neutral Isolation (temp) Install 3-phase line (perm) Improve ground (perm)
2	Swimming Pool – Concerns for shocks while getting out of the water using the handrail.	3.7 (water to handrail)	Bond the handrail, balance the load on 3-phase feeder
3	Swimming Pool – Concerns for shocks while getting out of the water on certain sides.	1.6 (water to wet concrete deck)	Bond concrete deck and coping stone, connect the neutral to the nearby transmission tower leg or balance 3-phase load with open-wye connection at the tap
4	Swimming Pool – Concerns for shocks while getting out of the water using the handrail.	7.0 (water to handrail)	Bond flagstone deck and handrail, transfer the load to adjacent taps, balance the 3-phase load upstream
5	Swimming Pool – Concerns for shocks while getting out of the water using the handrail and shocks on the sides with concrete deck	7.3 (water to hand rail)	Bond concrete deck, coping stone and handrail, balance 3-phase load, consider balancing the load on adjacent open-wye circuit
6	Swimming Pool – Concerns for shocks while getting out of the water from the ladder (pool is with concrete deck and shell).	2.0 (also high dc volts)	Convert 2400volt line to 7200 volt line, review dc voltage after the conversion of line
7	Swimming Pool – Concerns for shocks while getting out of the water on the sides.	2.75 (water to concrete deck)	Bond concrete deck and coping stone, Make line open-wye or three phase
8	Swimming Pool – Concerns for shocks while getting out of the water on the sides or using handrail.	3.1 (water to handrail)	Bond concrete deck, coping stone and handrail, replace #6 copper neutral with larger size, part of the load should be open-wye

∗ N-E Voltage at the customer facility for neutral current ranging from 2.9-4.1 amperes in the feeder neutral (1-phase)

Table 7-19 (Continued) Summary of Recommended Mitigation Methods for Human Shocking Incidents

Case Study #	Nature of Problem	Measured Shocking Voltages, Volts	Recommended Mitigation Method
9	Swimming pool under construction – Concerns for the shock from pool water to fill-in dirt on the sides	3.1 (water to soil around the pool area)	No shocking after concrete deck was poured, CATV line extension may help further, increase neutral size as an alternate solution
10	Home under construction – shocking while installing A/C ductwork in the crawlspace	2.45 (metal duct to soil on the floor)	Replace #6 copper neutral by 1/0 ACSR and bond the neutral to the adjacent circuit, either balance the 3-phase load or open-wye the 1-phase circuit up to the subdivision
11	Home – shocking while installing A/C ductwork in the crawlspace	10.0 (metal duct to soil on the floor)	Increase neutral size or install counterpoise wire at the customer location
12	Swimming Pool –Shocks while getting out of the water using the underwater steps.	8.0 (water to concrete deck)	Bind concrete deck near the steps, convert 2400volt line to 7200 volt line

SECTION 8

STUDY CASES

This section includes the analysis of several stray voltage related problems and their mitigation means. These study cases also demonstrate the diverse roles played by the primary and secondary neutral systems including their grounds in contributing to stray voltage problems at customer facilities. Each of these study cases contains a brief description of the problem, computer analysis of the problem, and possible corrective measures.

Dr. Sakis Meliopoulos, Georgia Tech School of ECE, developed the computer program[28] used in this section under EPRI sponsorship. The program is capable of analyzing a wide variety of 60 Hz problems and a limited number of transient problems. For the simplest problem where the grounding electrode current is known (either fault or stray current), the resulting touch, step or stray voltages can be computed. For more complex problems where the grounding electrode current is unknown, a part or the entire distribution feeder including grounding electrodes can be modeled and all necessary currents and voltages computed. The system may be analyzed during steady-state or faulted conditions, with specific loads and / or faults specified by the user. Most typical distribution circuit components can be modeled including one, two or three-phase lines and components.

Typical outputs include the voltages at each node and currents in each branch of the system. The grounding electrode related outputs include total resistance of grounding system, safety assessment and contours for touch voltage, voltage gradients and step voltages.

Dairy Farm Case

Concerns for Cows

Cows are considered to be more susceptible to stray voltage / current than humans because cows have lower body and contact resistances to the floor. The voltage alone cannot pose a problem for cows. The source impedance, body and contact resistance should be such that the voltage will result in a current that will affect the animal.

Review of all research publications on effects of electrical current on animals indicates that the findings of USDA Agricultural Handbook 696[79] are accurate. To eliminate the possibility of production loss, the amount of current that can flow through the body of an animal should be kept below 4 mA (60 Hz). None of the research showed a decrease in feed or water consumption or milk production at a level of current through the animal below 4 mA.

The voltage required to cause a response depends on the resistance of the pathway taken by the current through the cow's body. A number of such pathways have been examined. Differences among pathway resistances, including cow contact resistance, have been shown to be as great as six-fold or greater. While some pathway resistances approach 1,000 ohms or more, worst-case resistances of specific cows on specific farms may be as low as 500 ohms. Based on 4 mA tolerable current values, the safe voltage levels can be estimated to be 2 volts using the worst case circuit impedance of 500 ohms and 4 volts using a more realistic impedance value of 1000 ohms. As stated above, no research has found production losses for 60 Hz animal body currents below 4 mA or for voltages between animal contact points below 4 volts (1000 ohms circuit impedance). However, a conservative practice of keeping animal contact voltage below 2 volts (500 ohms circuit impedance) will provide a margin that will prevent stray voltage from causing a problem[32].

Analysis of Problem

For clarity, the modeled distribution system illustrating the concerns in a dairy farm is divided in to two parts. Figure 8-1 shows the distribution system from the source up to the pole serving the farm. Figure 8-2 shows the primary and the secondary distribution system in the farm. These figures provide details regarding the equipment, lines, and grounding parameters.

Referring to Figure 8-2, the dotted lines represent the energized primary and secondary circuits. Solid lines represent the neutral and ground circuits. A pole mounted, 50 kVA, single-phase transformer supplies power to the entire farm. An overhead triplex, 75 feet long, connects the transformer to the farm service panel. Services to the house and the barn area are run from the farm service panel. The X and Y coordinates of each location are shown in the figure. The grounding electrodes within the farm area are modeled in their exact physical shapes and sizes.

All metal structures and equipment in areas used by the animals are electrically connected together to avoid voltage differences in a typical dairy farm. The metalwork (waterers, feeders, stanchions, pipes, stall dividers, pipe lines and floor grates) is also connected to the grounding bus along with other equipment grounds at the barn service panel. In the barn service panel, the neutral bus is either bonded with the ground bus or is isolated from it. To reduce N-E voltages, the isolation of the neutral bus from the ground bus, is permitted by the NEC in Articles 250 and 547 under certain circumstances. However, Article 250 requires bonding of the neutral bus with the equipment ground bus at the main service panel (farm service panel), regardless of the bonding or isolation in the sub-panel.

The analysis presented in this section (Figure 8-2) assumes the bonding of the neutral bus with the equipment grounding bus in the barn service panel. However, to illustrate an alternate NEC method, one of the corrective measures scenario deals with isolation of these two buses in the barn service panel in accordance with Article 250 and 547.

In the modeling, the following should be noted:

- To provide conservative results, the conductive influence of one grounding electrode on the other is neglected.
- To provide conservative results, only two stall pipes connected to the barn service ground are modeled.
- To provide conservative results, the re-bars in the stall area concrete are not modeled.
- Unless noted otherwise, all neutral to ground connections and the piping system in the farm area are assumed to have zero impedance.
- Cable TV and telephone lines entering the farm facilities are not modeled.

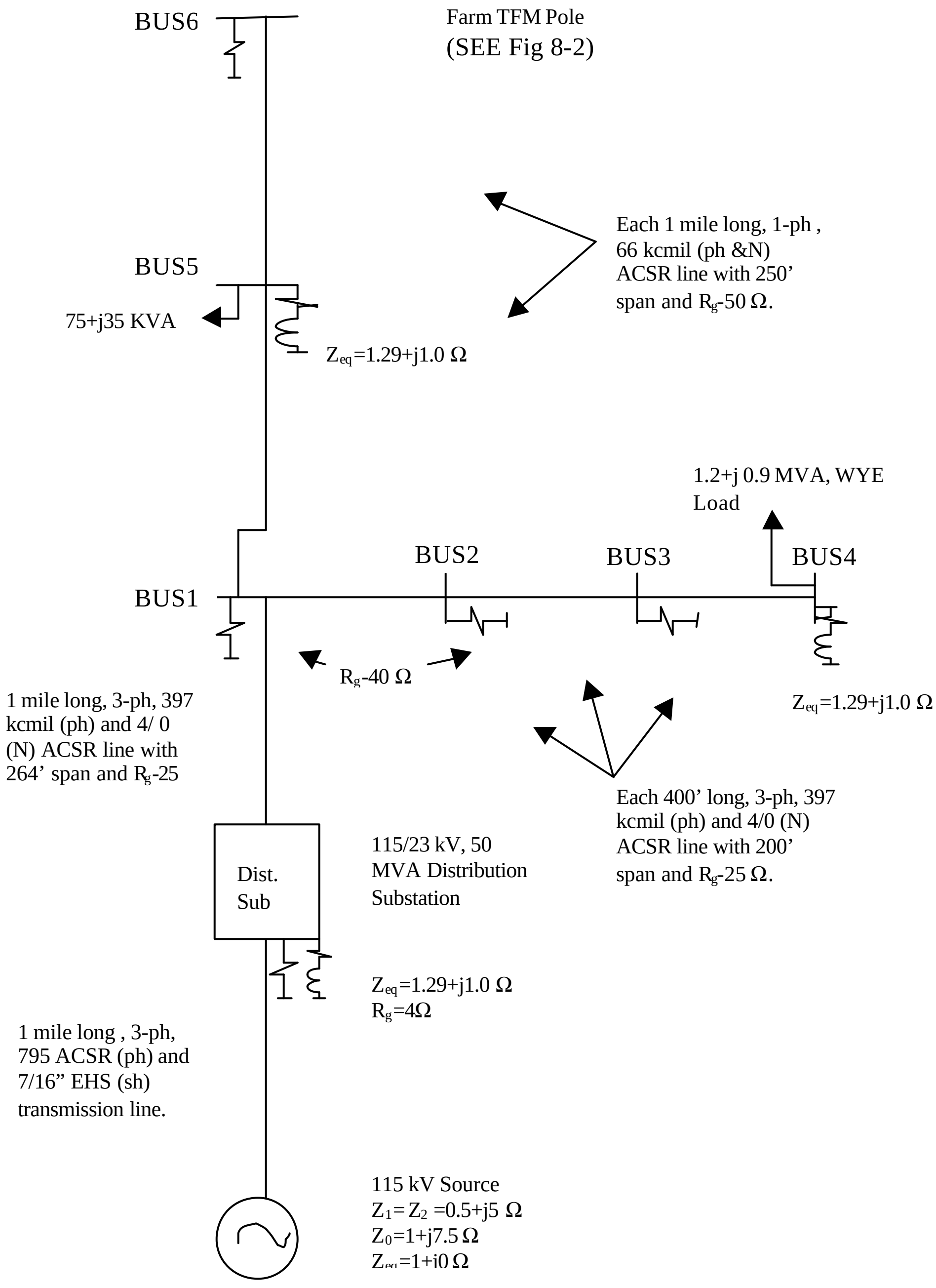


Figure 8-1 Modeled Transmission and Distribution System Up To the Farm Transformer Pole

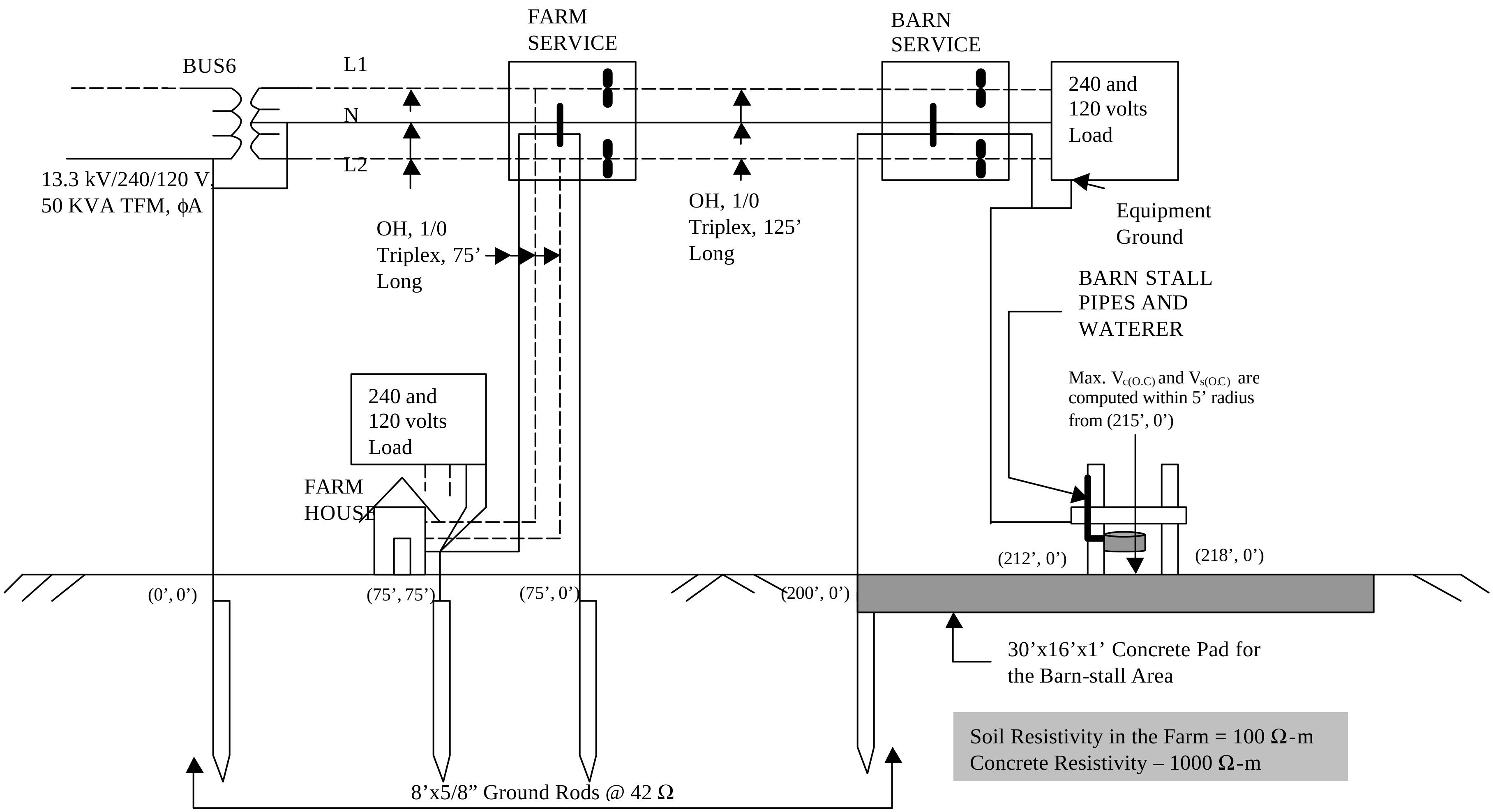


Figure 8-2 Modeled Farm Distribution System

Analysis Scenario-1 (Influence of Primary Loads) This scenario demonstrates the N-E voltage and resulting animal contact voltage and current with all loads in the farm switched off. In other words, the N-E voltages in the farm are entirely due to the Power Company's distribution system and its off-farm loads.

Table 8-1 shows the N-E voltages and corresponding grounding electrode currents in the farm. Table 8-2 shows the current flows in the farm neutrals. Table 8-3 shows the animal contact voltages, cow body current, and equivalent source resistance for this scenario.

Table 8-1 N-E Voltages and Grounding Electrode Currents - No Load in Dairy Farm

Ground Location	N-E Voltage, Volts	Grounding Electrode Current, A
BUS6 (TFM)	$3.64 \angle 24°$	$0.087 \angle 24°$
FARM SERVICE	$3.635 \angle 24°$	$0.087 \angle 24°$
HOUSE	$3.634 \angle 24°$	$0.087 \angle 24°$
BARN SERVICE	$3.633 \angle 24°$	$0.086 \angle 24°$

Table 8-2 Primary and Secondary Neutral Currents in the Farm - No Load in Dairy Farm

Neutral Path	Current, A
BUS6-BUS5 (Primary Neutral)	$0.347 \angle -156°$
BUS6-FARM SERVICE	$0.26 \angle 24°$
FARM SERVICE-HOUSE	$0.087 \angle 24°$
FARM SERVICE-BARN SERVICE	$0.086 \angle 24°$

Table 8-3 Animal Contact Voltages, Current, and Source Resistance - No Load in Dairy Farm

Open Circuit Contact Voltage (V_{oc}), Volts	Closed Circuit Contact Voltage (V_{cc}), Volts	Animal Current (I_c), mA	Equivalent Source Resistance (R_{sc}), Ohms	*Animal Body Resistance ($R_{b(mh)}$), Ohms	Open Circuit Step Voltage (V_{os}), Volts
3.4	1.32	2.64	788	500	2.9

* Assumed value – includes a) resistance from mouth to four hooves and b) contact resistance at both ends

The tables show:

- Secondary or farm neutrals carry small amount of current.
- Voltage drops in the secondary neutrals are insignificant and as a result, the N-E voltages are almost identical at each farm location.
- Animal contact and step voltages are entirely due to primary system including its loads.

Analysis Scenario-2 (Influence of Primary and 240-Volt Loads) This scenario demonstrates animal voltages and current with the farm carrying only the balanced 240 volt loads. The house is carrying 1+j0.2 KVA load while the barn-stall is carrying 2+j0.5 kVA.

Table 8-4 shows the N-E voltages and corresponding grounding electrode currents in the farm. Table 8-5 shows the current flows in the farm neutrals. Table 8-6 shows the animal contact voltages, cow body current, and equivalent source resistance for this scenario.

Table 8-4 N-E Voltages and Grounding Electrode Currents - Only Balanced (240 Volt) Loads in the Farm

Ground Location	N-E Voltage, Volts	Grounding Electrode Current, A
BUS6 (TFM)	4.06 ∠26°	0.097 ∠26°
FARM SERVICE	4.06 ∠26°	0.097 ∠26°
HOUSE	4.05 ∠26°	0.096 ∠26°
BARN SERVICE	4.05 ∠26°	0.096 ∠26°

Table 8-5 Primary and Secondary Neutral Currents in the Farm - Only Balanced (240 Volt) Loads in the Farm

Neutral Path	Neutral Current, A
BUS6-BUS5 (Primary Neutral)	0.165 ∠-141°
BUS6-FARM SERVICE	0.289 ∠26°
FARM SERVICE-HOUSE	0.097∠25°
FARM SERVICE-BARN SERVICE	0.095∠25°

Table 8-6 Animal Contact Voltages, Current, and Source Resistance - Only Balanced (240 Volt) Loads in the Farm

Open Circuit Contact Voltage (V_{oc}), Volts	Closed Circuit Contact Voltage (V_{cc}), Volts	Animal Current (I_c), mA	Equivalent Source Resistance (R_{sc}), Ohms	*Animal Body Resistance ($R_{b(mh)}$), Ohms	Open Circuit Step Voltage (V_{os}), Volts
3.8	1.473	2.95	790	500	3.2

* Assumed value – includes a) resistance from mouth to four hooves and b) contact resistance at both ends

The tables show:

- Slight increase in the secondary neutral current due to additional primary current contributed by the balanced loads.
- Farm N-E voltages are still identical at all locations.
- Animal contact voltages and current have increased slightly.

Analysis Scenario-3 (Influence of Primary, 240-Volt, and 120-Volt Loads) This scenario demonstrates the N-E voltage and resulting animal contact voltages and current with the farm carrying the unbalanced (120 volt) loads in addition to the balanced loads of Scenario-2. The house is carrying 2+j0.3 KVA load while the barn-stall is carrying 4+j2 KVA. To make this scenario a worst case, both of these loads are carried on L1.

Table 8-7 shows the N-E voltages and corresponding grounding electrode currents in the farm. Table 8-8 shows the current flows in the farm neutrals. Table 8-9 shows the animal contact voltages, cow body current, and equivalent source resistance for this scenario.

Table 8-7 N-E Voltages and Grounding electrode Currents - In Addition to Balanced Loads, Unbalanced Loads (120 Volt) are added on L1

Ground Location	N-E Voltage, Volts	Grounding Electrode Current, A
BUS6 (TFM)	$4.79 \angle 25°$	$0.115 \angle 25°$
FARM SERVICE	$5.49 \angle 26°$	$0.131 \angle 26°$
HOUSE	$5.70 \angle 27°$	$0.136 \angle 27°$
BARN SERVICE	$6.31 \angle 26°$	$0.149 \angle 26°$

Table 8-8 Primary and Secondary Neutral Currents in the Farm - In Addition to Balanced Loads, Unbalanced Loads (120 Volt) are added on L1

Neutral Path	Neutral Current , A
BUS6-BUS5 (Primary Neutral)	$0.225 \angle -26°$
BUS6-FARM SERVICE	$50.8 \angle -172°$
FARM SERVICE-HOUSE	$16.1 \angle -159°$
FARM SERVICE-BARN SERVICE	$35.3 \angle -177°$

Table 8-9 Animal Contact Voltages, Current, and Source Resistance - In Addition to Balanced Loads, Unbalanced Loads (120 Volt) are added on L1

Open Circuit Contact Voltage (V_{oc}), Volts	Closed Circuit Contact Voltage (V_{cc}), Volts	Animal Current (I_c), mA	Equivalent Source Resistance (R_{sc}), Ohms	*Animal Body Resistance ($R_{b(mh)}$), Ohms	Open Circuit Step Voltage (V_{os}), Volts
5.9	2.293	4.586	786	500	5.0

* Assumed value – includes a) resistance from mouth to four hooves and b) contact resistance at both ends

The tables show:

- Because all 120 volt loads are on L1, the secondary neutral currents have increased significantly.
- Overall N-E voltages in the farm have increased significantly.

- N-E voltages at each location are no longer identical but are proportional to the neutral length and the current.
- Animal contact voltages and current have increased significantly.
- In all three scenarios, the source resistance remained almost the same.

Analysis Scenario-4 (Influence of Corroded Secondary Neutral) A corroded, loose, or partially broken connection in the neutral circuit can increase the resistance of an otherwise low impedance path. This can happen on the primary as well as secondary neutrals. When this happens, the current flow through the grounding electrodes connected to this neutral would also increase. The increase in grounding electrode currents will ultimately increase the N-E voltage on the load side of the bad connection.

To illustrate the effect, a 0.2 Ω resistor representing the corroded connection is inserted in the middle of the neutral between the farm service panel and the barn service panel. All other parameters remain the same as described in the base case scenario (Analysis Scenario-3).

Table 8-10 shows the N-E voltages and corresponding grounding electrode currents in the farm. Table 8-11 shows the current flows in the farm neutrals. Table 8-12 shows the animal contact voltages and resulting current for this scenario.

Table 8-10 N-E Voltages and Grounding electrode Currents – a 0.2 Ω Resistor Inserted in the Neutral to Barn-stall, Other Parameters Same as Analysis Secnario-3

Ground Location	N-E Voltage, Volts	Grounding Electrode Current, A
BUS6 (TFM)	4.36 ∠24°	0.104 ∠25°
FARM SERVICE	5.01 ∠25°	0.120 ∠25°
HOUSE	5.22 ∠26°	0.125 ∠26°
BARN SERVICE	12.4 ∠14°	0.293∠26°

Table 8-11 Primary and Secondary Neutral Currents in the Farm – a 0.2 Ω Resistor Inserted in the Neutral to Barn-stall, Other Parameters Same as Analysis Scenario-3

Neutral Path	Neutral Current (A)
BUS6-BUS5 (Primary Neutral)	0.100 ∠-53°
BUS6-FARM SERVICE	47.84 ∠-170°
FARM SERVICE-HOUSE	16.16∠-159°
FARM SERVICE-BARN SERVICE	32.21∠-175°

Table 8-12 Animal Contact Voltages, Current, and Source Resistance - a 0.2 Ω Resistor Inserted in the Neutral to Barn-stall, Other Parameters Same as Analysis Scenario-3

Open Circuit Contact Voltage (V_{oc}), Volts	Closed Circuit Contact Voltage (V_{cc}), Volts	Animal Current (I_c), mA	Equivalent Source Resistance (R_{sc}), Ohms	* Animal Body Resistance ($R_{b(mh)}$), Ohms	Open Circuit Step Voltage (V_{os}), Volts
11.6	4.465	8.93	799	500	5.0

∗ Assumed value – includes a) resistance from mouth to four hooves and b) contact resistance at both ends

The tables show:

- Current in the neutral to the barn-stall has reduced in proportion to the increase in its impedance.
- Currents in other neutrals have reduced slightly.
- N-E voltage at the barn-stall has almost doubled.
- N-E voltages at other farm locations have reduced somewhat.
- Animal contact voltages and current have almost doubled from those in Scenario-3.

Analysis Scenario-5 (Influence of 120-Volt Fault to Earth) Undesired current may flow when a phase conductor in a buried cable system (triplex or quadruplex) shorts to the surrounding soil. The fault current in the short would depend on the resistivity of the soil at the point of contact. In general, this current would be small and most likely would not blow the fuse. The fault current would attempt to flow back to the transformer center tap via secondary and primary grounding electrodes. Depending on the magnitude of this fault current and its phase relationship with the current already flowing in the grounding electrode system, the N-E voltages may increase or decrease.

The above influence is illustrated by replacing the overhead triplex to barn-stall with an identical triplex buried 3’ in the soil and faulting L1 and L2 to soil. Referring to Figure 8-2, the fault point is located on the left side of the barn-stall ground rod at a distance of 25 feet. With respect to transformer ground rod (0’, 0’), the coordinates of the fault point are X=175’ and Y=0’. Note that the concrete resistivity at the faulted point remains the same (1000 Ω-m up to 1 foot depth) as that in Analysis Scenario-3.

The first three tables, Tables 8-13, 8-14, and 8-15, show the computer results when L1 is faulted to the soil. Table 8-13 shows the N-E voltages and corresponding grounding electrode currents in the farm. Table 8-14 shows the current flows in the farm neutrals. Table 8-15 shows the animal contact voltages, current, and the equivalent source resistance for this scenario.

Table 8-13 N-E Voltages and Grounding Electrode Currents - L1 of Buried Triplex to Barn-stall is Faulted to the Soil, Other Parameters Same as Analysis Scenario-3

Ground Location	N-E Voltage, Volts	Grounding Electrode Current, A
BUS6 (TFM)	3.76 $\angle$11°	0.090 $\angle$11°
FARM SERVICE	4.42 $\angle$14°	0.106 $\angle$14°
HOUSE	4.61 $\angle$16°	0.110 $\angle$16°
BARN SERVICE	5.44 $\angle$16°	0.103$\angle$12°
FAULT (L1 TO GROUND)	120 $\angle$16°	0.589 $\angle$29°

Table 8-14 Primary and Secondary Neutral Currents in the Farm, L1 of Buried Triplex to Barn-stall is Faulted to the Soil, Other Parameters Same as Analysis Scenario-3

Neutral Path	Neutral Current, A
BUS6-BUS5 (Primary Neutral)	0.335 $\angle$-134°
BUS6-FARM SERVICE	50.68$\angle$-171°
FARM SERVICE-HOUSE	16.16$\angle$-159°
FARM SERVICE-BARN SERVICE	35.17$\angle$-177°

Table 8-15 Animal Contact Voltages, Current, and Source Resistance - L1 of Buried Triplex to Barn-stall is Faulted to the Soil, Other Parameters Same as Analysis Scenario-3

Open Circuit Contact Voltage (V_{oc}), Volts	Closed Circuit Contact Voltage (V_{cc}), Volts	Animal Current (I_c), mA	Equivalent Source Resistance (R_{sc}), Ohms	* Animal Body Resistance ($R_{b(mh)}$), Ohms	Open Circuit Step Voltage (V_{os}), Volts
4.5	1.714	3.428	813	500	3.8

∗ Assumed value – includes a) resistance from mouth to four hooves and b) contact resistance at both ends

The next three tables, Tables 8-16, 8-17, and 8-18, show the computer results when L2 is faulted to the soil. Table 8-16 shows the N-E voltages and corresponding grounding electrode currents in the farm. Table 8-17 shows the current flows in the farm neutrals. Table 8-18 shows the animal contact voltages, current and equivalent source resistance for this scenario.

Table 8-16 N-E Voltages and Grounding Electrode Currents - L2 of Buried Triplex to Barn-stall is Faulted to the Soil, Other Parameters Same as Analysis Secnario-3

Ground Location	N-E Voltage, Volts	Grounding Electrode Current, A
BUS6 (TFM)	5.90 ∠33°	0.141 ∠33°
FARM SERVICE	6.61 ∠33°	0.158 ∠33°
HOUSE	6.83 ∠34°	0.163 ∠34°
BARN SERVICE	7.62 ∠32°	0.210∠32°
FAULT (L1 TO GROUND)	113 ∠-151°	0.554 ∠-151°

Table 8-17 Primary and Secondary Neutral Currents in the Farm - L2 of Buried Triplex to Barn-stall is Faulted to the Soil, Other Parameters Same as Analysis Secnario-3

Neutral Path	Neutral Current, A
BUS6-BUS5 (Primary Neutral)	0.602 ∠4°
BUS6-FARM SERVICE	50.52∠-172°
FARM SERVICE-HOUSE	16.11∠-159°
FARM SERVICE-BARN SERVICE	35.09∠-177°

Table 8-18 Animal Contact Voltages, Current, and Source Resistance – L2 of Buried Triplex to Barn-stall is Faulted to the Soil, Other Parameters Same as Analysis Scenario-3

Open Circuit Contact Voltage (V_{oc}), Volts	Closed Circuit Contact Voltage (V_{cc}), Volts	Animal Current (I_c), mA	Equivalent Source Resistance (R_{sc}), Ohms	*Animal Body Resistance ($R_{b(mh)}$), Ohms	Open Circuit Step Voltage (V_{os}), Volts
7.7	2.996	5.99	785	500	6.5

∗ Assumed value – includes a) resistance from mouth to four hooves and b) contact resistance at both ends

In the above example, the fault current magnitude is only 0.55 amperes, which resulted in small differences in N-E voltages from the base case values. Table 8-19 shows N-E voltages resulting from 2.8 amperes fault current for both faults. Comparing the data of Table 8-19, Table 8-16 and Table 8-13 with the data in Table 8-7 (base case), the user can readily see the influence of increased fault current on N-E voltages. Depending whether the fault is either on L_1 or L_2, the N-E voltages reduce or increase more from the base case values, respectively.

Table 8-19 N-E Voltages and Grounding electrode Currents – L_1 or L_2 of Buried Triplex to Barn-stall is Faulted to the Soil, Fault Current Increased from 0.55 Amps to 2.8 Amps, Other Parameters Same as Analysis Secnario-3

Fault from L_1 to Earth		
Ground Location	N-E Voltage, Volts	Grounding Electrode Current, A
BUS6 (TFM)	4.41 ∠-76°	0.1 ∠-76°
FARM SERVICE	4.26 ∠-67°	0.1 ∠-67°
HOUSE	4.17 ∠-64°	0.1 ∠-64°
BARN SERVICE	4.44 ∠-53°	0.15∠-111°
FAULT (L1 TO GROUND)	116∠27°	2.86 ∠27°
Fault from L_2 to Earth		
Ground Location	N-E Voltage, Volts	Grounding Electrode Current, A
BUS6 (TFM)	10.9 ∠47°	0.26 ∠47°
FARM SERVICE	11.6 ∠46°	0.27 ∠46°
HOUSE	11.8 ∠46°	0.28 ∠46°
BARN SERVICE	12.53 ∠45°	0.42∠40°
FAULT (L2 TO GROUND)	108 ∠-152°	2.68 ∠-152°

Comparing with Analysis Scenario-3 results, Tables 8-13 through 8-19 show:

- N-E voltages in the farm decreased when L1 (in phase with primary phase) was faulted and they increased when L2 (out of phase with primary phase) was faulted. Amount of increase or decrease depended on the fault current magnitude.
- Currents in farm grounding electrodes showed the same relationship as above.
- Currents in farm neutrals essentially remained the same.
- Animal contact voltages and current decreased when L1 was faulted and they increased when L2 was faulted.
- Changes in equivalent source resistances are small.

Corrective Measures

There are two fundamental approaches to mitigate or minimize the unacceptable contact voltage levels experienced by cows in a dairy farm. One approach is to reduce the N-E voltage at the barn-stall location. The second approach is to reduce the animal contact voltage for a given N-E voltage by providing an equipotential plane underneath the concrete floor.

The effectiveness of a solution or solutions will depend on which neutral contributes the most to the N-E voltage. If the primary neutral is a major contributor, then isolating the primary neutral from the secondary neutral with a properly designed isolator should be considered. Since interconnection of both neutrals is essential during a transformer fault for safety reasons, the isolator must be able to carry high energy with a low breakdown voltage (NESC Rule 97D)[5] across the isolation. Also, isolating the primary neutral from the secondary neutral will not accomplish the desired reduction in the N-E voltage if the cable TV or telephone line shield wires are tied with the farm facility grounds or water pipes. If economically feasible, other improvements such as over sizing the neutral conductor, improving the pole grounds and balancing the load on the primary side can be considered. If the voltage drop across the secondary neutral is a major cause of high N-E voltages at the barn-stall, then solutions such as converting some of the barn loads from 120 V to 240 V or balancing the 120 volt load should be considered.

Providing an equipotential plane underneath the barn-stall floor is a very effective mitigating means. For new construction, installing an equipotential plane can be easily justified economically. Retrofitting existing dairy farm facilities with equipotential planes, on the other hand, may not be a cost-effective solution.

In this section, several corrective measures are analyzed to determine the effectiveness of each in reducing the animal contact voltage in the barn-stall area. The worst stray voltage scenario described as Analysis Scenario-3 in the previous section is considered the base case for each of these corrective measures.

Corrective Measure Scenario-1 (Grounding Improvement) After verifying the complaint, the first attempt by the utility personnel would be to improve the grounding at the transformer pole and / or on the distribution system in the proximity of the farm. This study case illustrates some of these mitigating methods.

First, the ground rod at the transformer pole is driven to 50' depth. This reduces the pole ground resistances from 42 Ω to 8.6 Ω. Note that the same reduction in the resistance can also be accomplished by installing five or six parallel grounds in the vicinity of the pole.

All other parameters are the same as Analysis Scenario-3.

Table 8-20 shows the N-E voltages and the grounding electrode currents in the dairy farm facility. Table 8-21 shows corresponding contact voltages, current and the equivalent source resistance.

Table 8-20 N-E Voltages and Grounding Electrode Currents, 50' Deep Ground Rod at Transformer Pole (Compare the data with Analysis Scenario-3)

Ground Location	N-E Voltage, Volts	Grounding Electrode Current, A
BUS6 (TFM)	$3.99 \angle 18°$	$0.458 \angle 18°$
FARM SERVICE	$4.67 \angle 21°$	$0.112 \angle 21°$
HOUSE	$4.88 \angle 22°$	$0.117 \angle 22°$
BARN SERVICE	$5.49 \angle 22°$	$0.130 \angle 22°$

Table 8-21 Animal Contact Voltages, Current, and Source Resistance – 50' Deep Ground Rod at Transformer Pole (Compare the data with Analysis Scenario-3)

Open Circuit Contact Voltage (V_{oc}), Volts	Closed Circuit Contact Voltage (V_{cc}), Volts	Animal Current (I_c), mA	Equivalent Source Resistance (R_{sc}), Ohms	* Animal Body Resistance ($R_{b(mh)}$), Ohms	Open Circuit Step Voltage (V_{os}), Volts
5.1	1.994	3.988	778	500	4.3

∗ Assumed value – includes a) resistance from mouth to four hooves and b) contact resistance at both ends

Compared to Analysis Scenario-3 results, the N-E voltage at the transformer pole reduced approximately by 17%. However, the animal contact voltages and the current reduced by about 13%.

In addition to the 50' ground rod at the transformer pole, the pole ground resistances on the single-phase line (from BUS1 to BUS6, See Figure 8-1) were reduced from 50 Ω to 25 Ω. No significant reduction in the N-E voltage value in the farm was noted.

Upgrading the primary neutral wire is another mitigation means, which can reduce the N-E voltage at the transformer pole and in the farm. Starting with the base case, Analysis Scenario-3, the 66-kcmil neutral wire between BUS1 and BUS6 was replaced with 1/0 ACSR neutral. Computed results indicated reduction of about 10% in the N-E voltages at the farm.

Corrective Measure Scenario-2 (Primary Load Balancing) In this scenario, a second phase (ϕB) will be installed between BUS1 and BUS5 (See Figure 8-1) and BUS5 load would be transferred to this new phase. The single phase (ϕA) line from BUS5 to the dairy farm will remain as is.

Table 8-22 shows the N-E voltages and the grounding electrode currents in the dairy farm facility. Table 8-23 shows corresponding contact voltages, animal current and the equivalent source resistance.

Table 8-22 N-E Voltages and Grounding electrode Currents - Installing Additional Phase (ϕB) and Transferring the BUS5 Load to this Phase (Compare the results with Analysis Scenario-3)

Ground Location	N-E Voltage, Volts	Grounding Electrode Current, A
BUS6 (TFM)	2.59 ∠-80°	0.062 ∠-80°
FARM SERVICE	2.39 ∠-64°	0.057 ∠-64°
HOUSE	2.32 ∠-59°	0.056∠-59°
BARN SERVICE	2.50 ∠-45°	0.059 ∠-45°

Table 8-23 Animal Contact Voltages, Current, and Source Resistance – Installing Additional Phase (ϕB) and Transferring the BUS5 Load to this Phase (Compare the results with Analysis Scenario-3)

Open Circuit Contact Voltage (V_{oc}), Volts	Closed Circuit Contact Voltage (V_{cc}), Volts	Animal Current (I_c), mA	Equivalent Source Resistance (R_{sc}), Ohms	*Animal Body Resistance ($R_{b(mh)}$), Ohms	Open Circuit Step Voltage (V_{os}), Volts
2.3	0.902	1.804	775	500	2.0

∗ Assumed value – includes a) resistance from mouth to four hooves and b) contact resistance at both ends

As shown in the tables, adding a phase (ϕB) and transferring the BUS5 load to the new phase reduced the N-E voltages, animal contact voltages and resulting current almost by 61%. More reduction could have been achieved if the third phase (ϕC) was added and further divided the BUS5 load.

Corrective Measure Scenario-3 (Neutral Isolation) In this scenario, the primary neutral is isolated from the secondary neutral by installing an isolator or a blocker at the transformer pole. Note that a dairy farm served with a three-wire distribution system (no neutral on primary side) would have the same effect as that with neutral isolation.

Note that the N-E voltage reduction as illustrated in this example would not occur if a cable TV or telephone line enters the farm facility and their shields are grounded to the farm neutral or piping system. The same would also be true if the farm piping system were to connect with the distribution neutral outside the farm facilities. If any of these services interferes with the neutral isolation, additional isolation will be required.

Table 8-24 shows the N-E voltages and the grounding electrode currents in the dairy farm facility. Table 8-25 shows corresponding contact voltages and the current.

Table 8-23 N-E Voltages and Grounding electrode Currents - Isolation of Primary Neutral from Secondary Neutral (Compare the data with Analysis Scenario-3)

Ground Location	N-E Voltage, Volts	Grounding Electrode Current, A
BUS6 (TFM), PRIMARY	5.78 ∠34°	0.138∠34°
BUS6 (TFM), SECONDARY♣	0.79 ∠-147°	0.019 ∠-147°
FARM SERVICE	0.08 ∠-152°	0.002 ∠-152°
HOUSE	0.153 ∠56°	0.004∠56°
BARN SERVICE	0.74 ∠28°	0.018 ∠28°

♣ 8’ ground rod was added to the TFM secondary neutral as required by NESC Rule 97D2

Table 8-25 Animal Contact Voltages, Current, and Source Resistance – Isolation of Primary Neutral from Secondary Neutral (Compare the data with Analysis Scenario-3)

Open Circuit Contact Voltage (V_{oc}), Volts	Closed Circuit Contact Voltage (V_{cc}), Volts	Animal Current (I_c), mA	Equivalent Source Resistance (R_{sc}), Ohms	*Animal Body Resistance ($R_{b(mh)}$), Ohms	Open Circuit Step Voltage (V_{os}), Volts
0.7	0.268	0.536	806	500	0.6

∗ Assumed value – includes a) resistance from mouth to four hooves and b) contact resistance at both ends

The example shows that the neutral isolation at the transformer is by far the most effective mitigating solution. The contact voltages and resulting current reduced by 88% from the base case (See Analysis Scenario-3). Note that the neutral isolation at the transformer would be less effective if the N-E voltages due to voltage drop in the farm neutrals were to dominate. These voltage drops may be due to long neutrals carrying large currents or a corroded splice in one of the neutrals.

One disadvantage of neutral isolation is that it causes N-E voltage at the transformer pole to rise. Magnitude of this N-E voltage rise would depend on the resistance value of the customer ground with respect to that of the transformer pole ground. The lower the value of the customer ground resistance, the higher the rise in N-E voltage at the transformer pole. In the example above, the N-E voltage increased almost by 21% compared to the base case. This result suggests that before deciding in favor of neutral isolation as a mitigation method, it is prudent to assess its influence on neighboring customers.

Corrective Measure Scenario-4 (Equipotential Plane) In this scenario, an equipotential plane is installed underneath the barn-stall floor (concrete floor). This plane consists of 2’x 2’ meshes each of #6 solid copper conductor. The meshes are installed in the 100 Ω-m soil below the concrete pad and cover 30’x16’ area.

Table 8-26 shows the N-E voltages and the grounding electrode currents in the dairy farm facility. Table 8-27 shows corresponding contact voltages, current and the equivalent source resistance.

Table 8-26 N-E Voltages and Grounding electrode Currents - Equipotential Plane below the Barn-stall Floor (Compare the data with Analysis Scenario-3)

Ground Location	N-E Voltage, Volts	Grounding Electrode Current, A
BUS6 (TFM)	$3.36 \angle 11°$	$0.080 \angle 11°$
FARM SERVICE	$4.01 \angle 15°$	$0.096 \angle 15°$
HOUSE	$4.21 \angle 17°$	$0.101 \angle 17°$
BARN SERVICE	$4.80 \angle 17°$	$0.772 \angle 17°$

Table 8-27 Animal Contact Voltages, Current, and Source Resistance – Equipotential Plane below the Barn-stall Floor (Compare the data with Analysis Scenario-3)

Open Circuit Contact Voltage (V_{oc}), Volts	Closed Circuit Contact Voltage (V_{cc}), Volts	Animal Current (I_c), mA	Equivalent Source Resistance (R_{sc}), Ohms	* Animal Body Resistance ($R_{b(mh)}$), Ohms	Open Circuit Step Voltage (V_{os}), Volts
0.2	0.103	0.206	471	500	1.2♣

∗ Assumed value – includes a) resistance from mouth to four hooves and b) contact resistance at both ends

♣ Maximum step voltage occurred at the corner of the equipotential plane (229’, -7.5’).

Installing the equipotential plane underneath the concrete floor is yet another effective means to mitigate the stray voltage problem. Notice in the tables that farm N-E voltages reduced only about 25 % while the animal contact voltage reduced about 97% and the step voltage reduced about 76% compared to the base case (Analysis Scenario-3). Also notice that installation of the equipotential plane reduced the grounding electrode resistance from 42 Ω to 6 Ω and as a result increased the current through the electrode from 0.149 A to 0.772 A (see BARN SERVICE results in Tables 8-7 and 8-26).

A comment regarding the animal step voltage is in order at this point. Table 8-27 indicates that the maximum step voltage is significantly larger than the contact voltage and that it occurred at the edge of the equipotential plane. The animal may respond to this step voltage and, for that reason, voltage ramps at the entrance and at the exit of a barn area are commonly installed.

In all the previous analysis scenarios and corrective measure scenarios, the source resistance value did not vary significantly. Referring to Table 8-27, the equivalent source resistance reduced almost by 50 % compared to those in all previous scenarios. This result points to the fact that the density of the grounding electrode system around the hooves is one of the two parameters which influences the source resistance greatly. The other variable is the electrical resistivity of the concrete or the soil on which the cow may be standing.

The influence of reducing the concrete resistivity from 1000 Ω-m to 100 Ω-m (permanently wet concrete) on equivalent source resistance and the contact current is shown in Table 8-28. All other parameters for this illustration are the same as above.

Table 8-28 Animal Contact Voltages, Current, and Source Resistance – Equipotential Plane below the Barn-stall Floor but Concrete Resistivity Reduced from 1000 Ω-m to 100 Ω-m (Compare the data with Table 8-27 data)

Open Circuit Contact Voltage (V_{oc}), Volts	Closed Circuit Contact Voltage (V_{cc}), Volts	Animal Current (I_c), mA	Equivalent Source Resistance (R_{sc}), Ohms	* Animal Body Resistance ($R_{b(mh)}$), Ohms	Open Circuit Step Voltage (V_{os}), Volts
0.3	0.199	0.398	254	500	-

∗ Assumed value – includes a) resistance from mouth to four hooves and b) contact resistance at both ends

Referring to Table 8-28, the equivalent source resistance with 100 Ω-m concrete floor reduced almost by 50 % compared to that with 1000 Ω-m concrete floor. The closed circuit contact voltage and animal current increased proportionately.

Corrective Measure Scenario-5 (Secondary Load Balancing) Load balancing on the secondary side, like the primary side, also reduces the N-E voltages in the farm. This influence is illustrated by moving the barn 120-Volt load (4+j2 KVA) from L1 to L2. Note that the house 120-Volt load (2+j0.3) continues to be on L1.

Table 8-29 shows the N-E voltages and the grounding electrode currents in the dairy farm facility. Table 8-30 shows corresponding contact voltages, current and the equivalent source resistance. All other variables are the same as Analysis Scenario-3.

Table 8-29 N-E Voltages and Grounding electrode Currents – Coarse Balancing of 120-Volt Load between L1 and L2 (Compare the data with Analysis Scenario-3)

Ground Location	N-E Voltage, Volts	Grounding Electrode Current, A
BUS6 (TFM)	5.03 ∠27°	0.120 ∠27°
FARM SERVICE	4.74 ∠28°	0.113 ∠28°
HOUSE	4.96 ∠28°	0.119∠28°
BARN SERVICE	3.91 ∠27°	0.092 ∠27°

Table 8-30 Animal Contact Voltages, Current, and Source Resistance - Coarse Balancing of 120-Volt Load between L1 and L2 (Compare the data with Analysis Scenario-3)

Open Circuit Contact Voltage (V_{oc}), Volts	Closed Circuit Contact Voltage (V_{cc}), Volts	Animal Current (I_c), mA	Equivalent Source Resistance (R_{sc}), Ohms	* Animal Body Resistance ($R_{b(mh)}$), Ohms	Open Circuit Step Voltage (V_{os}), Volts
3.7	1.42	2.84	804	500	4.6

∗ Assumed value – includes a) resistance from mouth to four hooves and b) contact resistance at both ends

As indicated in the tables, farm load balancing reduced the N-E voltages significantly. The most notable reduction was in the N-E voltage at the barn where the entire load was moved from L1 to L2. Compared to the base case, the animal contact voltages and corresponding current also reduced substantially (about 42%).

Corrective Measure Scenario-6 (Oversizing Secondary Neutral) Over sizing the neutrals may reduce the N-E voltages in the farm. The benefit of changing the farm service cables from 1/0 triplex to 4/0 triplex is illustrated in this study case.

Table 8-31 shows the N-E voltages and the grounding electrode currents in the dairy farm facility. Table 8-32 shows corresponding contact voltages, current and the equivalent source resistance.

Table 8-31 N-E Voltages and Grounding Electrode Currents - Farm Neutrals upgraded from 1/0 ACSR to 4/0 ACSR (Compare the data with Analysis Scenario-3)

Ground Location	N-E Voltage, Volts	Grounding Electrode Current, A
BUS6 (TFM)	$4.88 \angle 25°$	$0.117 \angle 25°$
FARM SERVICE	$5.28 \angle 27°$	$0.126 \angle 27°$
HOUSE	$5.40 \angle 28°$	$0.129 \angle 28°$
BARN SERVICE	$5.77 \angle 29°$	$0.136 \angle 29°$

Table 8-32 Animal Contact Voltages, Current, and Source Resistance - Farm Neutrals upgraded from 1/0 ACSR to 4/0 ACSR (Compare the data with Analysis Scenario-3)

Open Circuit Contact Voltage (V_{oc}), Volts	Closed Circuit Contact Voltage (V_{cc}), Volts	Animal Current (I_c), mA	Equivalent Source Resistance (R_{sc}), Ohms	* Animal Body Resistance ($R_{b(mh)}$), Ohms	Open Circuit Step Voltage (V_{os}), Volts
5.4	2.1	4.2	788	500	4.6

∗ Assumed value – includes a) resistance from mouth to four hooves and b) contact resistance at both ends

The tables show that upgrading the farm neutral system reduced the N-E voltages a little. Compared to the base case, only about 8% reduction in the animal contact voltages and resulting current was accomplished.

Corrective Measure Scenario-7 (Isolation of Neutral and Ground) To reduce N-E voltages in the barn or other animal areas, the NEC allows using a four-wire system with an isolated neutral and equipment grounding bus in the panel serving a livestock building. However, this isolation is not allowed for the main service panel (farm service panel). The NEC also attaches several constraints with this allowance in Article 250. Users should refer to Section 2 for more details on the NEC's allowance and constraints.

Use of the four-wire system as a mitigation means is illustrated in this study case. Figure 8-3 shows the four-wire system between the farm service and barn service panels. The figure also shows the waterer and the stall pipes connecting to the ground at the barn service panel. In the barn service panel, the neutral bus is isolated from the equipment grounding bus. All other parameters including the loads remain the same as the base case (Analysis Scenario-3).

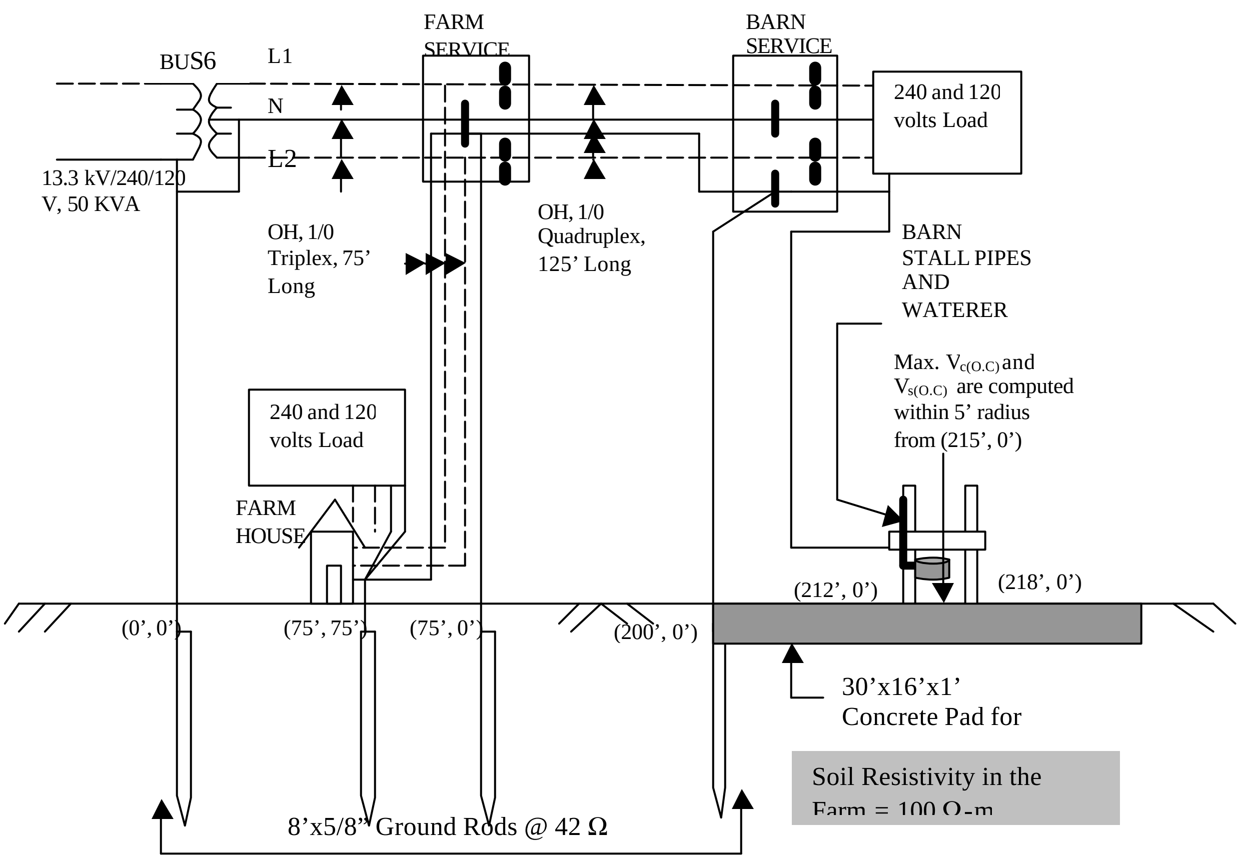


Figure 8-3 Four-wire Service between Farm Service and Barn Service Panels, Neutral Bus is isolated from Ground Bus in the Barn Service Panel

Table 8-33 shows the N-E voltages and the grounding electrode currents in the dairy farm facility. Table 8-34 shows corresponding contact voltages, current and the equivalent source resistance.

Table 8-33 N-E Voltages and Grounding Electrode Currents - Neutral and Ground Isolated in Barn Service Panel (Compare the data with Analysis Scenario-3)

Ground Location	N-E Voltage, Volts	Grounding Electrode Current, A
BUS6 (TFM)	4.83 ∠25°	0.116 ∠25°
FARM SERVICE	5.53 ∠26°	0.132 ∠26°
HOUSE	5.74 ∠27°	0.137∠27°
BARN SERVICE (GROUND BUS)	5.5 ∠26°	0.131 ∠26°

Table 8-34 Animal Contact Voltages, Current, and Source Resistance - Neutral and Equipment Ground Isolated in Barn Service Panel
(Compare the data with Analysis Scenario-3)

Open Circuit Contact Voltage (V_{oc}), Volts	Closed Circuit Contact Voltage (V_{cc}), Volts	Animal Current (I_c), mA	Equivalent Source Resistance (R_{sc}), Ohms	* Animal Body Resistance ($R_{b(mh)}$), Ohms	Open Circuit Step Voltage (V_{os}), Volts
5.2	1.997	3.994	802	500	4.4

∗ Assumed value – includes a) resistance from mouth to four hooves and b) contact resistance at both ends

Referring to the tables, isolating the neutral bus from the equipment grounding bus in the barn service panel does not help much in reducing the N-E voltage and animal contact voltage. The four-wire system as shown in Figure 8-3 will only reduce the contribution (to N-E voltage) made by the neutral current due to 120-volt load of the barn building. Note that the N-E voltage at the farm service panel (main service panel) is still carried to the barn service panel.

Study Case for Residential Subdivision

Concerns for Humans

Receiving annoying shocks while touching outside faucets is the most common complaint received from the residential customers. Theoretically, this concern may exist at any of the distribution facilities such as pole downleads, padmount casings or grounded appliances. The safety concerns exist when the touch or step voltage near a distribution facility exceeds the tolerable voltage limit. The tolerable voltages for humans as a result of steady state operation of a power system are discussed in Section 5 of this handbook.

Many times, the complaints involve annoying shocks around the house. These shocks occur at significantly lower current levels than the tolerable limit. Section 5 also describes the perception current levels for the humans.

The stray voltage concerns and their corrective measures as related to humans are analyzed in this section. This study case consists of a residential subdivision at the end of a long distribution feeder.

Analysis of Problem

Sometimes, houses in a single residential area may have unacceptable N-E voltages at their water pipes. This situation may occur due to one or more of the following reasons:

- High load density in the subdivision
- Location at the end of a long feeder
- The entire load is served by a single-phase feeder
- High impedance neutral and ground paths back to the source.

Figure 8-4 shows the modeled distribution system. A 46/12 kV substation serves several commercial and residential loads from an overhead distribution feeder seven miles long. The residential subdivision under investigation is tapped from the main feeder at BUS40. The first 4.75 miles of this feeder consists of three phases and serves primarily commercial loads. The last 2.25 mile section serves a major portion of the residential load. Note that ϕB serves the entire residential load.

The substation is modeled as a balanced voltage source behind its sequence impedance Z_1, Z_2 and Z_0. The substation ground grid is represented by its resistance value. Overhead grounding networks of 46 kV lines and a second 12 kV feeder are modeled by equivalent impedance. Along the main feeder, each major tap point is represented by a bus with a load and an equivalent grounding impedance of branches pulled from the tap. To investigate N-E voltages at the subject houses accurately, it is necessary to model the distribution system in the subdivision in more detail. Representing each transformer pole in the subdivision as a bus with the indicated house loads and ground rod resistance values accomplished this. For accuracy, the transformer and overhead secondary serving the three houses under study (HOUSE1, HOUSE2 and HOUSE3) and their grounding electrodes are represented in detail. The grounding electrode at each location consists of a 10’ ground rod (258 Ω).

For clarity, some of the input data such as transformer impedance, loads, and pole ground resistance are not shown in Figure 8-4. However, the figure provides enough detail to understand the concerns, analysis and results for this study case.

Figure 8-5 shows a close-up view of the houses being investigated. Each of these houses and the transformer pole are grounded with a 10’ ground rod. Ground rods are driven below the energy meters on the outside. All ground rods are connected to the neutral. At HOUSE2 and HOUSE3, the outside water faucets are located just above the ground rod locations and can be contacted by the residents with their feet within a 3' radius from the rods. A worse situation exists at HOUSE1 where the outside water faucet is located on the opposite side, 35 feet from the ground rod location. For all residents, the touch voltages within a three feet radius around each faucet location are investigated. The water pipes in the houses are of copper material and are connected to the neutral.

The distribution system shown in Figure 8-4 was modeled first and N-E voltages and branch currents at each bus were computed using the computer program. Figure 8-6 shows computed N-E voltages at the key buses in the subdivision. Note that the N-E voltages in the subdivision range from 7.6 Volts to 10.2 Volts and are clearly higher than the normal voltage range. Based on several measurements, a range of 0 to 4 Volts can be considered normal around a residential house. Steps must be taken to reduce these voltage levels in the example subdivision.

The computed touch voltages experienced by the three residents are also shown in Figure 8-6. Note that due to the water faucet being 35 feet from the meter ground, HOUSE1 resident contacts almost the entire N-E voltage existing at the ground rod.

The results in Figure 8-6 are the results for "as is" conditions on the feeder including the tap to the subdivision. These results should be used to compare the results corresponding to each corrective measure.

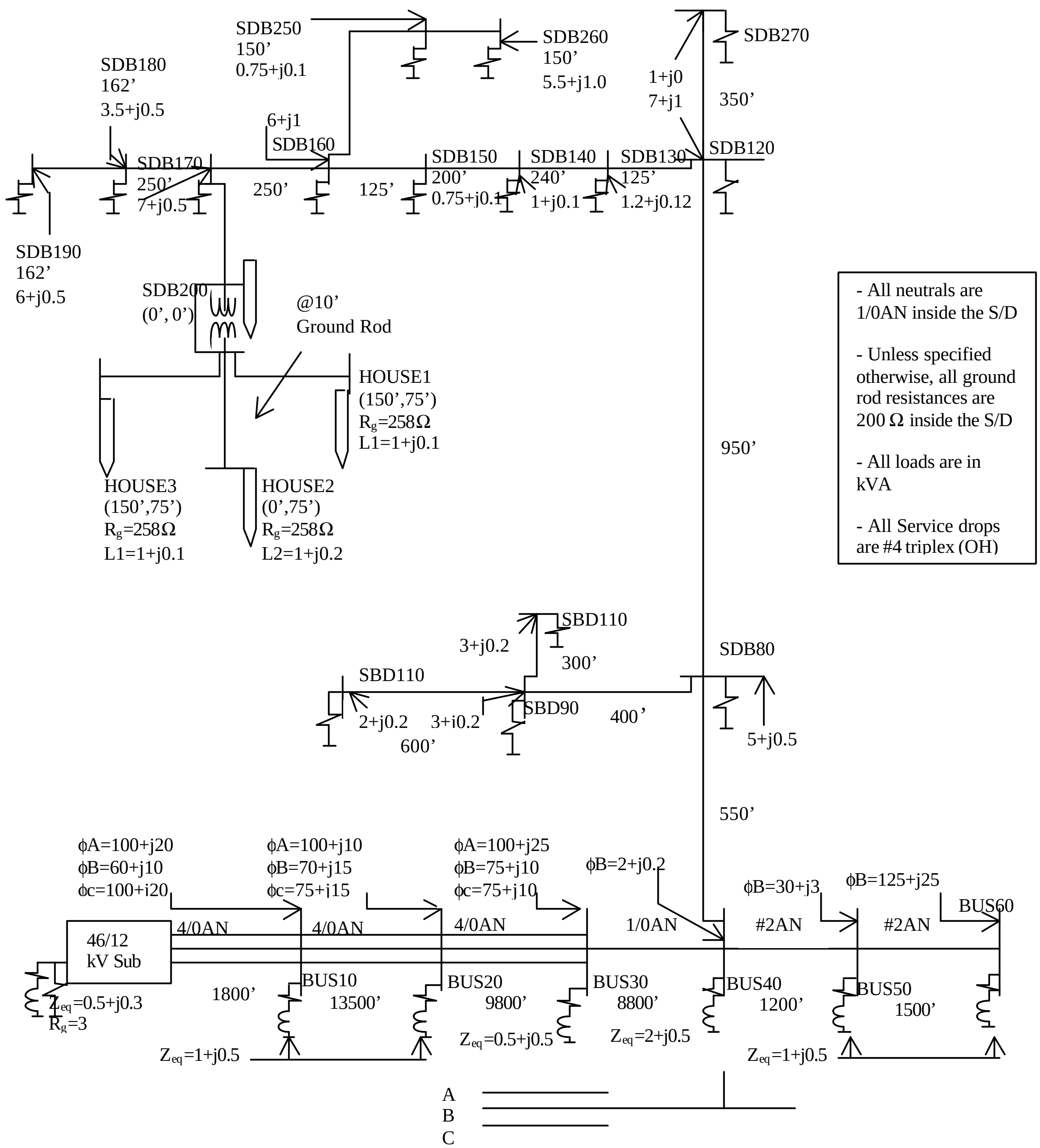


Figure 8-4 Modeled Distribution System to Investigate N-E Voltage Concerns in a Residential Subdivision

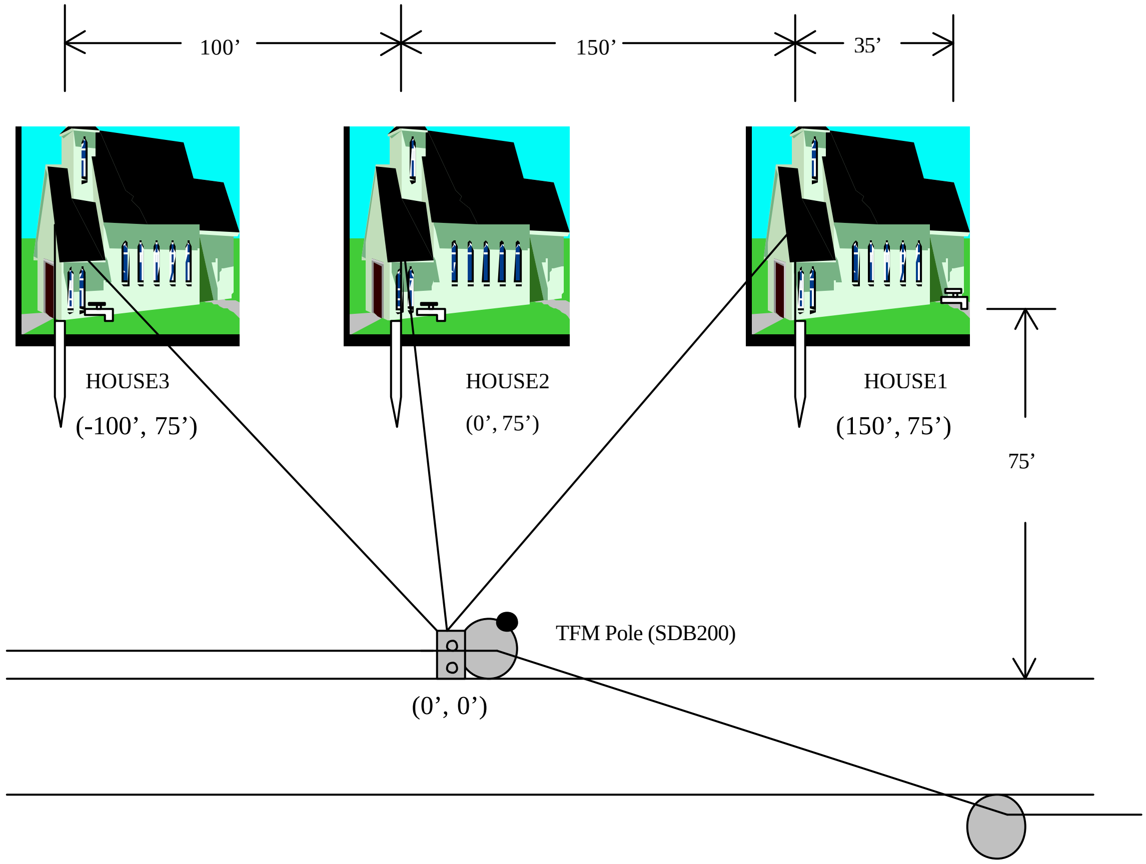


Figure 8-5 Modeled Locations of Transformer Pole and Investigated Houses

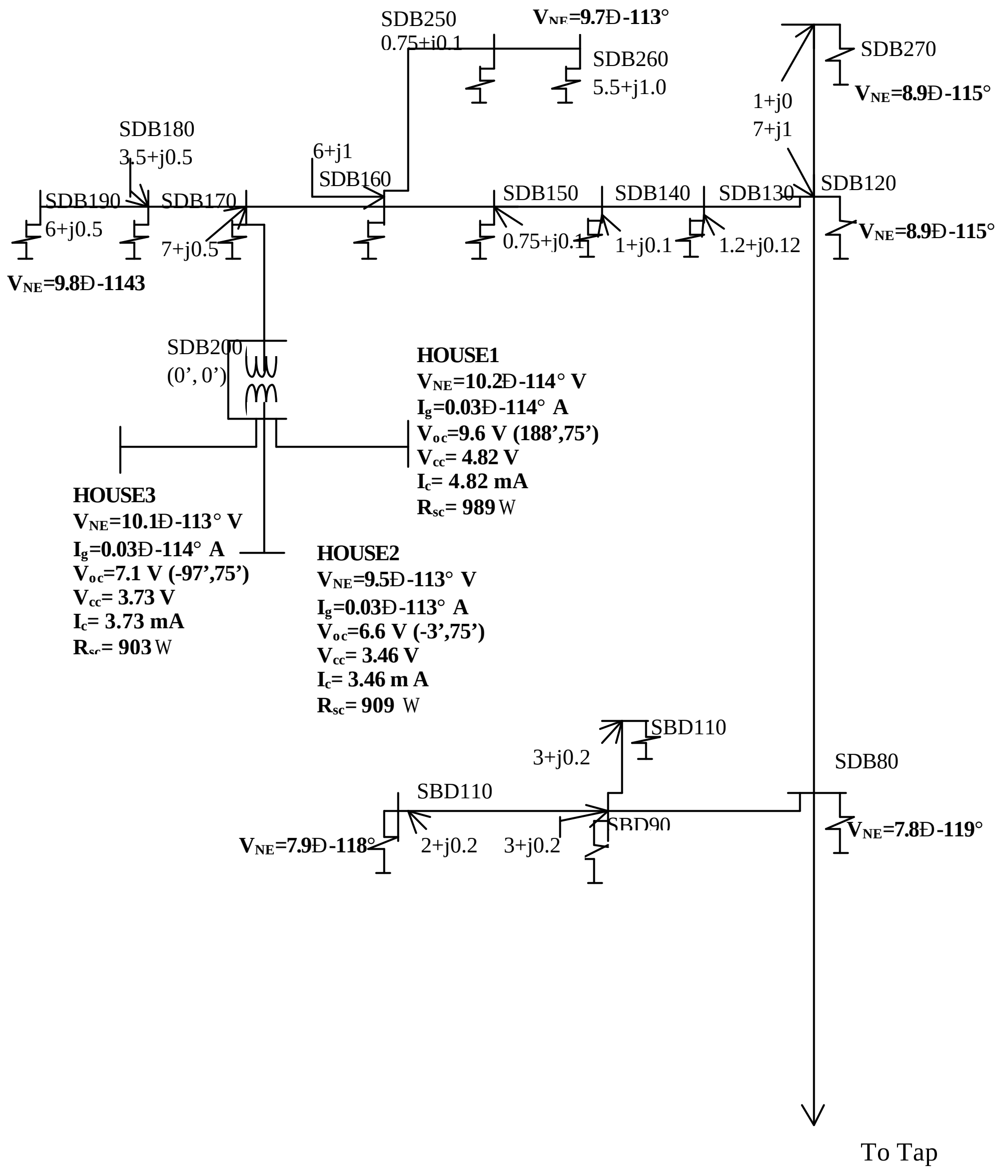


Figure 8-6 Computed N-E Voltages, Contact Voltage, and Contact Current in the Residential Subdivision (Base Case)

Corrective Measures

Three different corrective measures are investigated and evaluated for their effectiveness in reducing the N-E voltages in the subdivision as well as around the houses under study.

A normal response to complaints by the residents would be to improve grounding at the houses and the transformer pole. To see how effective this solution is, depths of ground rods were increased to 20' at the houses and at the transformer. The ground rod resistances at these locations reduced from 258 Ω to 142 Ω. Figure 8-7 shows the computed N-E voltages at selected locations.

Referring Figure 8-7, the N-E voltages reduced a little from the base case (with no corrective measure, see Figure 8-6). Among the investigated houses, reduction due to this corrective measure was 4%, 14%, and 12% in House-1, House-2, and House-3 respectively. Other locations in the subdivision showed a little or no reduction in the N-E voltages.

Providing a larger size neutral should reduce the voltage drop across its length for the same current flowing through it. Ultimately, this should result in lower N-E voltages at the beginning of the current return path (the neutrals at the transformer poles). The effectiveness of this solution is illustrated next. Increasing the neutral size just around the transformer poles may not effectively reduce the N-E voltages. For this solution to be effective, the entire feeder may have to be considered for neutral upgrading. In our example, a 4/0 ACSR neutral replaced all neutrals beyond BUS20 (Figure 8-4). The computed N-E voltages are shown in Figure 8-8.

As shown in Figure 8-8, replacing the neutrals by 4/0 ACSR reduced the N-E voltages by 25% on the average. Although a significant reduction in the voltages has been achieved, they still are above the acceptable levels.

The last corrective measure consists of extending the three phases to the end of the feeder and bringing an additional phase (ϕC) into the subdivision. Additional phases facilitate load balancing which in turn reduces the current flowing in the neutral. Figure 8-9 illustrates the modeled distribution system for this corrective measure.

The computed N-E voltages are shown in Figure 8-10. Reduction of 75% in N-E voltages on the average clearly favors this solution, provided its' cost is justified.

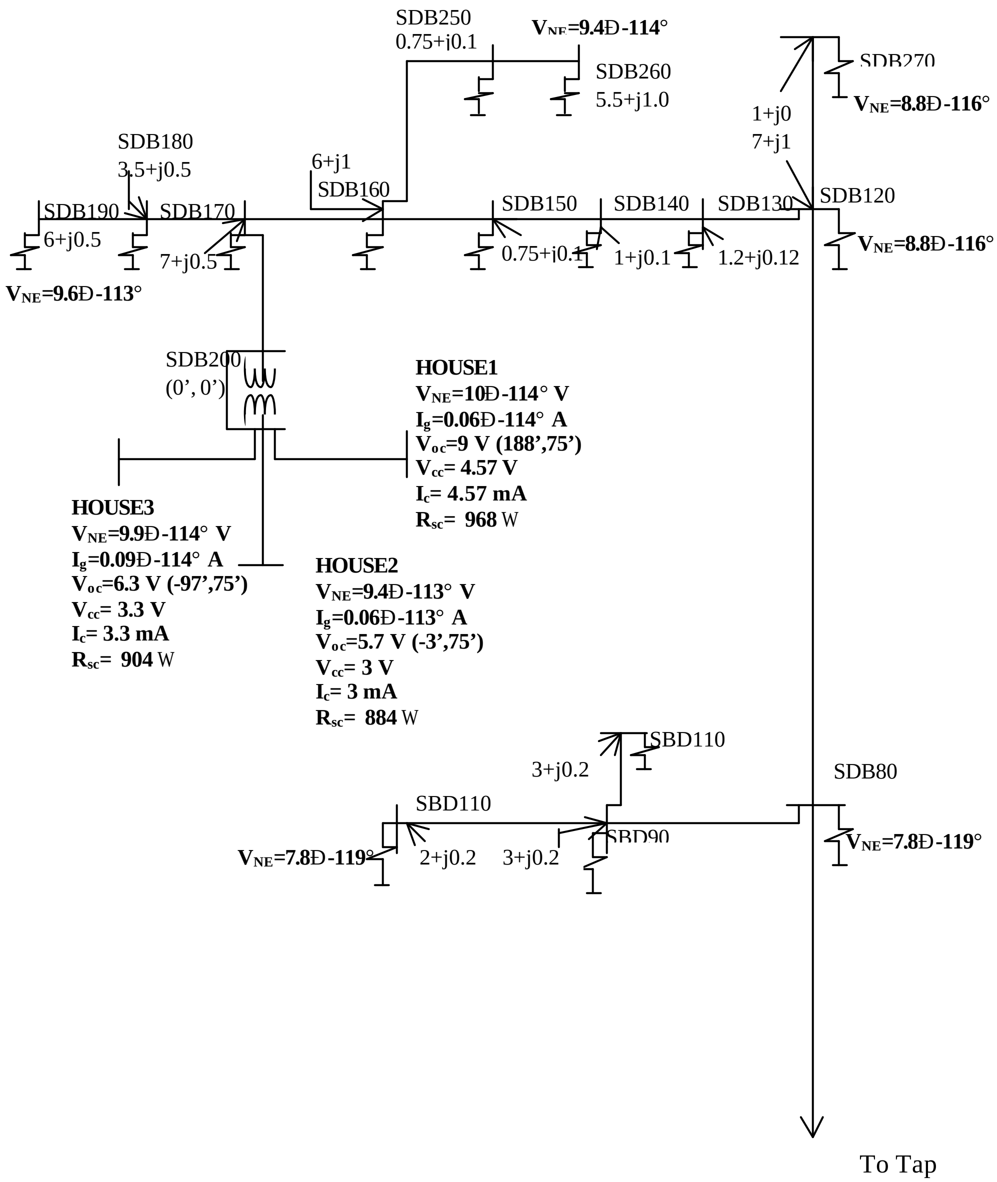


Figure 8-7 N-E Voltages in the Subdivision – 20' (142 W) Ground Rods replaced the 10' (258 W) Ground Rods at the Houses and at the Transformer (Compare with Figure 8-6)

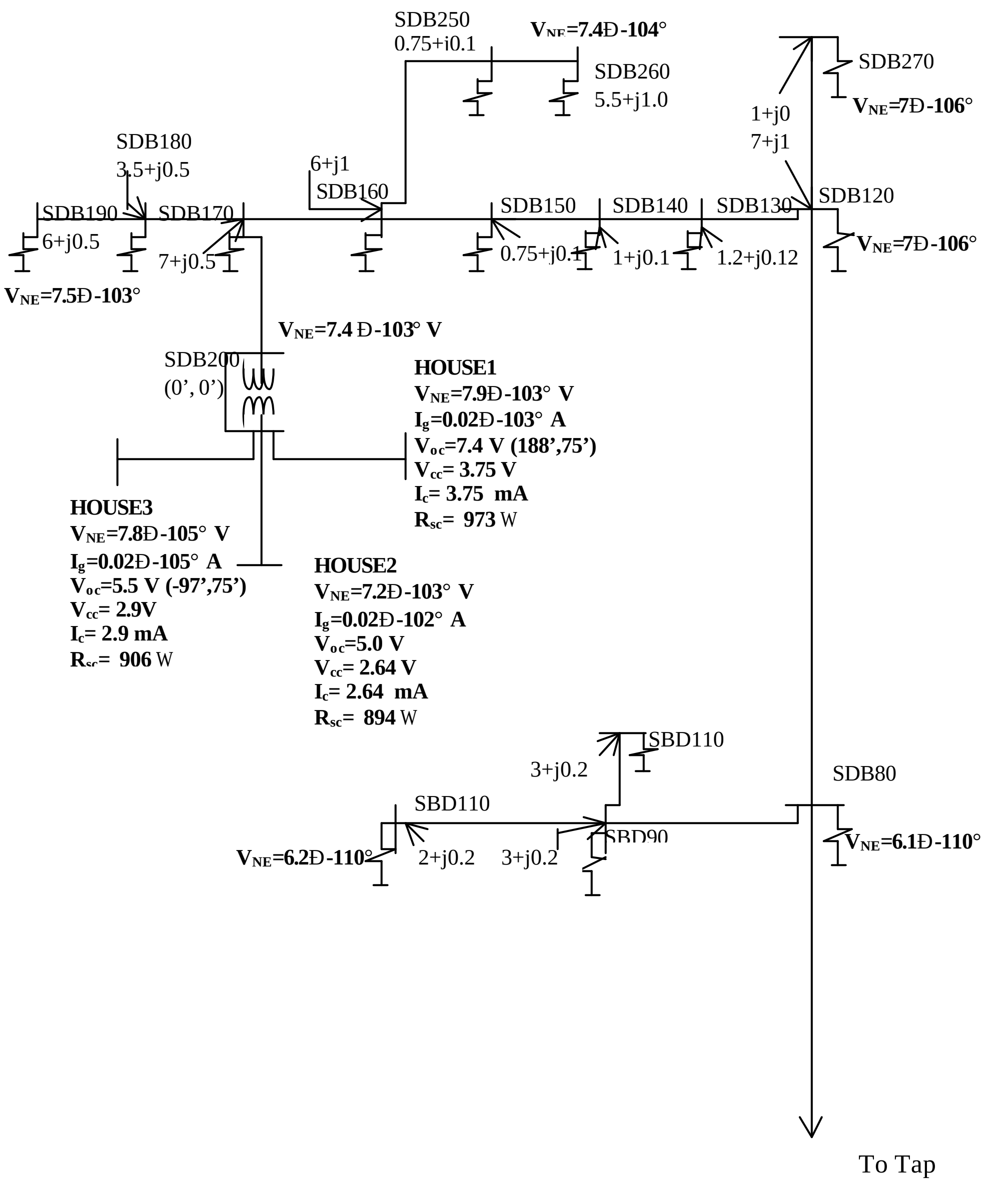


Figure 8-8 N-E Voltages in the Subdivision – 4/0 ACSR Neutral Replaced #2 ACSR Neutral between BUS40 and BUS60 and 1/0 ACSR Neutral in the Subdivision (Compare with Figure 8-6)

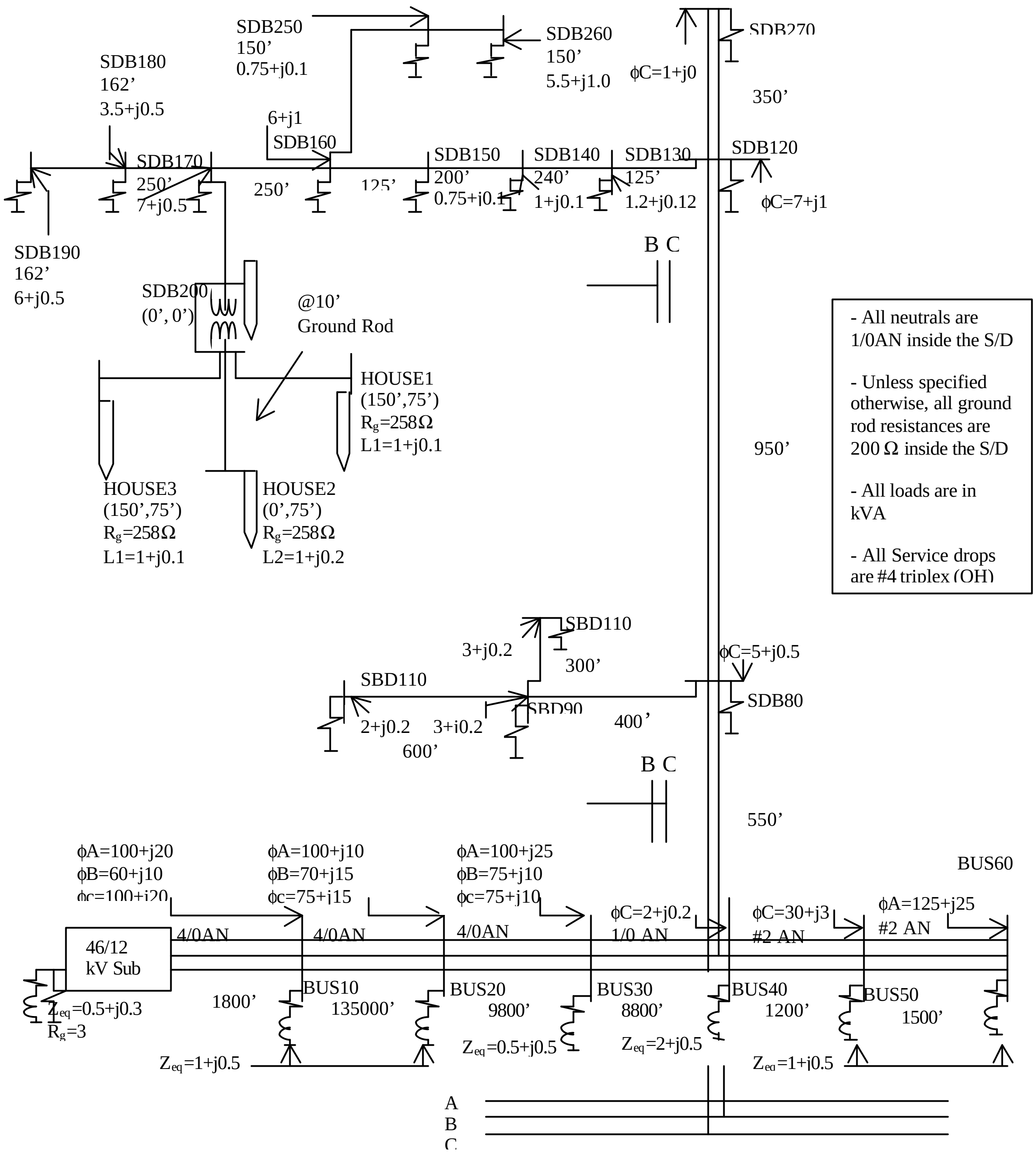


Figure 8-9 Modeled Distribution System Showing 1) Three-Phase Line Extended to the End of the Feeder, 2) Additional Phase in the Subdivision, and 3) Load Balancing

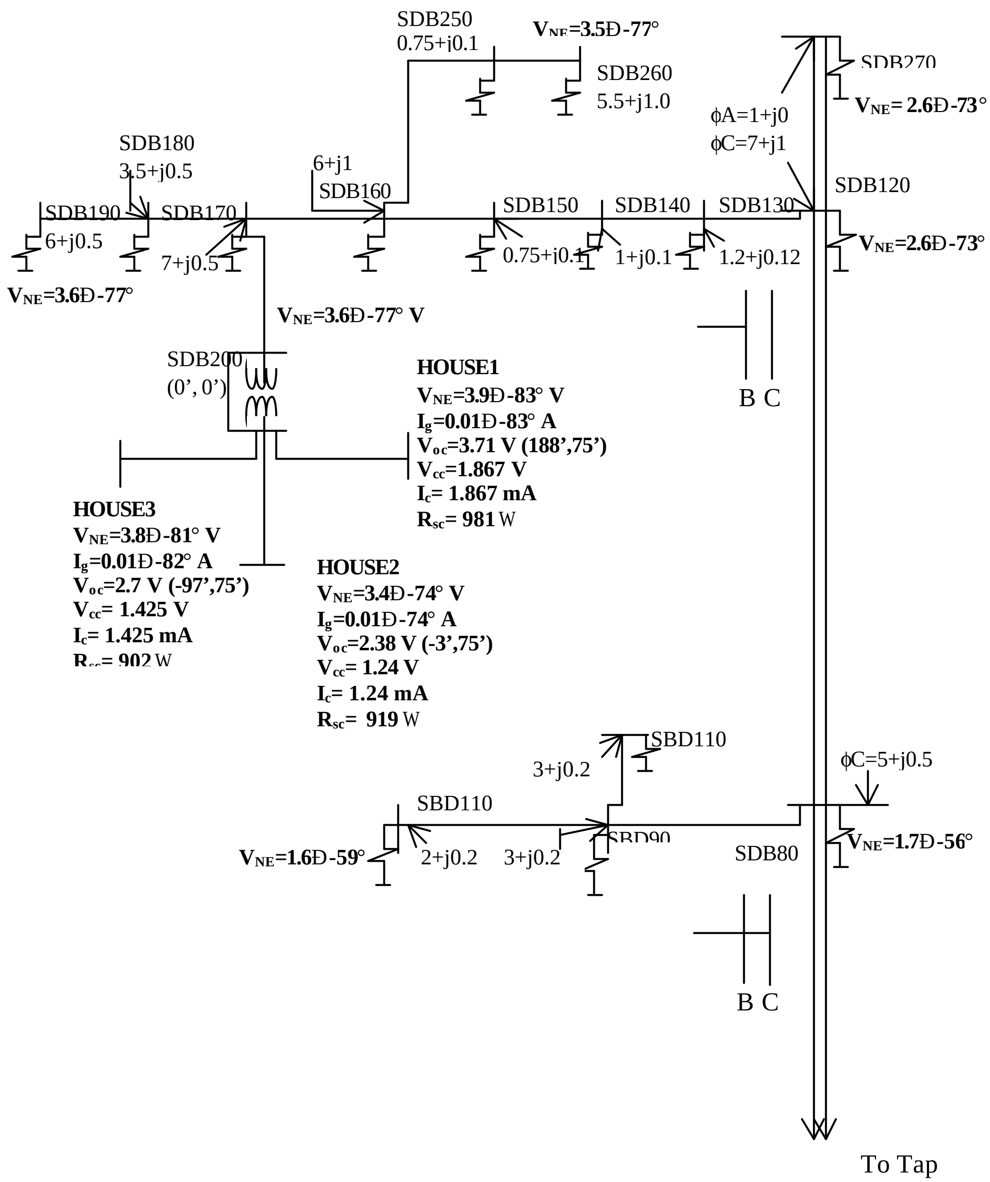


Figure 8-10 N-E Voltages in the Subdivision – Additions of Phases and Load Balancing (Compare with Figure 8-6)

Study Case for Boat Dock Shocking Problem

Concerns for Shocks on Wet Surfaces

Human shocking problems at swimming pools and boat docks are more common than the problems in and around the houses primarily due to two fatctors. One factor is common to all shocking problems involving humans. In the case of dairy farms and cows, the loss of milk production more or less determines the permissible current level. On the other hand, in the case of humans, the perception level of shocking current is suficient to initiate a complaint. Another factor responsible for frequent complaints is more specific to the cases involving boat docks and swimming pools. The lower values of equivalent source resistance due to wet surfaces and the body of water at the contact points result in higher current magnitudes. This in combination with the previous factor may be the reason for more frequent complaints.

In the case of a swimming pool, it is not uncommon for a person to get a shock while coming out of the water with the hands on the handrails. The equivalent source resistance measured from the part of the body in the water to remote earth would obviously be of a much lower value compared to a person contacting the handrail while standing on a dry soil. A similar situation exists when a person contacts a boat lift rope (metal) or a gas pump nozzle while standing on the wet boat.

A study case illustrating a human shocking problem on a boat dock is presented next. The case involves a marina with a gas pump at the end of a boat dock and is based on an investigation conducted by a member company. The marina complained that the boaters receive shocks while pumping gas into their boats. The contact points were defined as the gas pump nozzle (connected to the neutral) at one end and the wet boat surface (or lake water) at the other end.

Analysis of Problem

Figures 8-11 and 8-12 show the primary and secondary distribution systems, respectively. Referring to Figure 8-11, the primary distribution system consists of a 12.47 kV, three phase feeder. Approximately 6.0 miles of this feeder including the source substation has been modeled (SUB to BUSN). The 0.4 miles long three phase line to the marina is tapped at 1.25 miles from the substation (at BUSD). Figure 8-11 shows the modeled loads and ground impedances at each bus. These are assumed values and represent the equivalent values for all loads and grounds exisiting between the buses and at the buses.

The marina receives power from a 12.47 kV / 240-208-120 volts, 75 kVA, three-phase transformer. This three phase transformer with the meter is located at BUSF. Referring to Figure 8-12, there are three secondary circuits serving the customer. The main three-phase, 240/120 volts, circuit, is a 4/0 quadraplex and serves the dock and the gas pump (BUSF to BUSDK). One #2 Aluminum triplex circuit (single-phase, 240/120 volts), serves a shop first and then a cabin. Another single-phase 240/120 volts circuit, a triplex, serves lights and boat slips approximately 550 feet from the tap point.

Due to limtations in the software being used for modeling, the modeled system is not identical to the actual system. Another reason for the mismatch is the several assumed parameters for the model. Some of the software limitations which are siginificant to the this study case are listed below.

- Limited transformer models – the transformer model used in this study case is slightly different from the transformer used in the field,
- Inability to model horizontally varying soil resistivities (or the dividing line between the land and the water can not be modeled), and
- Inability to connect the same grounding electrode system to more than one bus (presently, the stray voltages at the marina are mitgated by an extensive grounding system which connects to the neutral at the dock and at the pole as well. This scenario can not be modeled using the software.)

Assuming that the stray voltage sources due to a corroded neutral splice or a low voltage earth fault (leakage current) are absent, there are three possible sources which can cause the stray voltages in a customer facility. As discussed in Section 4, these sources include 1) the neutral current due to unbalanced load in the primary, 2) the primary neutral current resulting from the transformer secondary load, and finally 3) the voltage drop in the secondary neutral. In this study case only two of the three sources are responsible for the stray voltages at the dock. Referring to Figure 8-12, the customer transformer is a three-phase transformer with an open delta connection on the primary side. Because the transformer neutral on the primary side does not exist or is not tied with the system neutral, the neutral current resulting from the transformed secondary load (source #2 as listed above) is eliminated. As expected with the remaining two sources, the most dominating source turns out to be the neutral current resulting from the unbalanced load in the primary system. This is illustrated in two steps. First, N-E and open circuit contact voltages (V_{oc} at CP1 and CP2) are computed with the system in the “as found” condition (see Figures 8-11 and 8-12). Second, the computations are repeated with customer’s meter pulled off (no load on the secondary side) to show that the voltages did not reduce much. For convinience, the data for both cases are displayed in the same figure: Figure 8-13.

The data presented in Figure 8-13 show that pulling the customer meter out reduces the N-E and contact voltages by about 22%. Alternately, this suggests that approximately 78% contribution to the stray voltage is coming form the primary side. As usually is the case, the unbalanced load current on the primary side is primarily reponsible for this contribution.

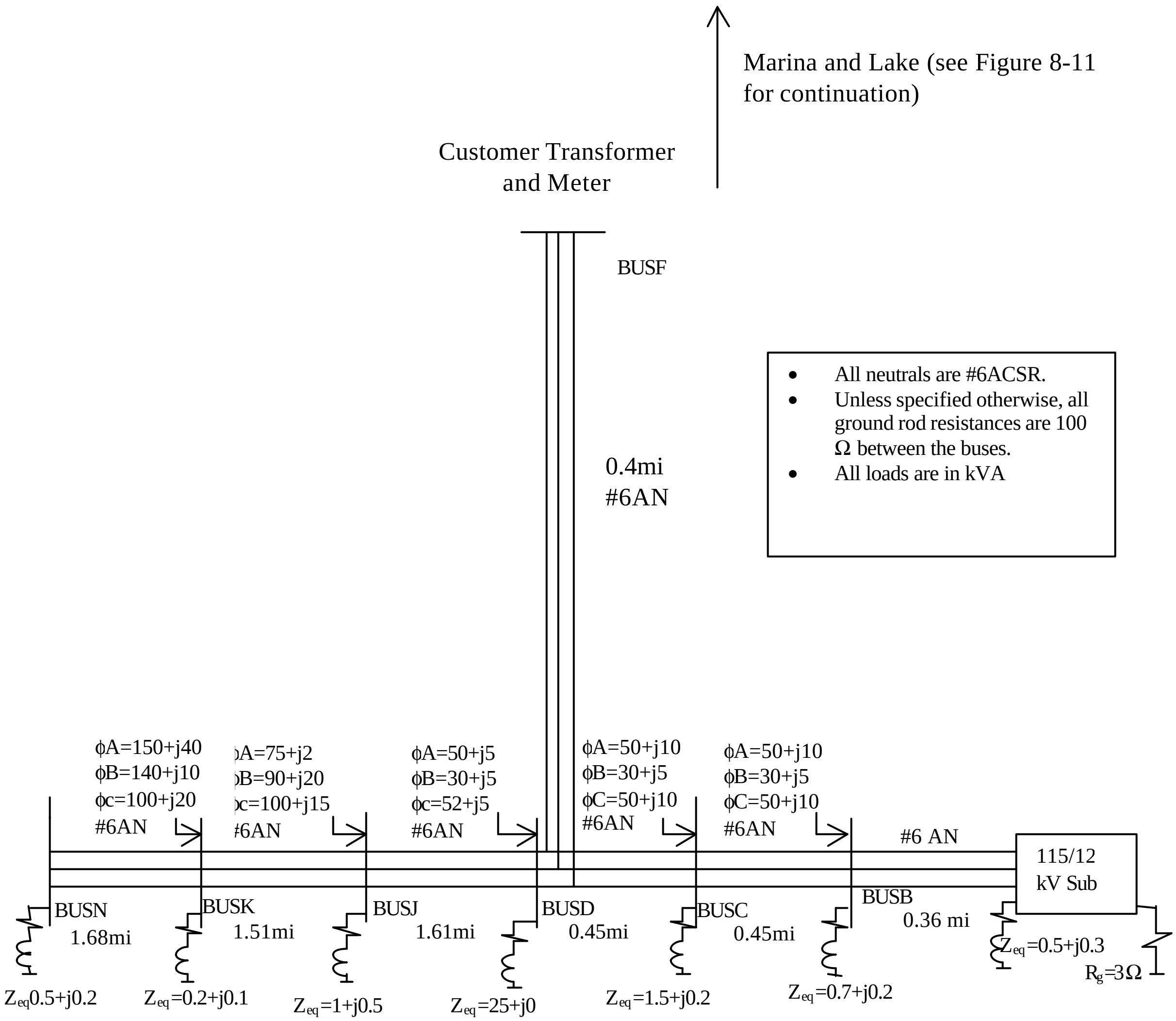


Figure 8-11 Modeled Distribution System (Primary) for Boat Dock Study Case

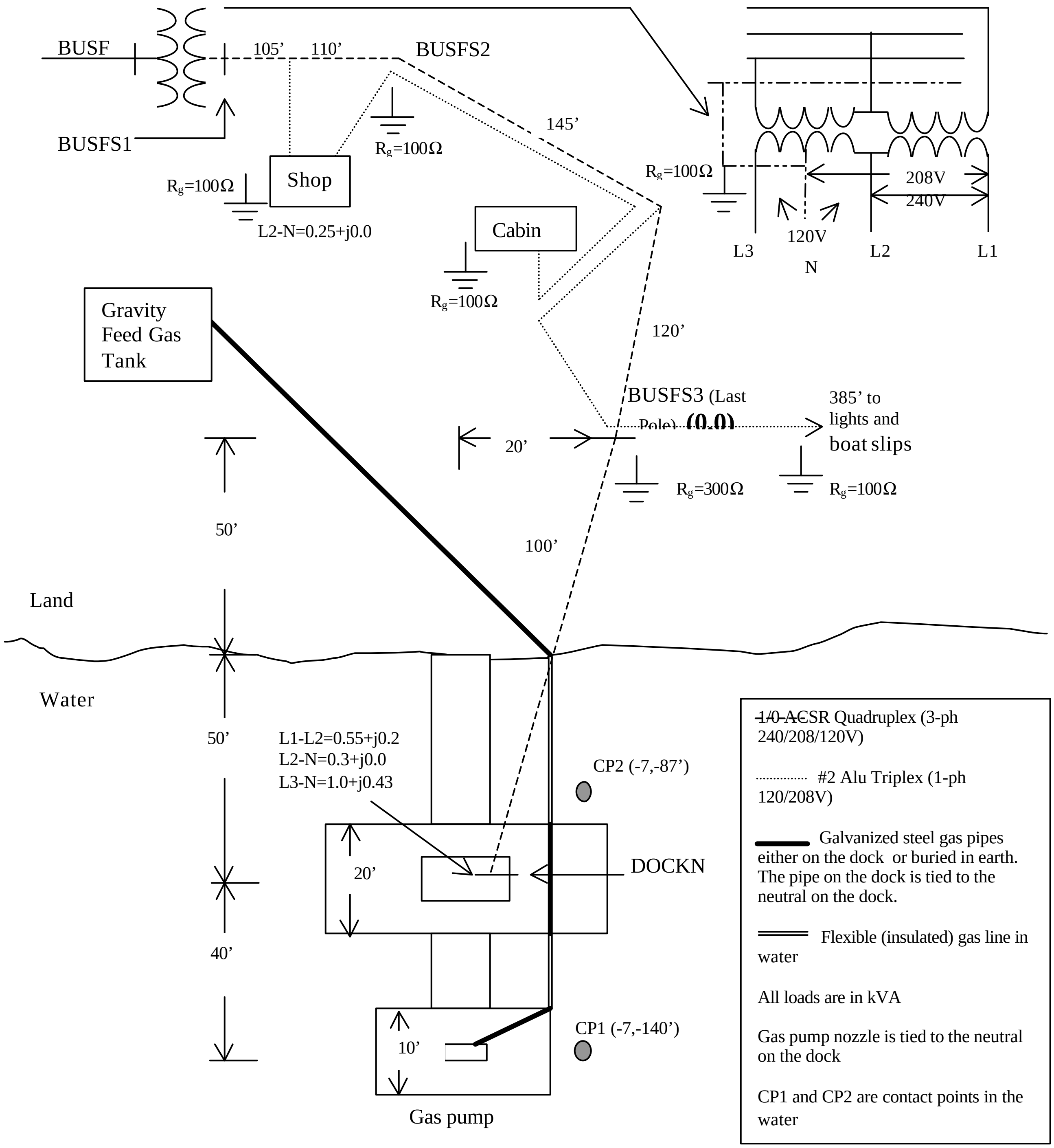


Figure 8-12 Modeled Secondary System for Boat Dock Study Case

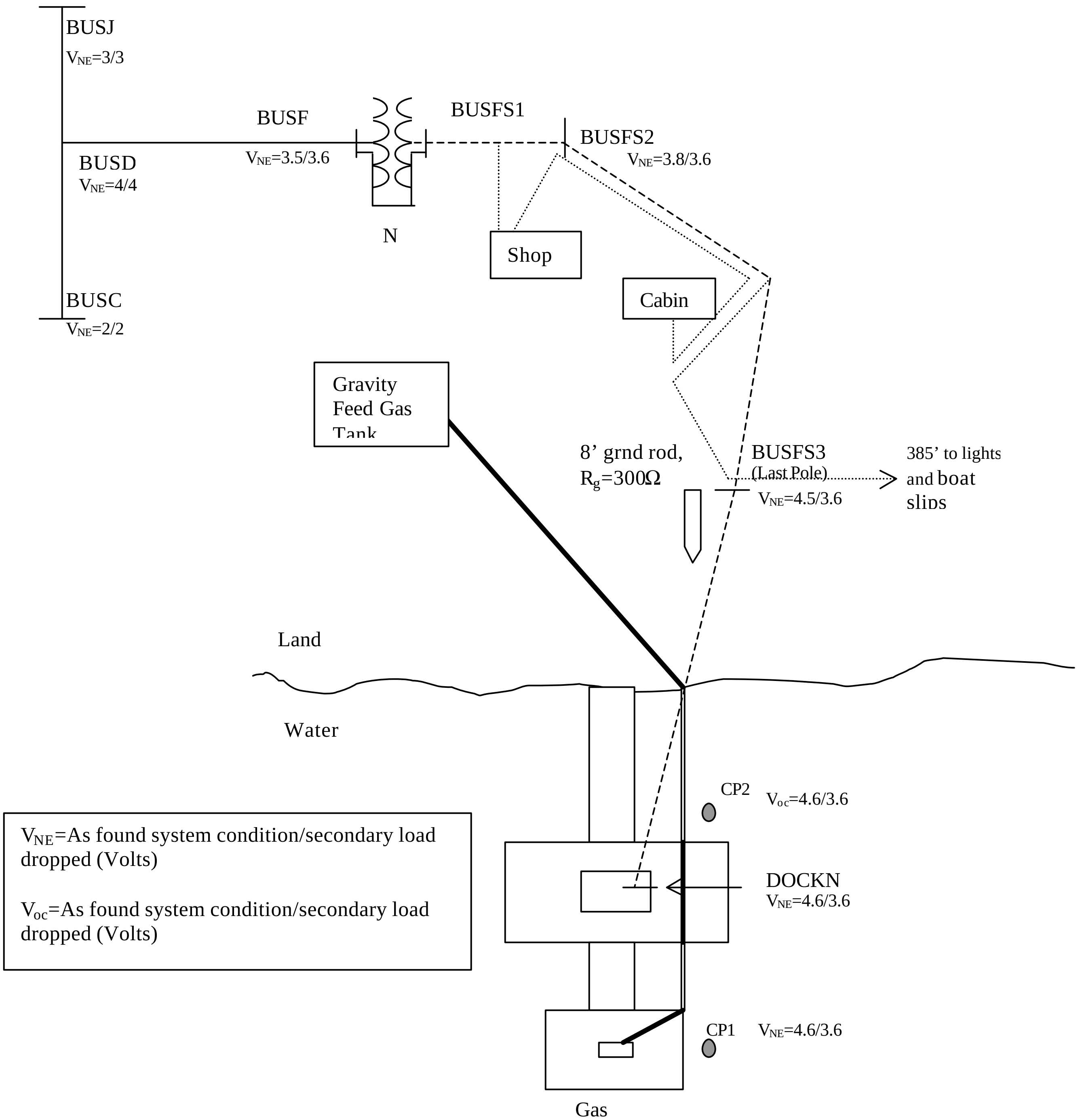


Figure 8-13 Boat Dock Study Case – N-E and Open Circuit Contact Voltages with As Found System Conditions and with Customer Load Dropped

Corrective Measures

The host utility company methodically investigated the stray voltage problem at the marina and attempted several corrective measures until the maximum reduction in stray voltages were accomplished. They started with checking the wiring and the connections at the dock. A bad connection was found and was replaced. Next, they dropped a #6 bare copper wire in the water bypassing the flexible (insulated) gas line from the main dock to the land. This wire was connected to the galvanized pipes at each end. Finally the #6 conductor was extended to tie to the pole ground (at BUSFS3 in Figure 8-12). With no significant reduction in the dock voltages, the personnel lifted the #6 wire temporarily from the land and started improving the grounding system from BUSFS3 towards the dock. They drove several 8' ground rods in the earth first. When the lake water was reached, the ground rods were driven in the water along the shore on one side first and with no significant improvement, the rods were driven on the other side of the pier. On the other side of the pier, a 24' driven ground rod made a significant difference in the dock stray voltages. Finally the #6 copper wire was reconnected to the pole ground with very significant reduction in the dock voltages.

Due to software limitations stated previously, the steps taken by the host utility company will not be exactly followed in this study case. Also, no attempt will made to match the voltages measured by the host company following the application of each corrective measure. However, a good number of these corrective measures will be analyzed and presented in this section. Also, it will be added benefit to the users if additional corrective measures are also illustrated using the same system.

With the above considerations, this section anlayzes the following corrective measures:
1) Installing two counterpoises (#6 copper wire) in the water- one counterpoise along the flexible gas line from the gas pump dock to the main dock and another from the main dock to the land
2) Installing ground rod / counterpoise system from the "last pole" (BUSFS3) to the lake
3) Combination of 1) and 2)
4) Attaching ground rings to the main and gas-pump docks
5) Provide neutral isolation at the transformer

The data corresponding to various corrective measures are presented in Figures 8-14 through 8-18. Analysis and comparison of these measures follow the figures.

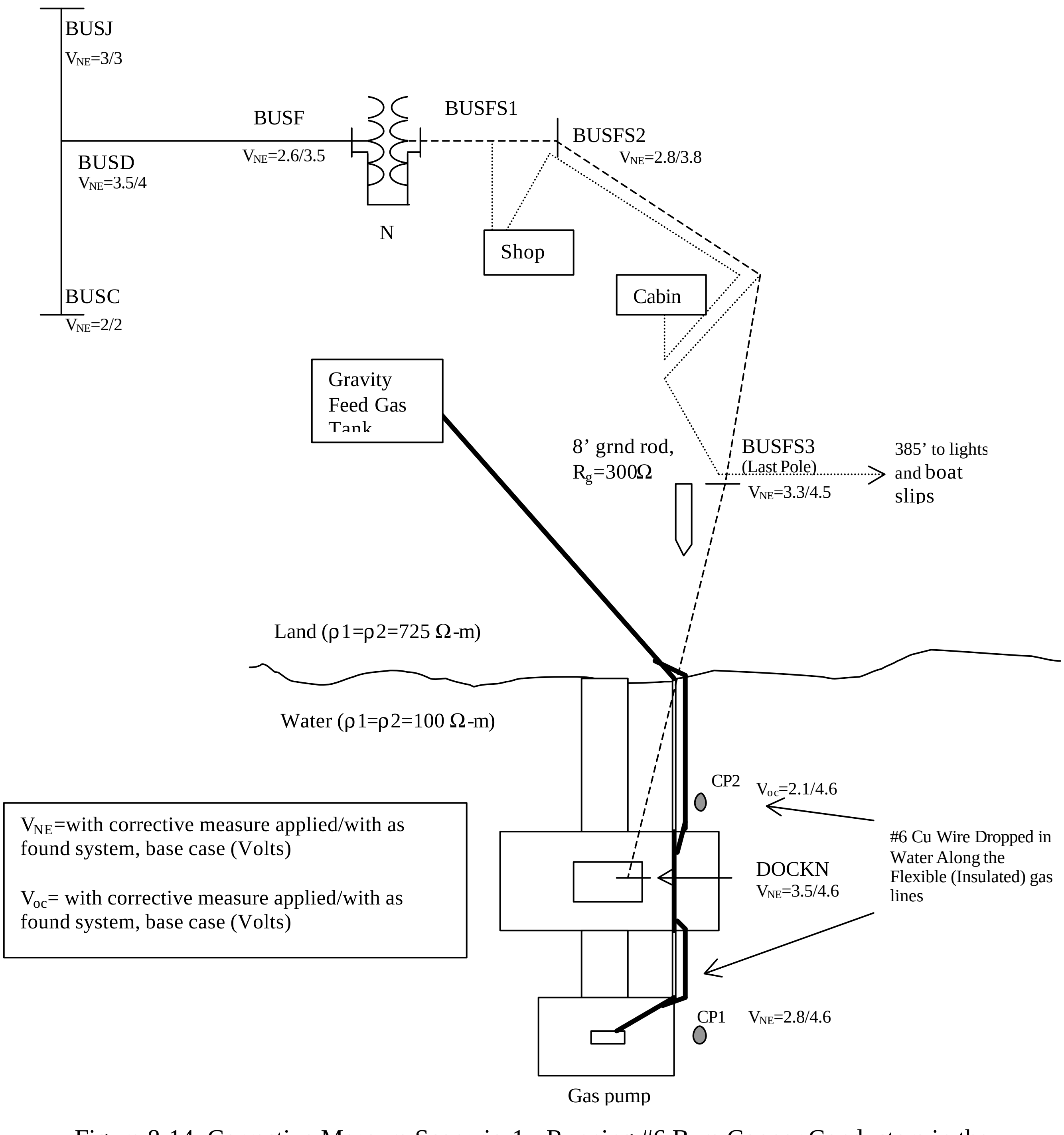


Figure 8-14 Corrective Measure Scenario-1 - Running #6 Bare Copper Conductors in the Water along Flexible (Insulated) Gas Lines

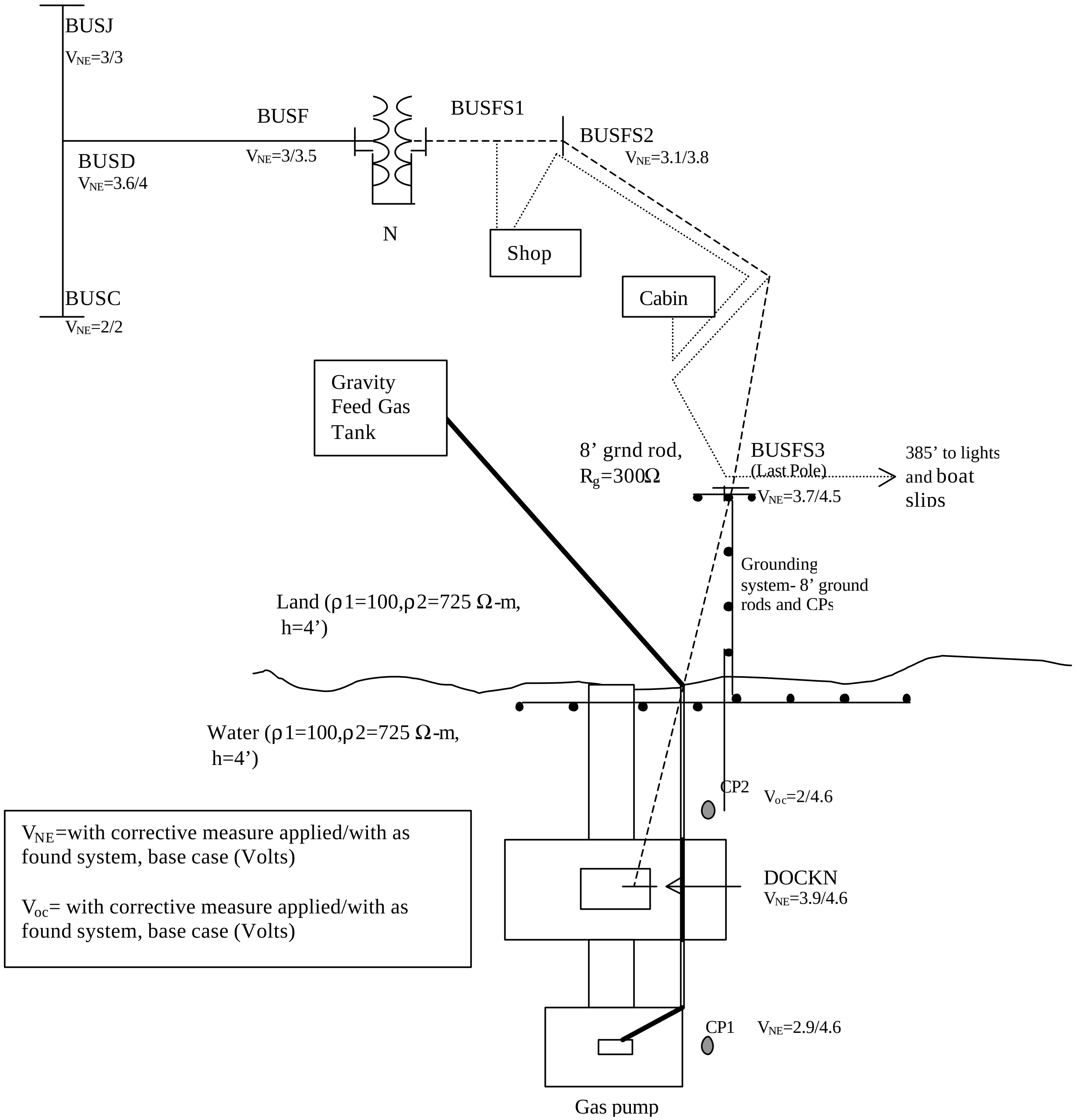


Figure 8-15 Corrective Measure Scenario-2 – Installing Ground Rod / Counterpoise System from the "Last Pole" to the Lake Water

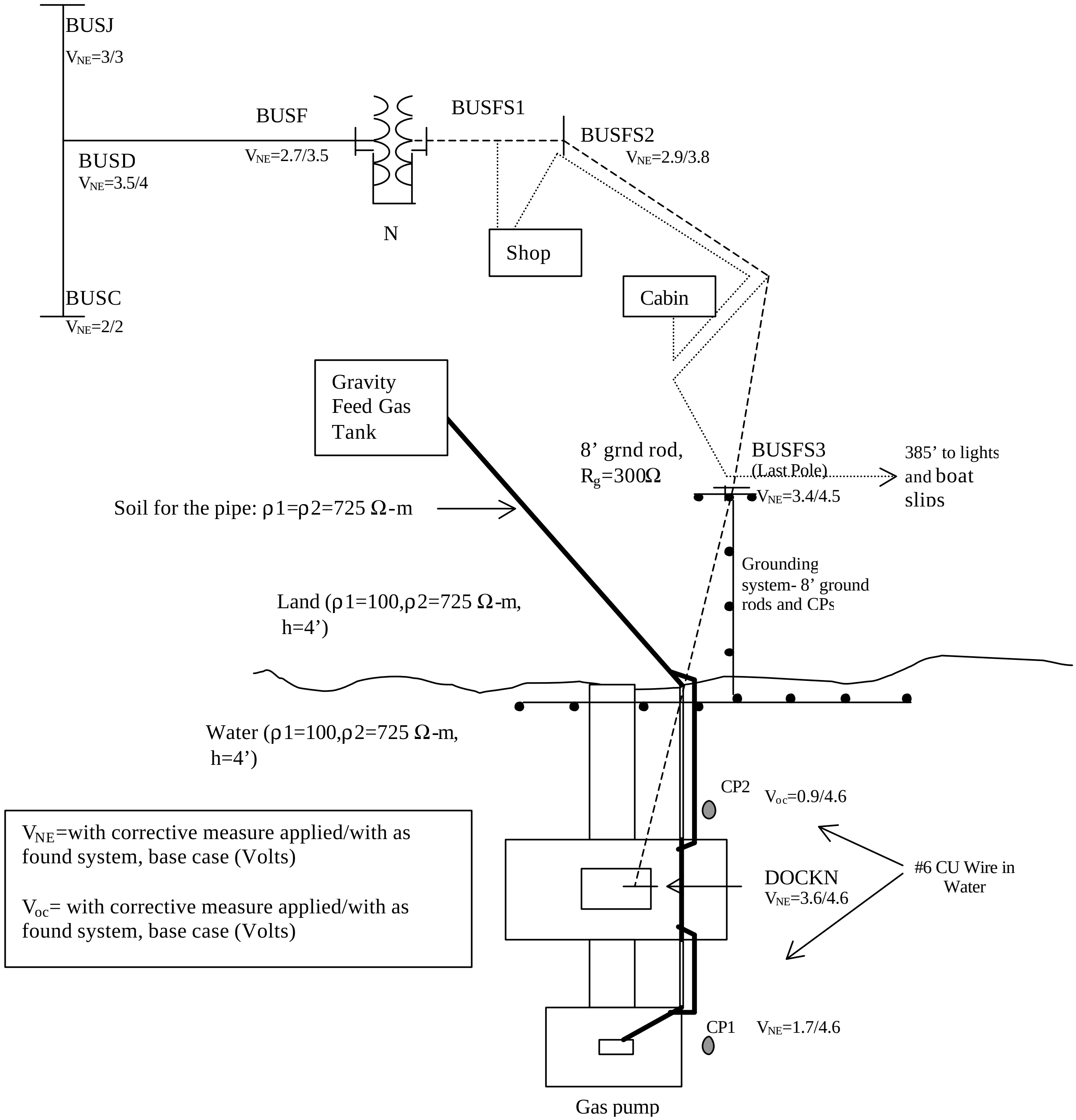


Figure 8-16 Corrective Measure Scenario-3 – Combination of Installing Ground Rod / Counterpoise System from the "Last Pole" to the Lake Water and Dropping #6 Copper Wire in the Water along the Flexible (Insulated) Gas Lines

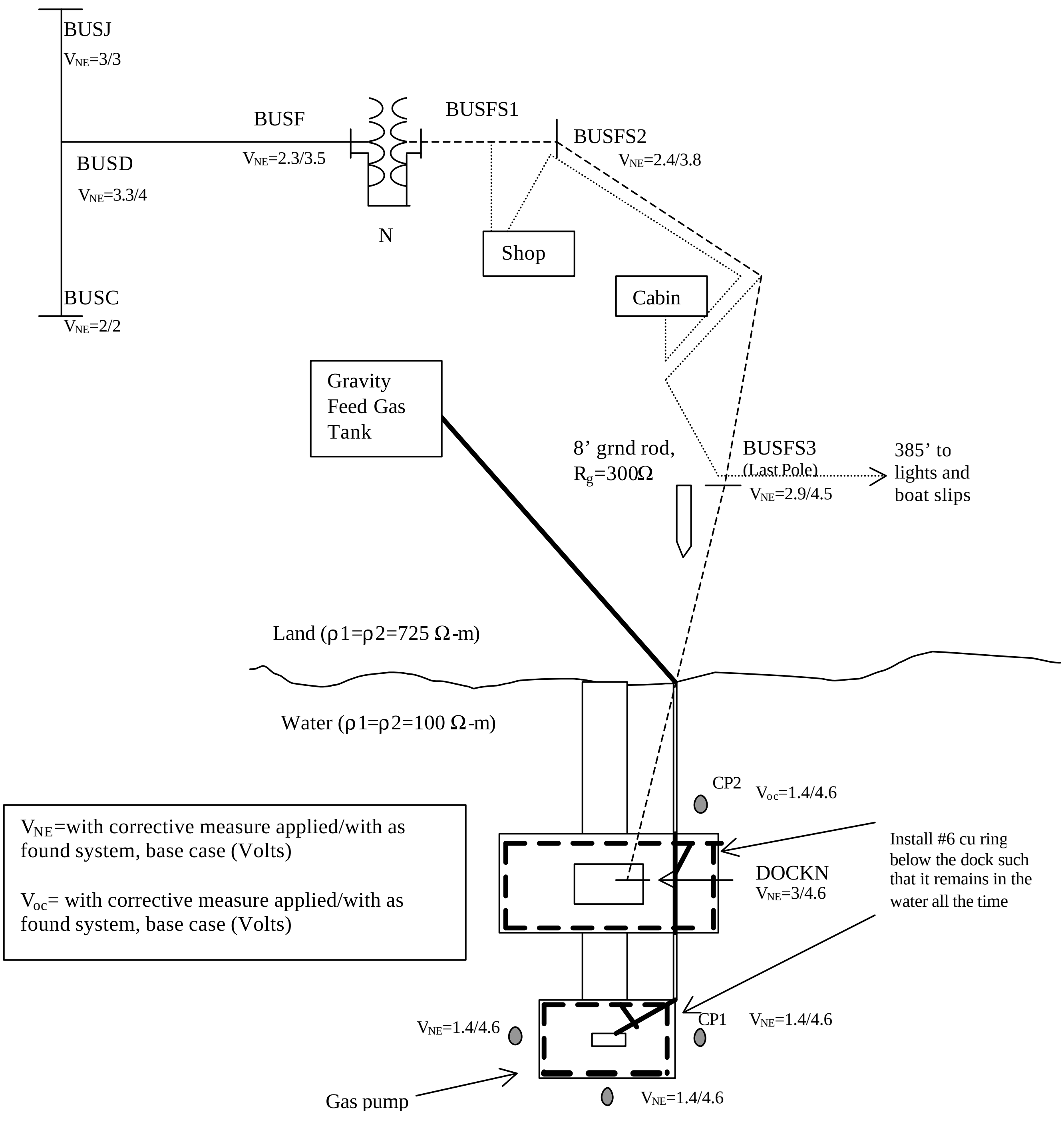


Figure 8-17 Corrective Measure Scenario-4 – Installing Ground Ring (#6 CU) Around and Below Both Docks

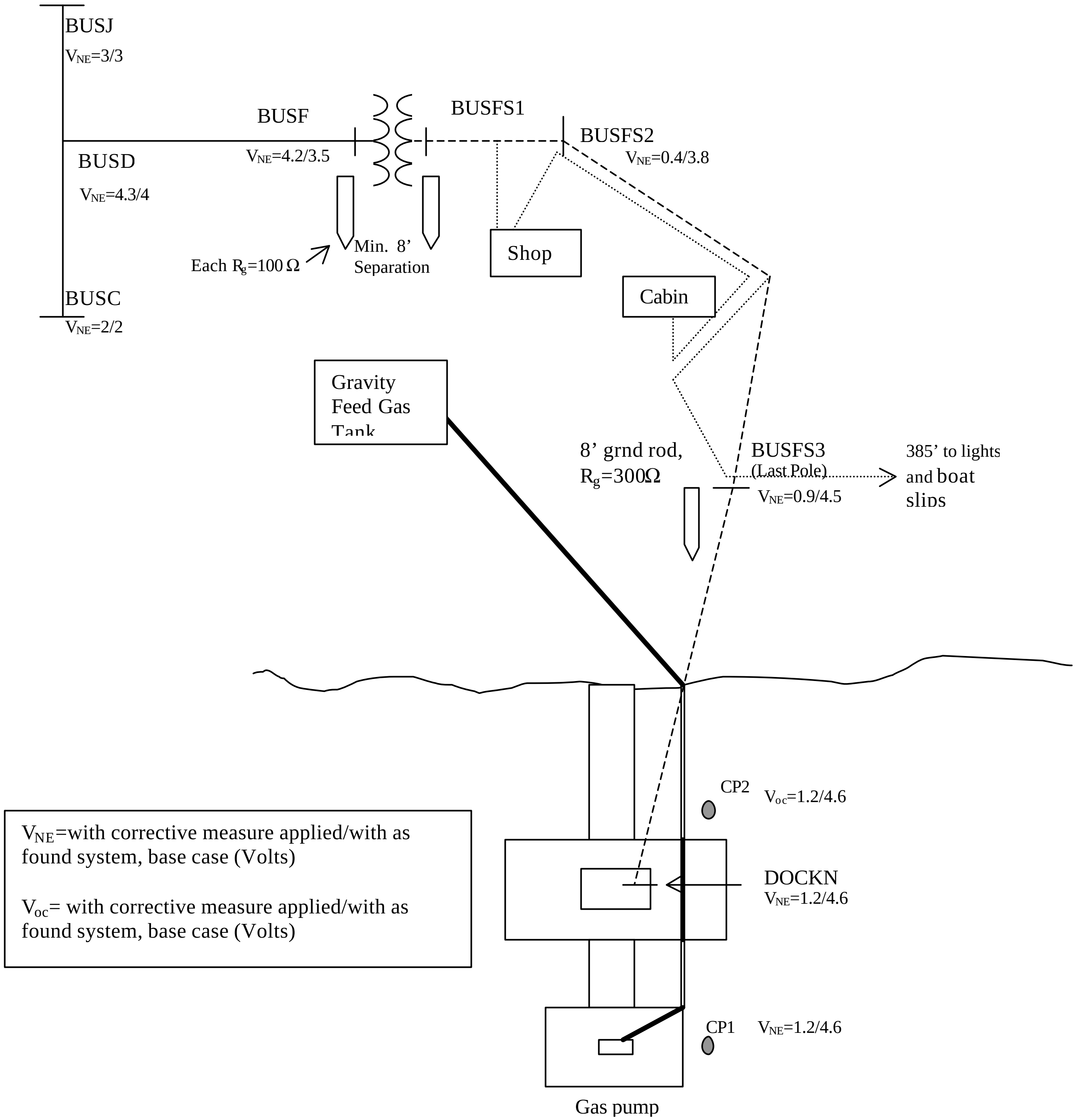


Figure 8-18 Corrective Measure Scenario-5 – Isolation of Neutral at the Transformer

The analysis indicates that the major contibution to dock stray voltages is from the primary side sources. Obviously, the isolation of the neutral at the transformer should provide effective mitigation. The data in Figure 8-18 show that the neutral isolation does provide an effective mitigation. The stray voltages near the gas pump (CP1) reduced almost by 75%. However, this may not be a viable solution if cable TV or telephone circuits enter the premises and their shields are directly or indirectly connected to the power system neutral.

The combination of installing the ground rod / counterpoise system at the pole and dropping #6 copper wires in the water (along the flexible gas lines) is another effective solution. The data in Figure 8-16 indicate that the stray voltage near the gas pump (CP1) reduced by about 65%. The stray voltage near the main dock (CP2) reduced by about 80%. Note that the mitigation method implemented by the host company is nearly the same as the the method analyzed in this scenario.

Attaching ground rings to the bottom of the docks can be an effective corrective measure. This method can also be a cost effective method. The data in Figure 8-17 illustrate the effectiveness of this measure. The stray voltages at both contact points (CP1 and CP2) reduced almost by 70%. Compared to just dropping a #6 copper wire in the water, attaching the ground ring to the dock has an advantage. The ground ring provides a uniform protection all around the dock. For example, referring to the area around gas-pump dock in Figure 8-17, the ground ring provides nearly the same protection all around the dock.

Dropping #6 copper wires in the water as shown in Figure 8-14 or installing the extensive ground rod / counterpoise system at the pole as shown in Figure 8-15 do seem to help reduce the stray voltages in the dock area. Their effectiveness is less compared to the measures described above. In the case of #6 copper wire in water, the stray voltage near the gas pump reduces by 40%. The reduction in the case of ground rod / counterpoise system is about 37 %.

Study Case for Induced Voltage / Current

Stray Voltage Concern from Parallel Transmission Lines

It is not uncommon for a distribtuion line to co-exist with a transmission line, either on the same right-of-way or as an underbuilt circuit. Underbuilt distribution circuits are commonplace in many urban areas where new right-of-ways are so hard to find. For such systems, high N-E voltages on the distribution system due to induction from the transmission line is always a concern. The induced voltage being inversely proportional to the distance, underbuilt distribtuion lines compared to the lines on the same right of ways are subject to significantly higher voltages. In addition, the current flowing in transmission shield wire may also add to the problem if the neutral is connected to the shield wire at the common poles.

The following factors contribute to stray voltages on the distribution system due to induction from transmission lines:

- Proximity of yhe distribution line to transmission lines (underbuilt distribution line represents the worst situation)
- Longer parallel distance
- Additive phase angle between the normal and induced currents in the neutral

Analysis of Problem

This study case involves a resident who complained of shocks at their swimming pool located in the back of the house. The shocks were received when resting their arms on the concrete deck with their bodies in the water. The measurement of stray voltage (open circuit contact voltage) showed 4 volts between the wet concete deck and the pool water. Identifying the parallel 240 kV line as the stray voltage source, the utility company's personnel switched the four customers served by the same transformer to a different feeder that does not parallel any transmission line. Folowing the switch-over, the stray voltage measured less than 1 volt.

Figure 8-19 represents the transmission and distribution systems involved in this study case. To increase reliability, the 240 kV / 13.8 kV distribution substation is fed from two 240 kV sources in a loop configuration. The substation has two 18 kVA delta-wye transformers each serving three distribution feeders. One of the six feeders serves the customer. A 25 kVA transformer serves four houses including the subject house. One of the two transmission lines serving the substation parallels the subject distribution line for two miles. The distribution line is located on the same right-of-way and at a distance of 60 feet from the transmission line. Note that the neutrals and the shield wires are tied together only at the substation.

According to the member company, the maximum unbalance on their distribution phases is kept under 50 amperes and the maximum neutral current allowed is approximately 33% of the phase unbalance. Approximately 1,200 amperes of load current normally flows in the subject transmission line and the average load on each feeder is 8 MVA. Since actual loads were not known at the time of investigation, the reported load conditions were used only as guidelines for the computer modeling. The loads actually modeled (see Figure 8-19) were a result of a few trial values to obtain the desired N-E voltage (approximately 4 volts) value at the customer's meter point. System parameters such as line length, span length, and conductor sizes were modeled close to that existing in host company's system.

Figure 8-20 shows the system voltages and currents including the problem N-E voltage of 4.63 volts at the meter point of the subject house (House-1). As discussed previously, the neutral current on distribtuion system depends on whether the induced current is additive or substractive to the normal current flow due to unbalanced loads. Users should note that the distribution system currents shown in Figure 8-20 are the result of subtractive induced currents. If the phase angle θ is reversed between the two 240 kV sources, the induced currents become additive increasing the distribtuion neutral curents significantly as shown in Figure 8-21.

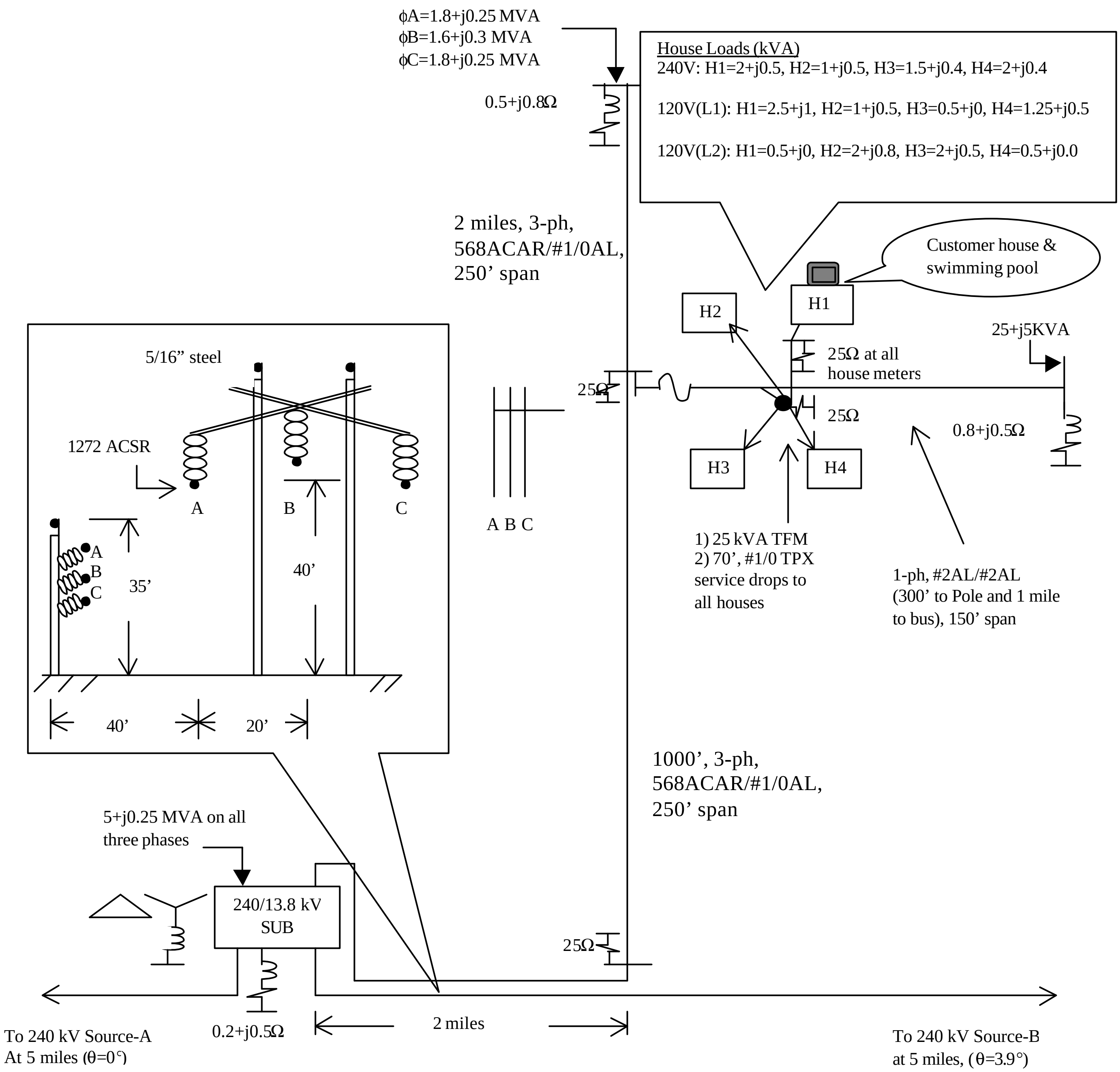


Figure 8-19 Modeled Transmission and Distribution Systems for Induction Study Case

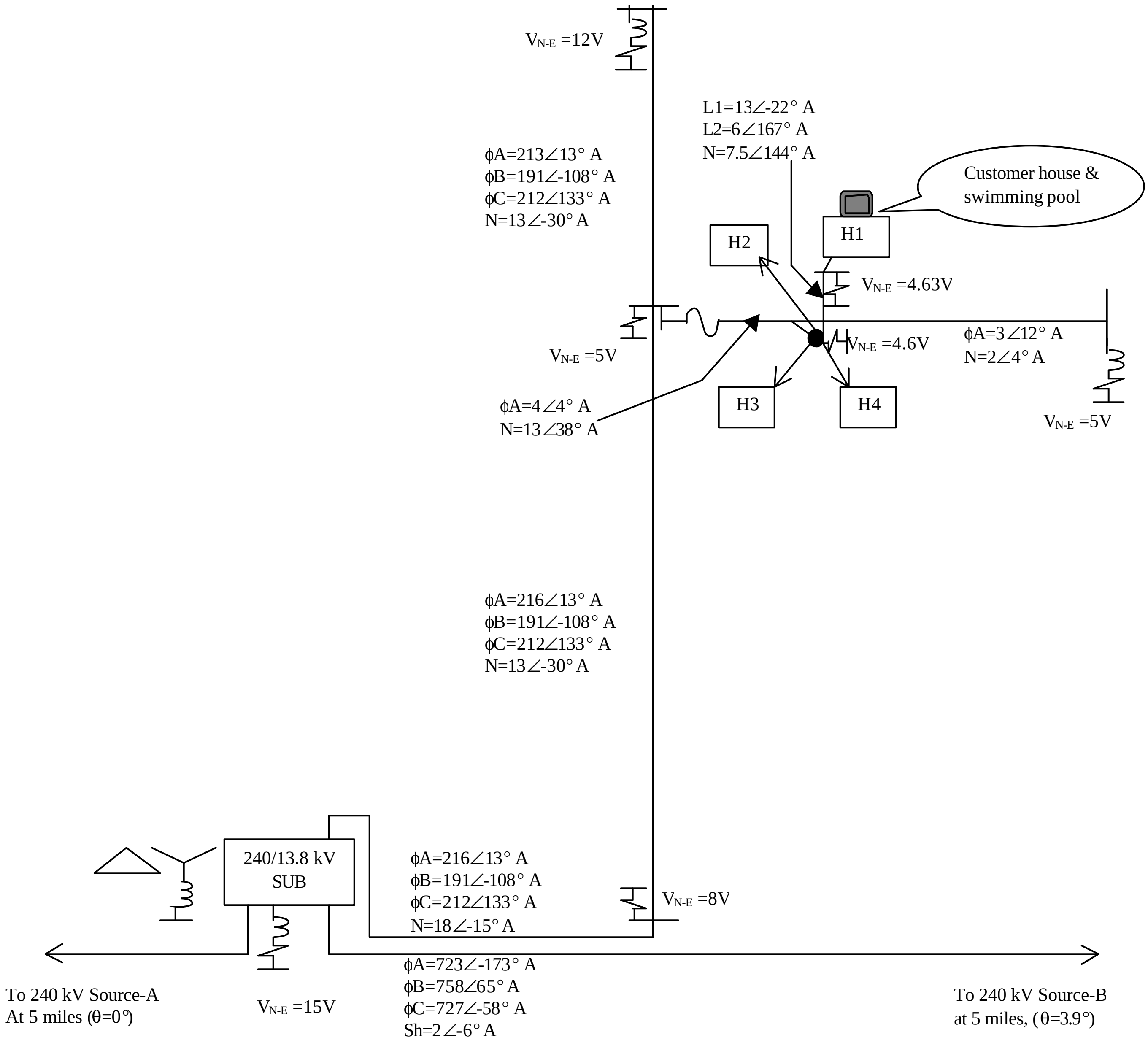


Figure 8-20 System Currents and N-E Voltages for As Found Conditions - Subtractive Induction from Transmission Line

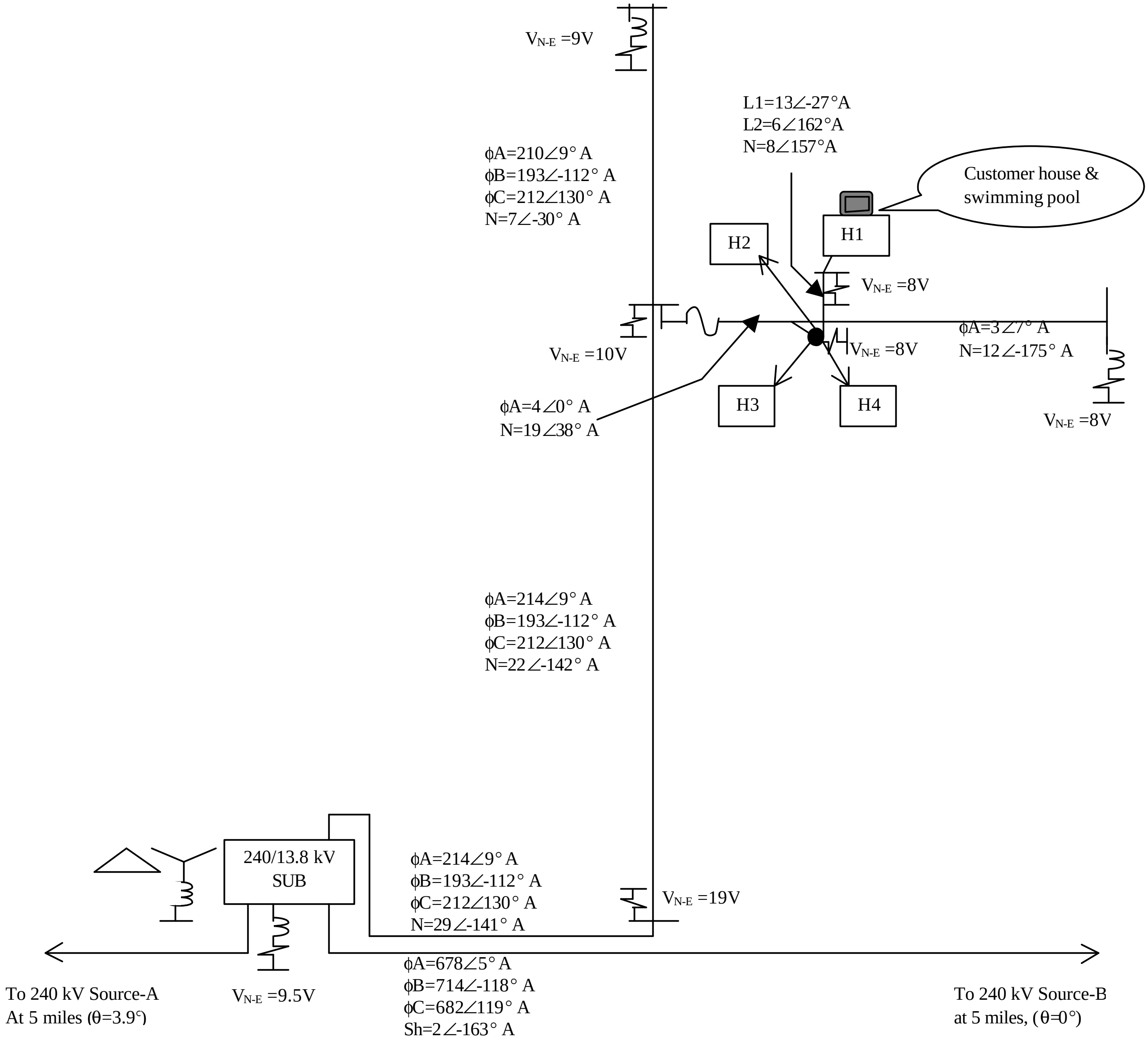


Figure 8-21 System Currents and N-E Voltages - Additive Induction from Transmission Line

Corrective Measures

After determining that the stray voltage problem at the swimming pool is due to electromagnetic induction from the transmission line, the host company switched the transformer with its four customers to another feeder that was free from any induction. Although, there was a significant reduction in the stray voltage at the swimming pool (rduced from 4 volts to 1 volt) due to this switchover, the customers now ended up at the end of a long single-phase feeder. With the original feeder, these customers were in the beginning of the tapped feeder. The host company would like to switch the customers back to the original feeder provided other mitigation methods, such as neutral isolation or changing the position of the neutral on the poles along the parallel section can be worked out. All three of these mitgation methods will be analyzed.

Figure 8-22 shows the system currents and N-E voltages as a result of switching the customers from the original feeder (feeder parallel to transmission line) to the alternate feeder which is free from any induction. In the interest of time, the alternate feeder was not modeled separately to illustrate the effectiveness of this mitgation means. Instead, the parallel section of original feeder was decoupled from the transmission line keeping all other parameters the same.

Referring to Figure 8-22, reduction in system currents and N-E voltages is obvious. The N-E voltage at (swimming pool) customer's house (House-1) reduced from 4.63 volts to 1.2 volts. Noting that the measured voltages are contact voltages while the computed voltages are N-E voltages at the meter point, the anlaystical results compare well with the measured data.

Recall in Figure 8-19, the neutral wire for the parallel section is positioned on the top of the pole to provide protection against lightning. The host company wants to know whether induced currents and N-E voltages would reduce if the neutral wire is lowered to its normal position, below the phase conductors. Figure 8-23 shows resulting system voltages and currents. Interestingly, lowering the neutral on the poles the increased the currents and voltages significantly. The N-E voltage at the customer's meter point increased from 4.63 volts (see Figure 8-22) to 7 volts.

Neutral isolation at customer's transformer is the last mitigation method analyzed. Figure 8-24 presents the system current and voltage data. Similar to other study cases, the neutral isolation blocks all the currents resulting from primary sources. In this study case, the N-E voltage at the cutomer meter point reduced to 0.1 volts.

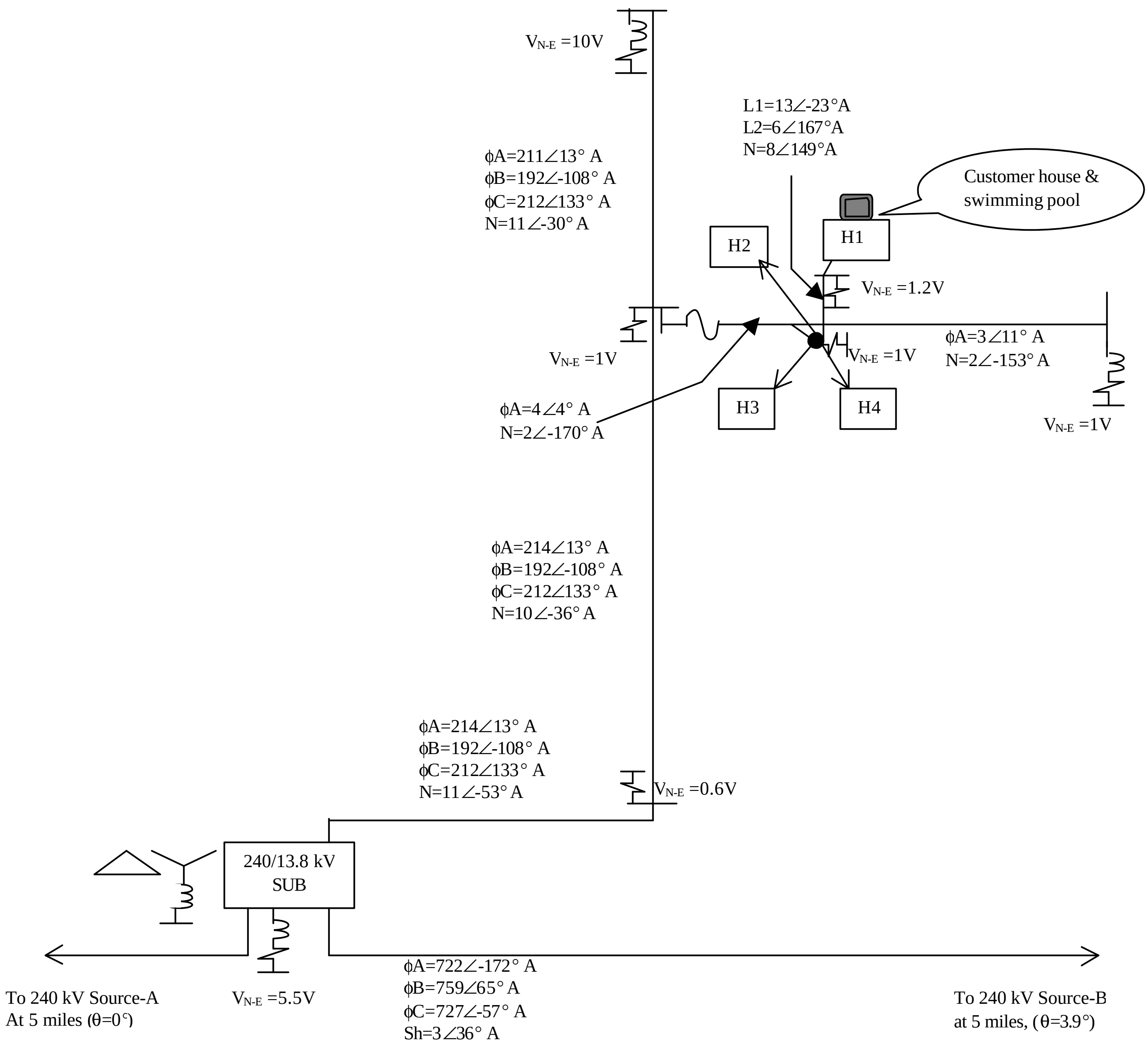


Figure 8-22 Corrective Measure – Customer Transformer Switched Over to Alternate Feeder Free from any Induction

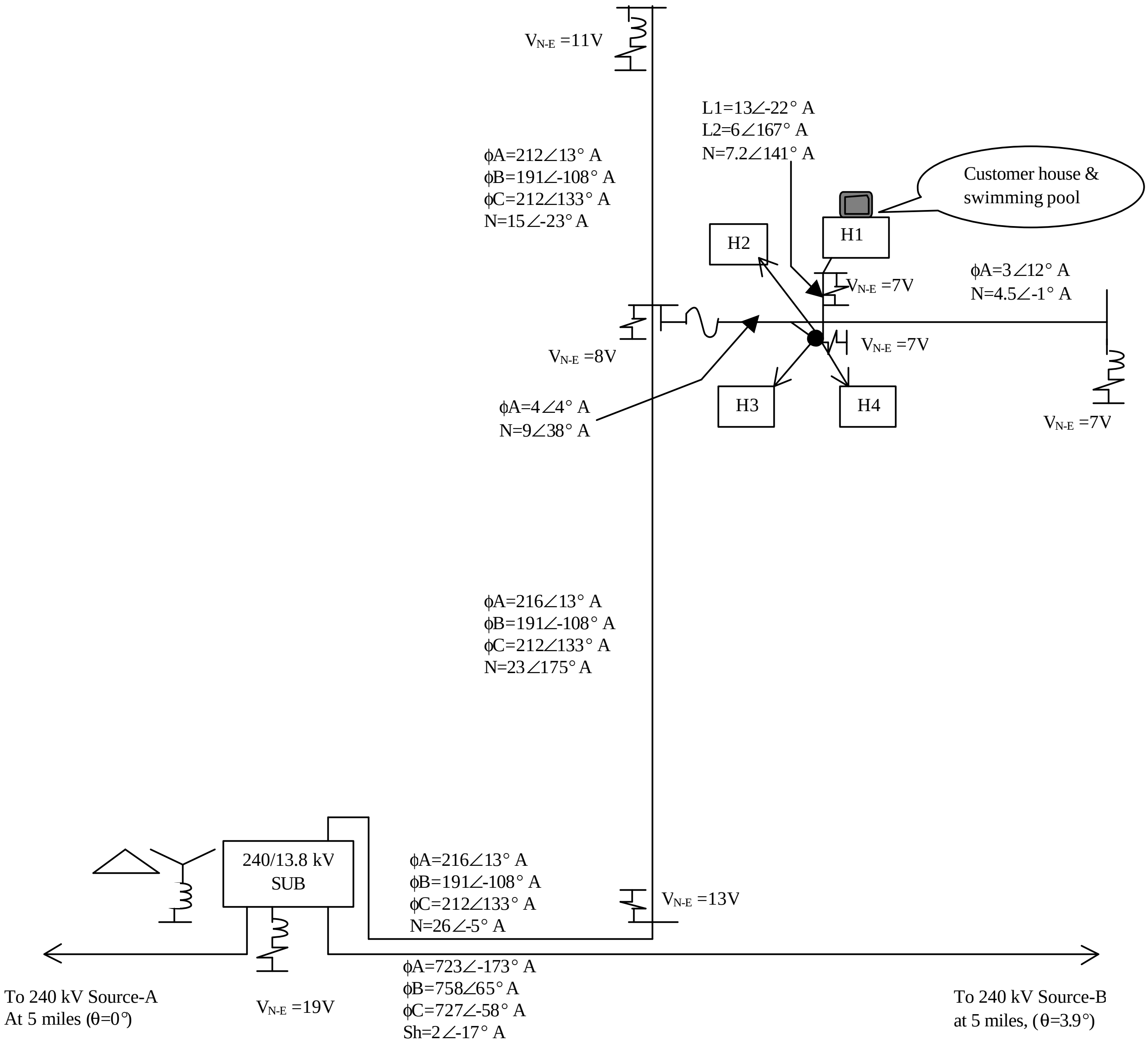


Figure 8-23 Influence of Lowering the Neutral below the Phase Conductors along the Parallel Section – Induction Study Case

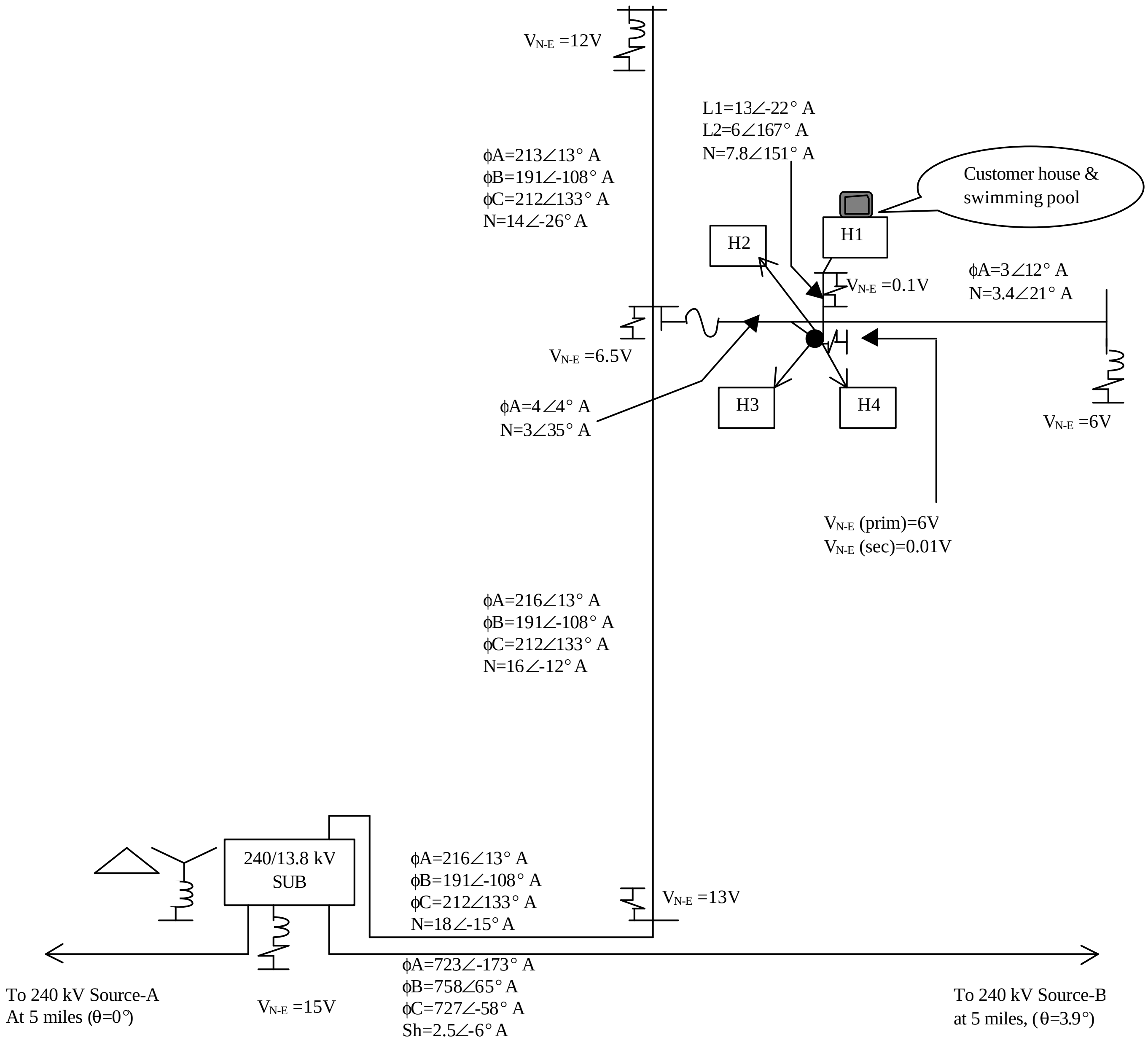


Figure 8-24 Corrective Measure – Neutral Isolation at Customer Transformer

SECTION 9

Stray Voltage Investigation – Flow Charts

Complaints and claims against utility companies by customers have been more common in the past two decades. Residential customers are more likely to initiate complaints while commercial customers such as dairy farmers would be more inclined towards filing claims demanding reimbursement of lost revenue, diminished herd assets and excess labor costs. Given these situations, utility companies need to fully understand the various aspects of stray voltage and attempt to prevent such complaints or claims from arising. Should a complaint or threat of a claim arise, the utility must be prepared to initiate a timely and accurate investigation and provide for resolution or defense of the claim.

It is important for a stray voltage investigator to have a thorough understanding of stray voltage sources, identification procedures, animal or human exposure paths and mitigation means. While the basic principles behind the concept of neutral current and resulting N-E voltages are not difficult to grasp, an organized training program may help avoid initial confusion that often attends self-learning attempts in this field. Attempts to learn on-the-job should be avoided by all means. This is because the customer, most likely, has called as a last resort and is in no mood to tolerate any fumbling. Even the experienced investigator should not take these matters for granted and should be prepared to spend time listening to the customer rather than brushing his or hers concerns aside. In other words, a sympathetic approach, as opposed to a condescending attitude, can make the difference between a quick solution to a minor problem and a long and difficult adversarial procedure.

There are four key elements to a successful conclusion of a stray voltage complaint. These include:

1) Focus on customer relations,
2) Identification of stray voltage source(s) by measurements,
3) Effective mitigation, and
4) Record keeping.

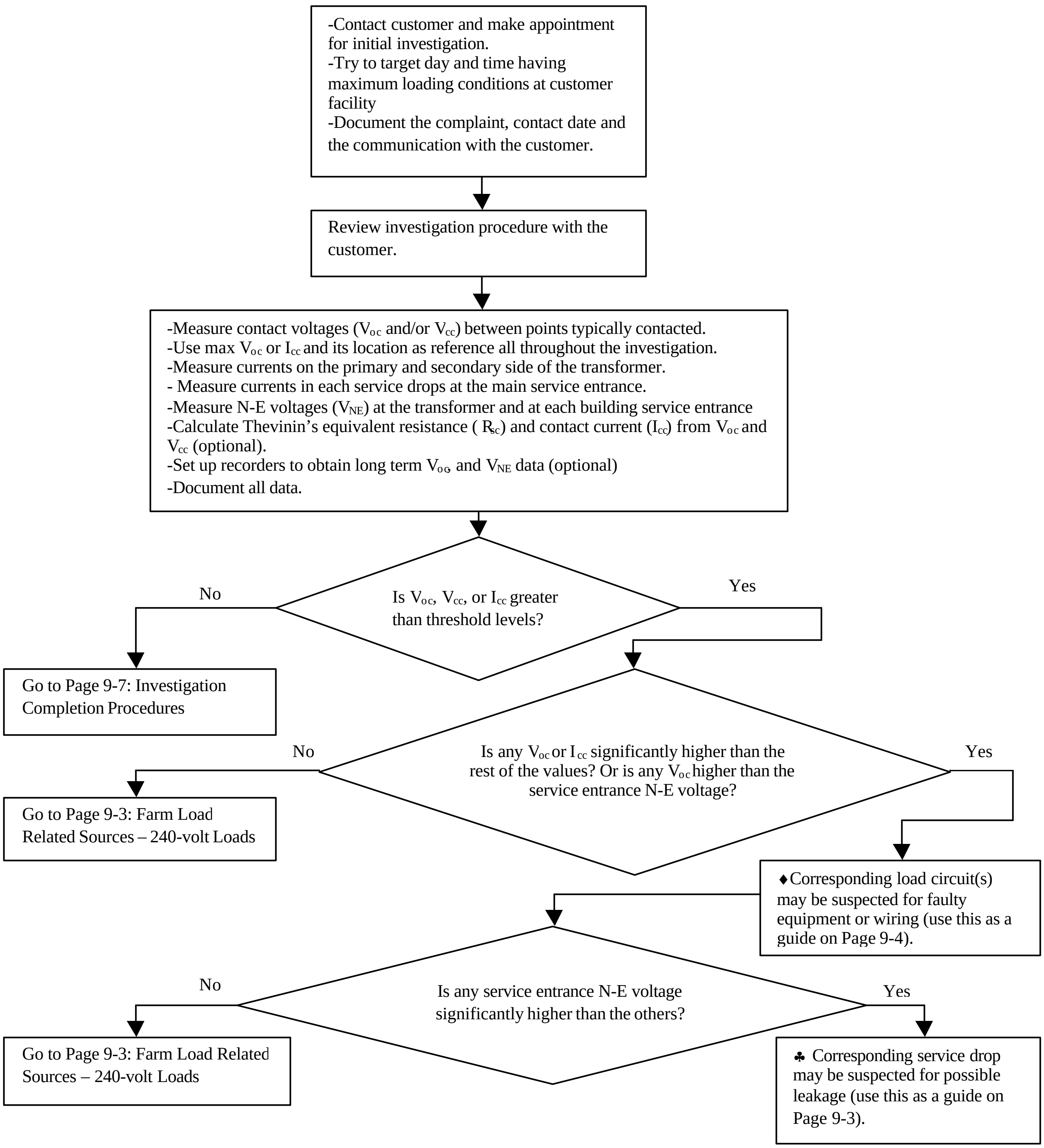
To achieve the above objectives, an effective communications plan must be in place for customers. There may be number of communication means each customized for different customer type. The communication means typically include brochures, videos, and training schools. For internal use, flow charts streamlining the investigation steps are very effective in successfully concluding the stray voltage problems. To that end, this section provides three different flow charts, which can be used as guidance for conducting and concluding stray voltage investigations.

The categories of flow charts presented in this section include:

1) Investigation Flowchart – Animal or Poultry Farms
2) Investigation Flowchart using Loadbox Tests – Animal or Poultry Farms
3) Investigation Flowchart – Stray Voltage Incidents Involving Humans

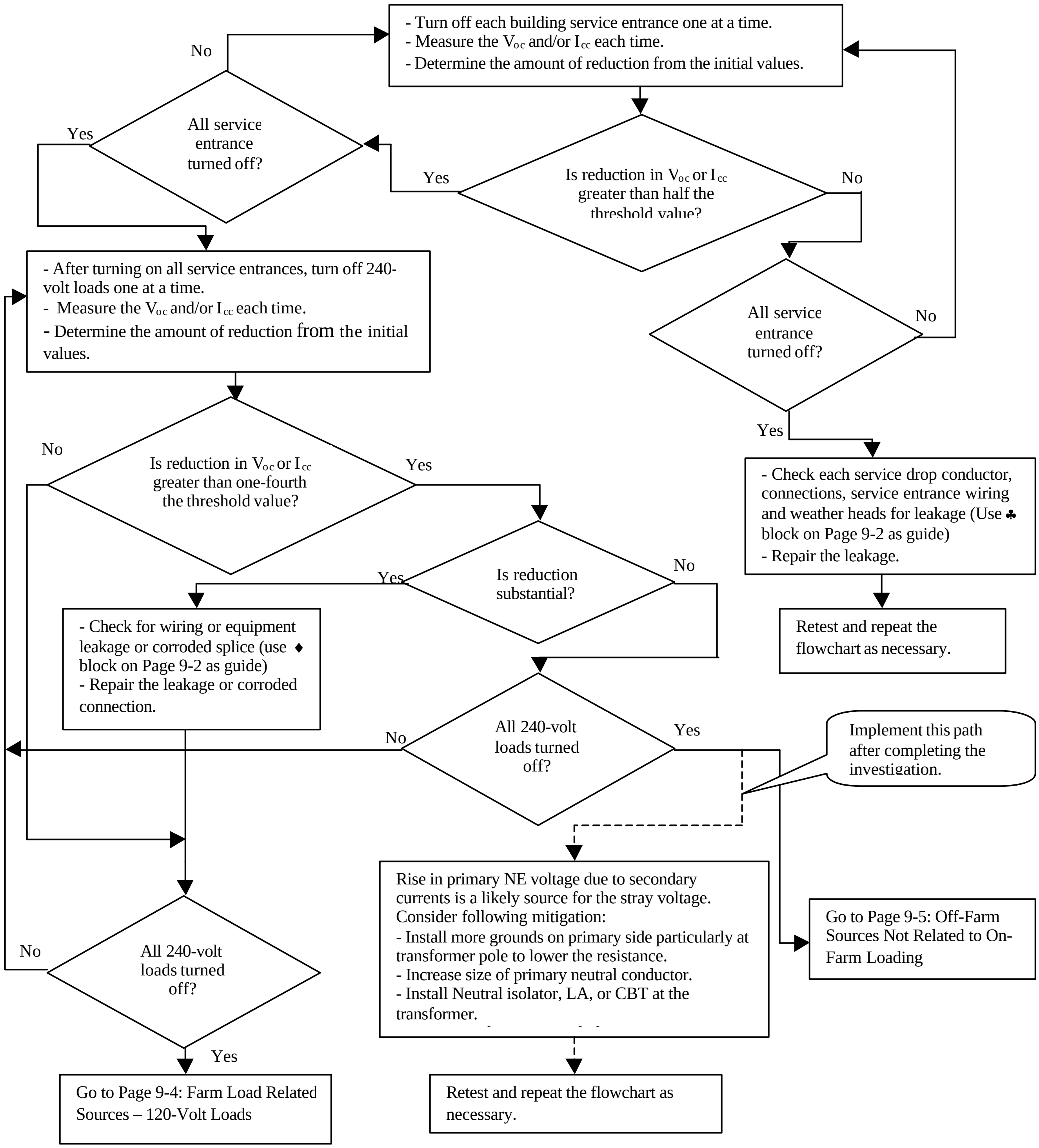
Investigation Flowchart – Animal or Poultry Farms

Customer Contact and Initial Measurements



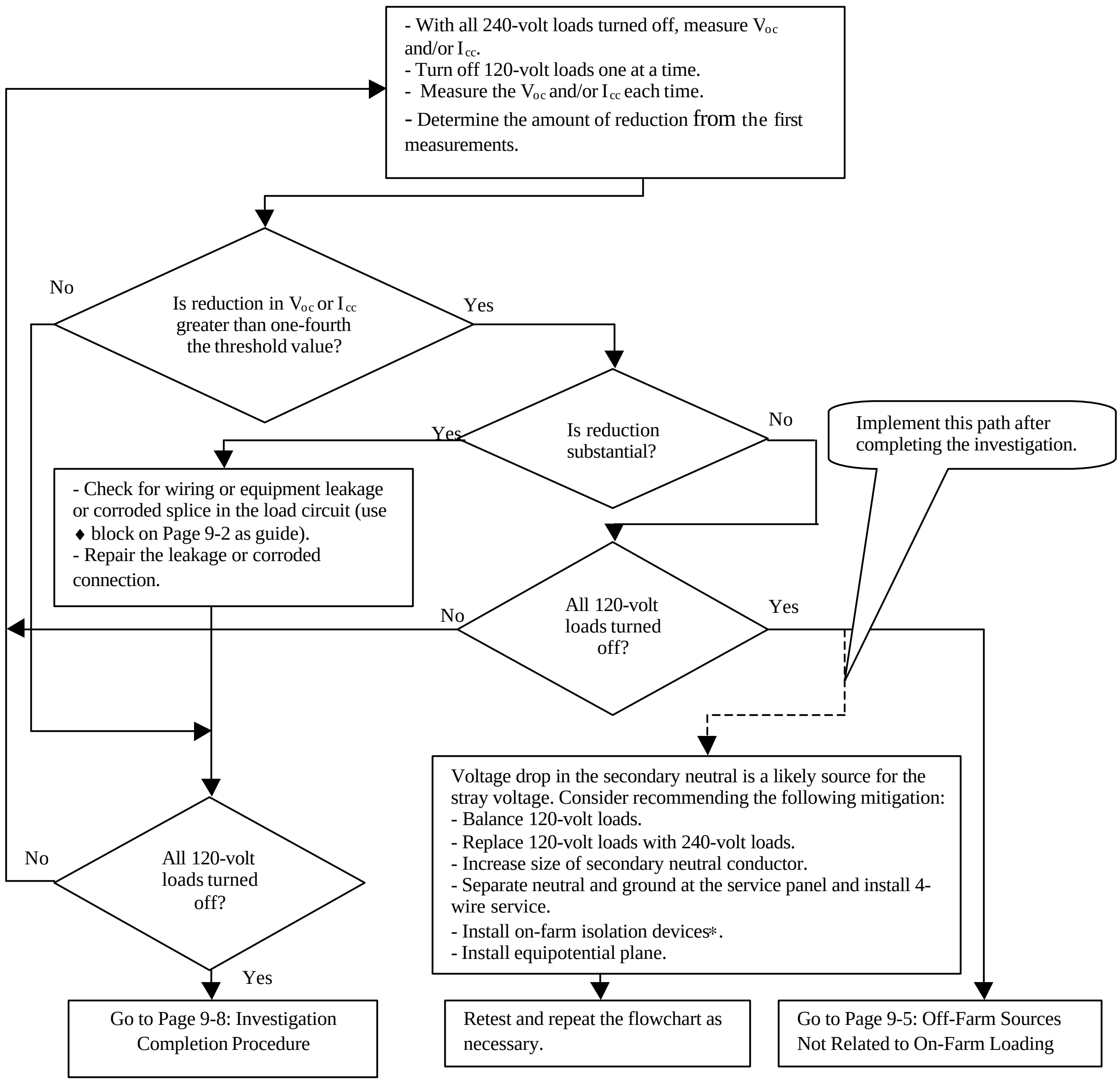
Flowchart – Animal or Poultry Farms (Continued)

Farm Load Related Sources – 240-Volt Loads



Flowchart – Animal or Poultry Farms (Continued)

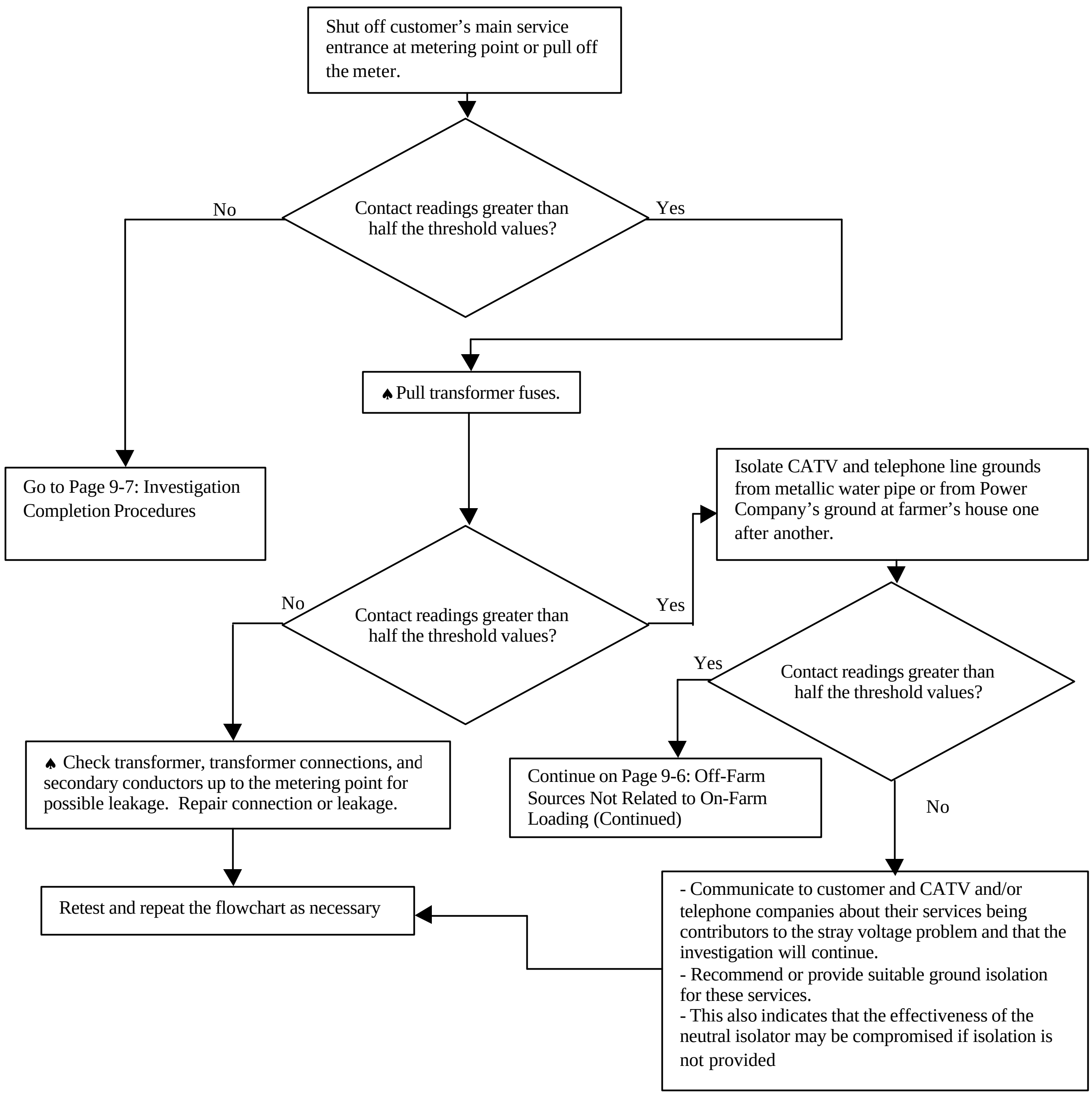
Farm Load Related Sources – 120-Volt Loads



∗ Certain devices may not be used under U.S. code. Refer to Section-7 on Mitigation Methods.

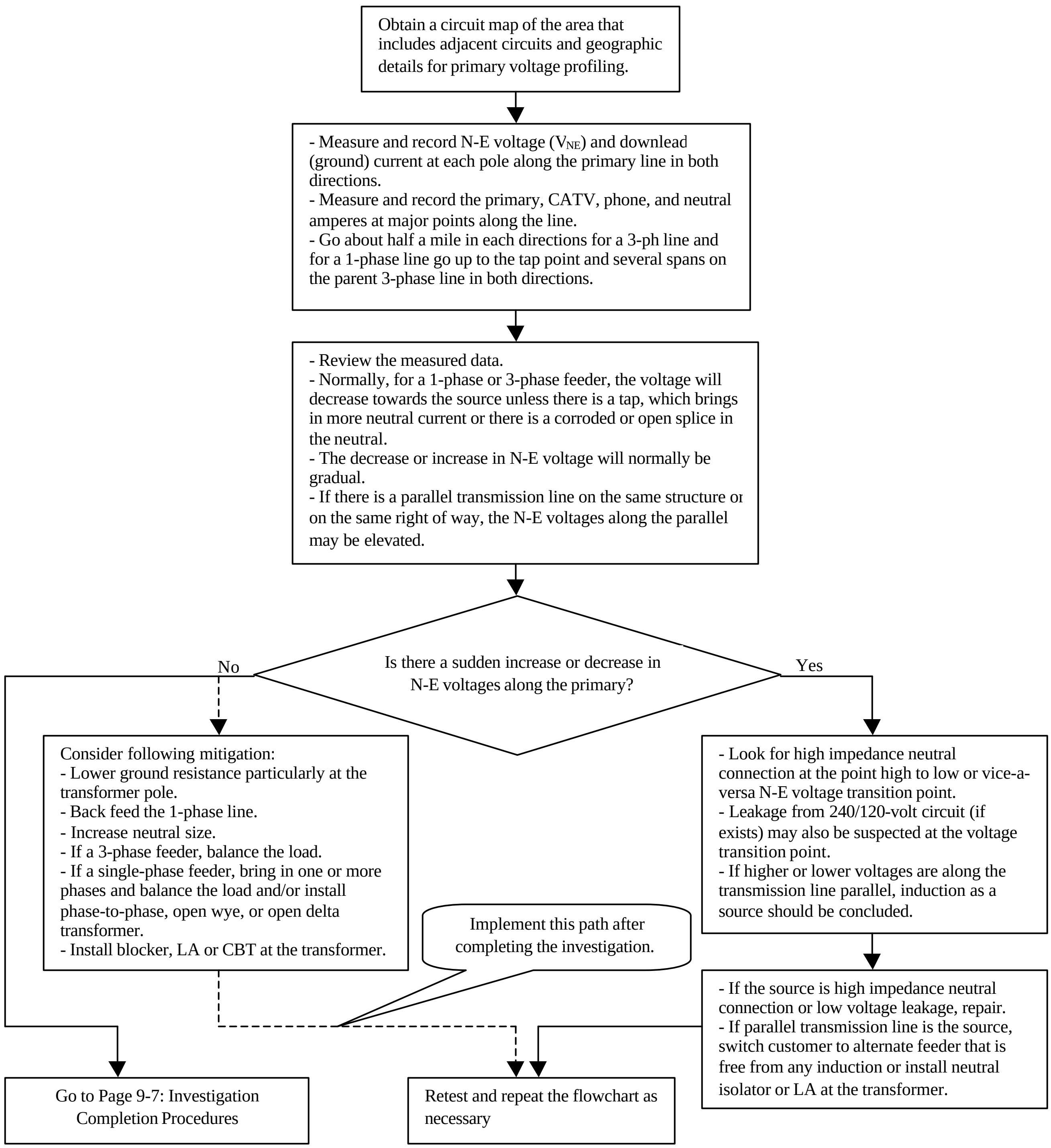
Flowchart – Animal or Poultry Farms (Continued)

Off-Farm Sources Not Related to On-Farm Loading



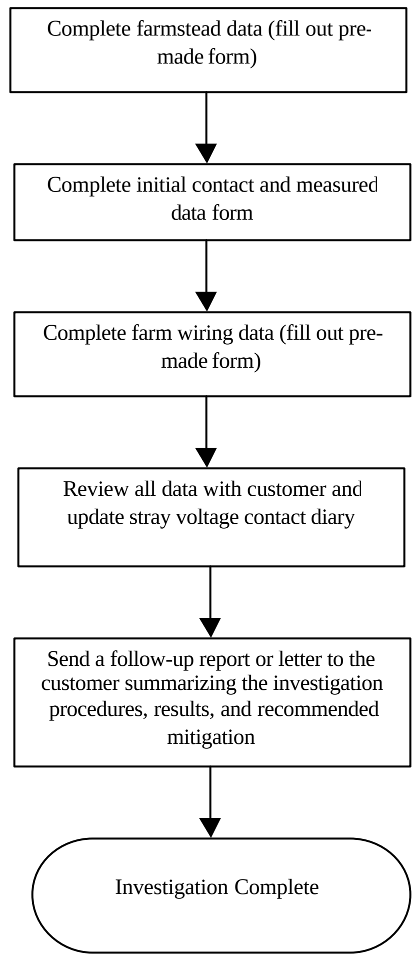
Flowchart – Animal or Poultry Farms (Continued)

Off-Farm Sources Not Related to On-Farm Loading (Continued)



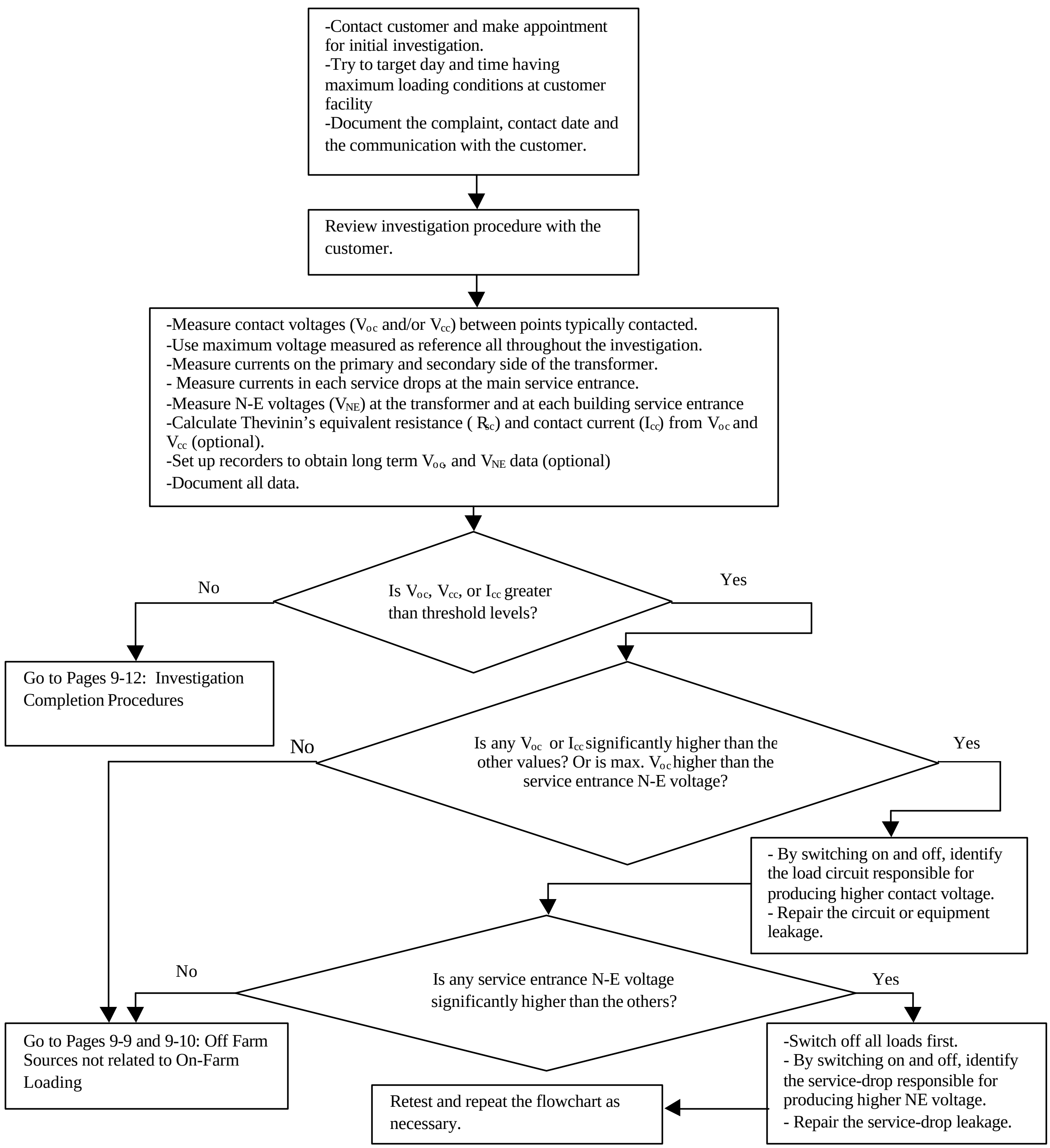
Flowchart – Animal or Poultry Farms (Continued)

Investigation Completion Procedures



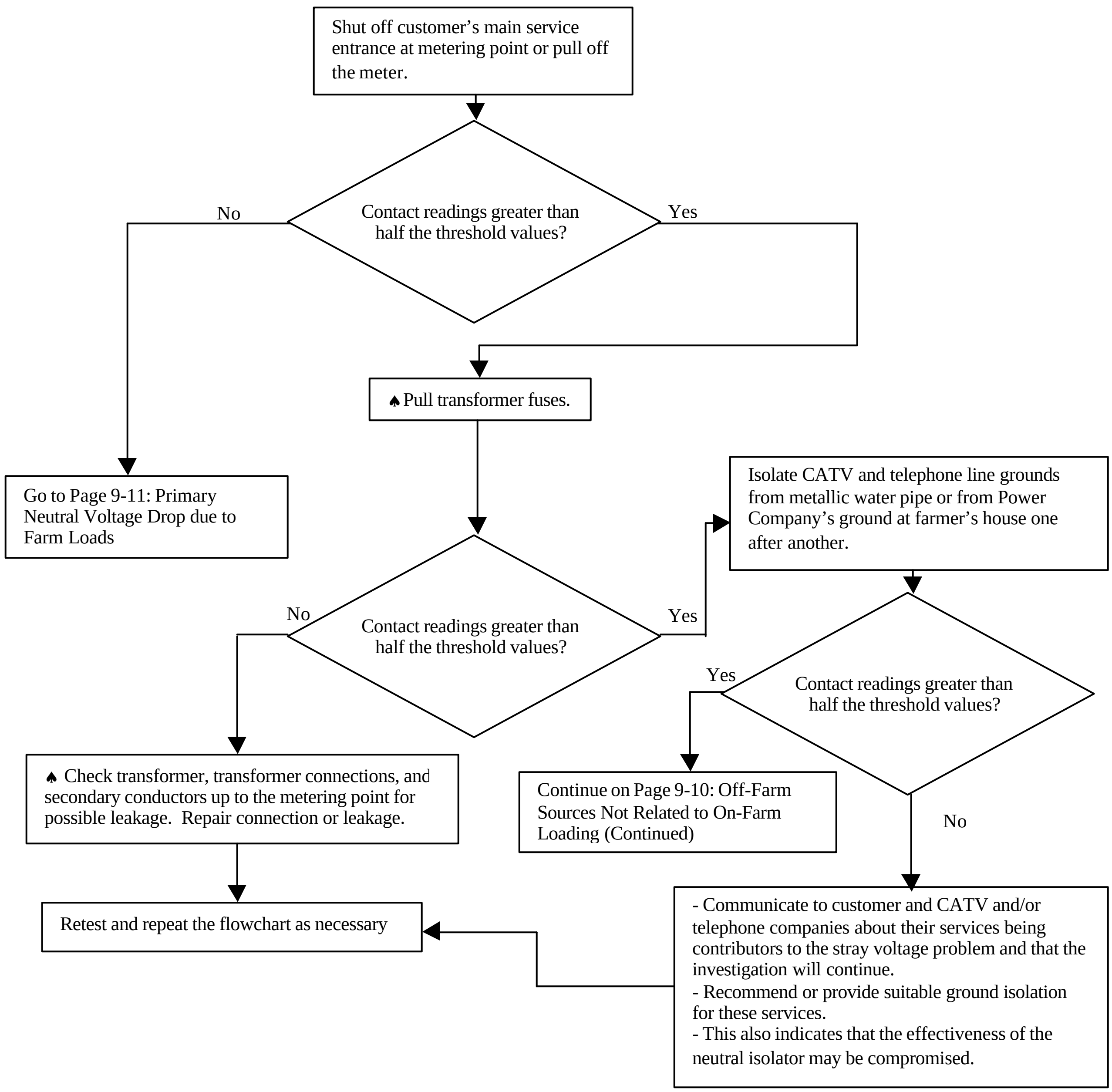
Investigation Flowchart using Loadbox Tests – Animal or Poultry Farms

Consumer Contact and Initial Measurements



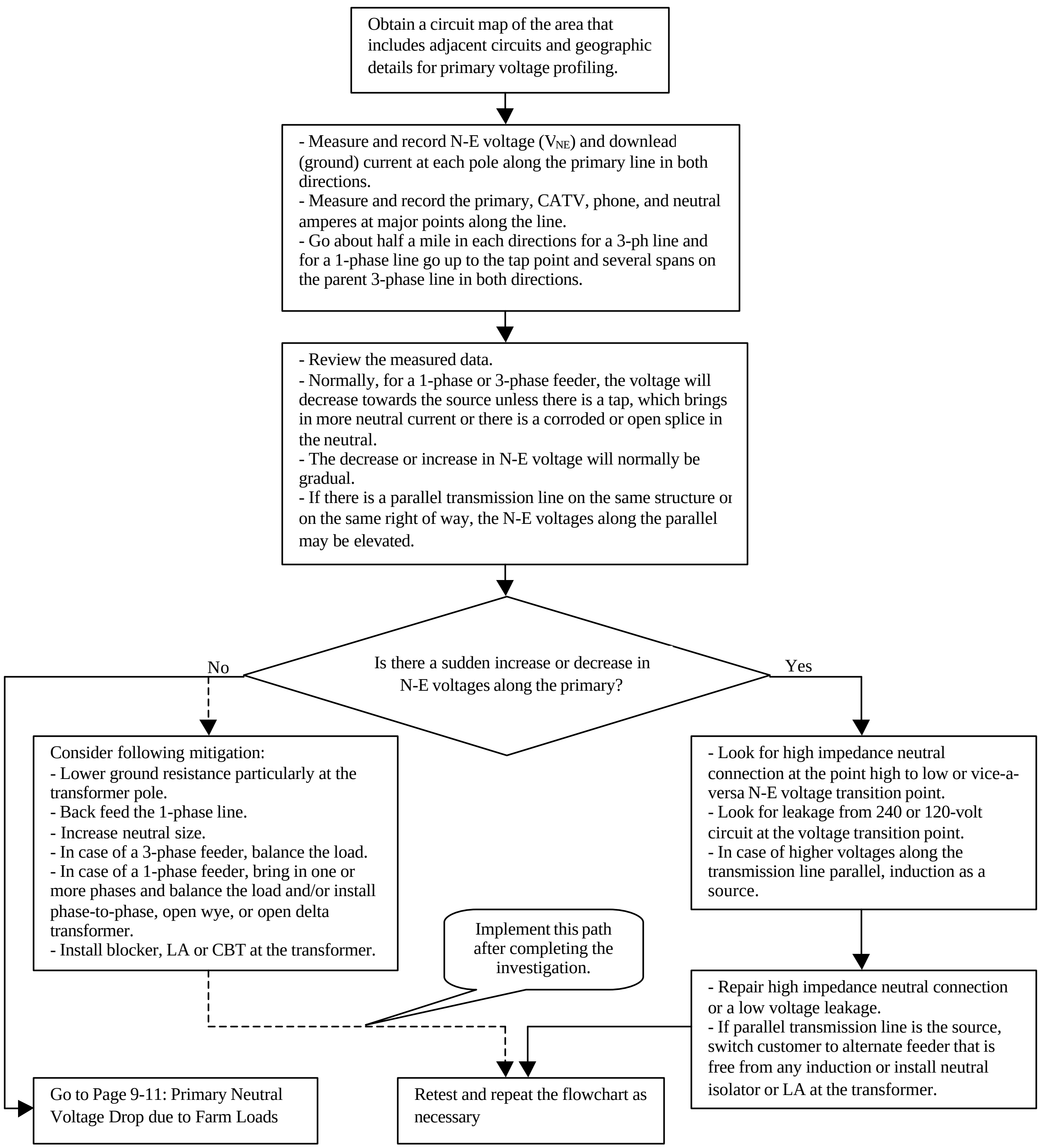
Flowchart using Loadbox Tests – Animal or Poultry Farms (Continued)

Off-Farm Sources Not Related to On-Farm Loading



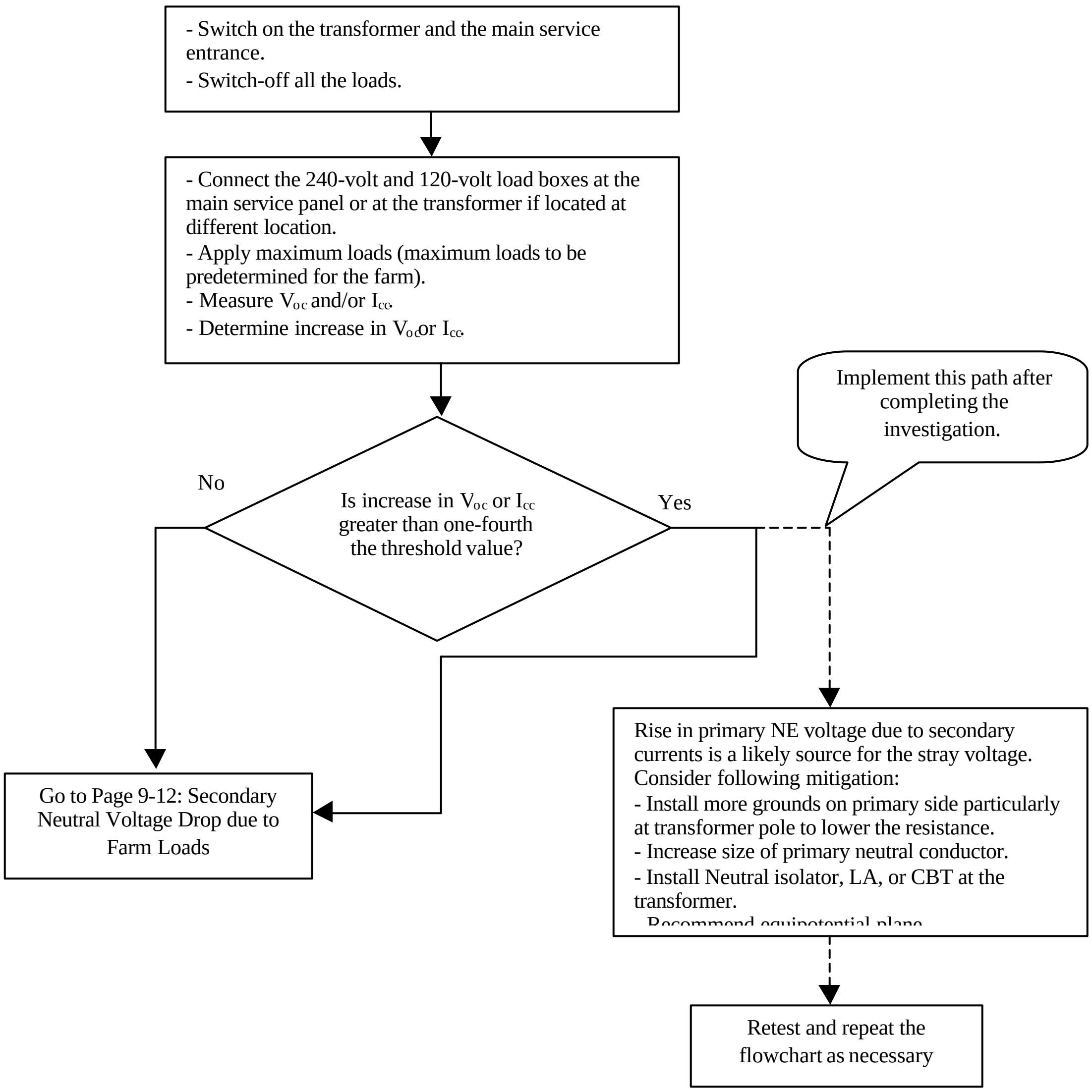
Flowchart using Loadbox Tests – Animal or Poultry Farms (Continued)

Off-Farm Sources Not Related to On-Farm Loading (Continued)



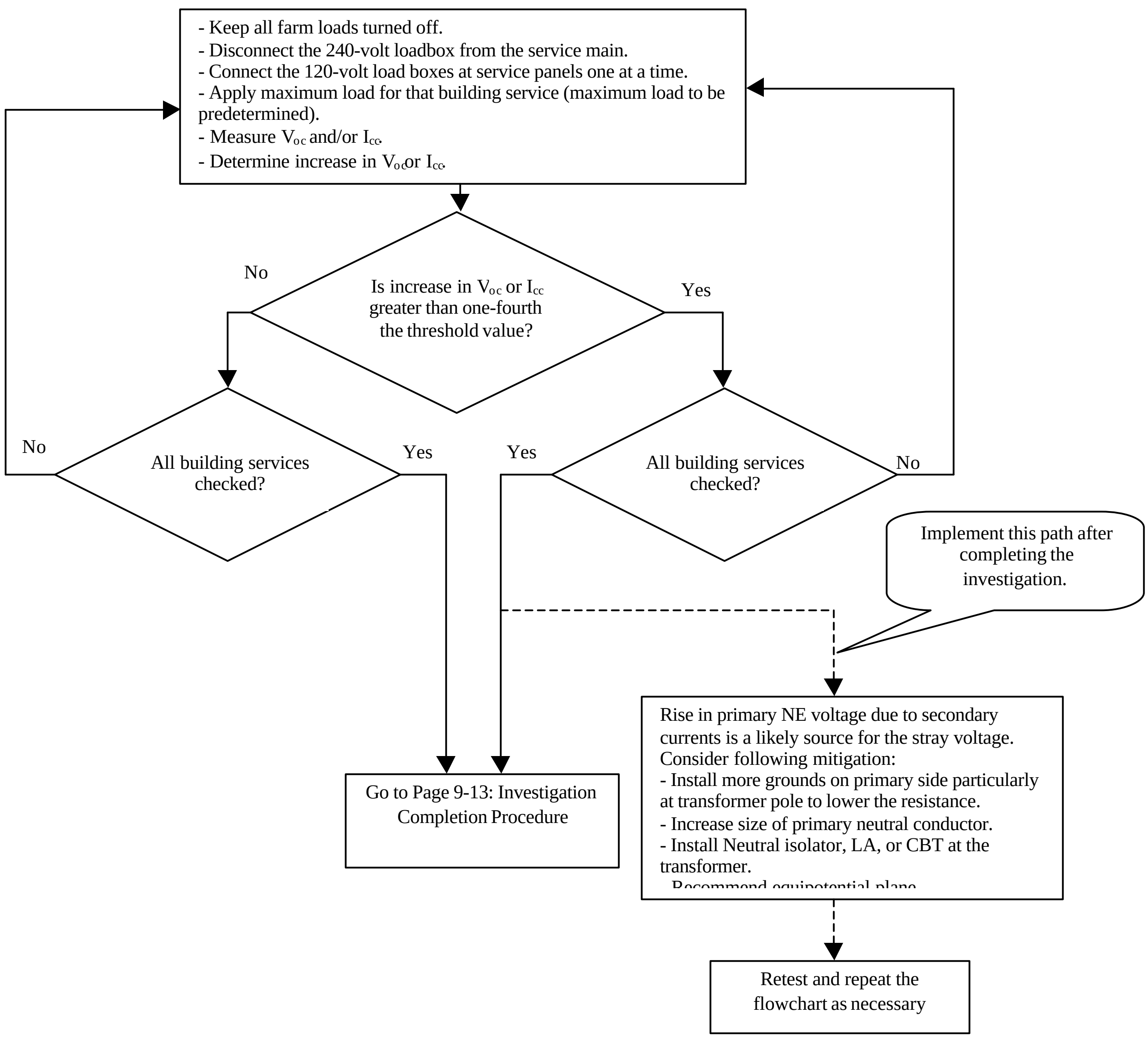
Flowchart using Loadbox Tests – Animal or Poultry Farms (Continued)

Primary Neutral Voltage Drop due to Farm Loads



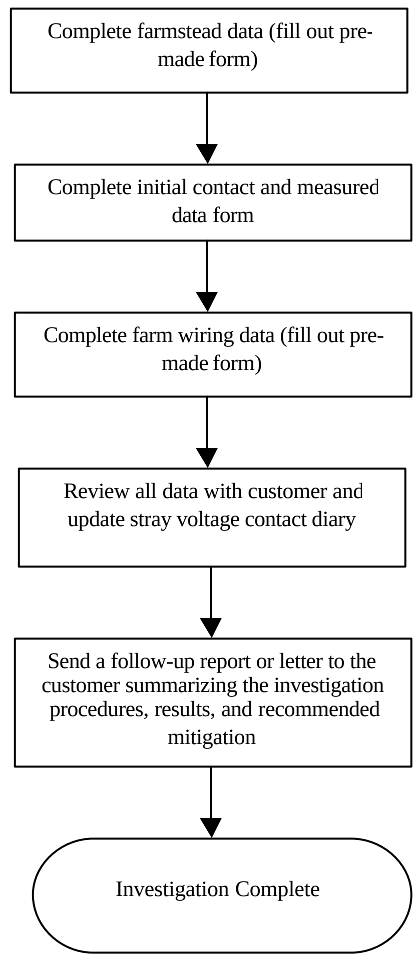
Flowchart using Loadbox Tests – Animal or Poultry Farms (Continued)

Secondary Neutral Voltage Drop due to Farm Loads



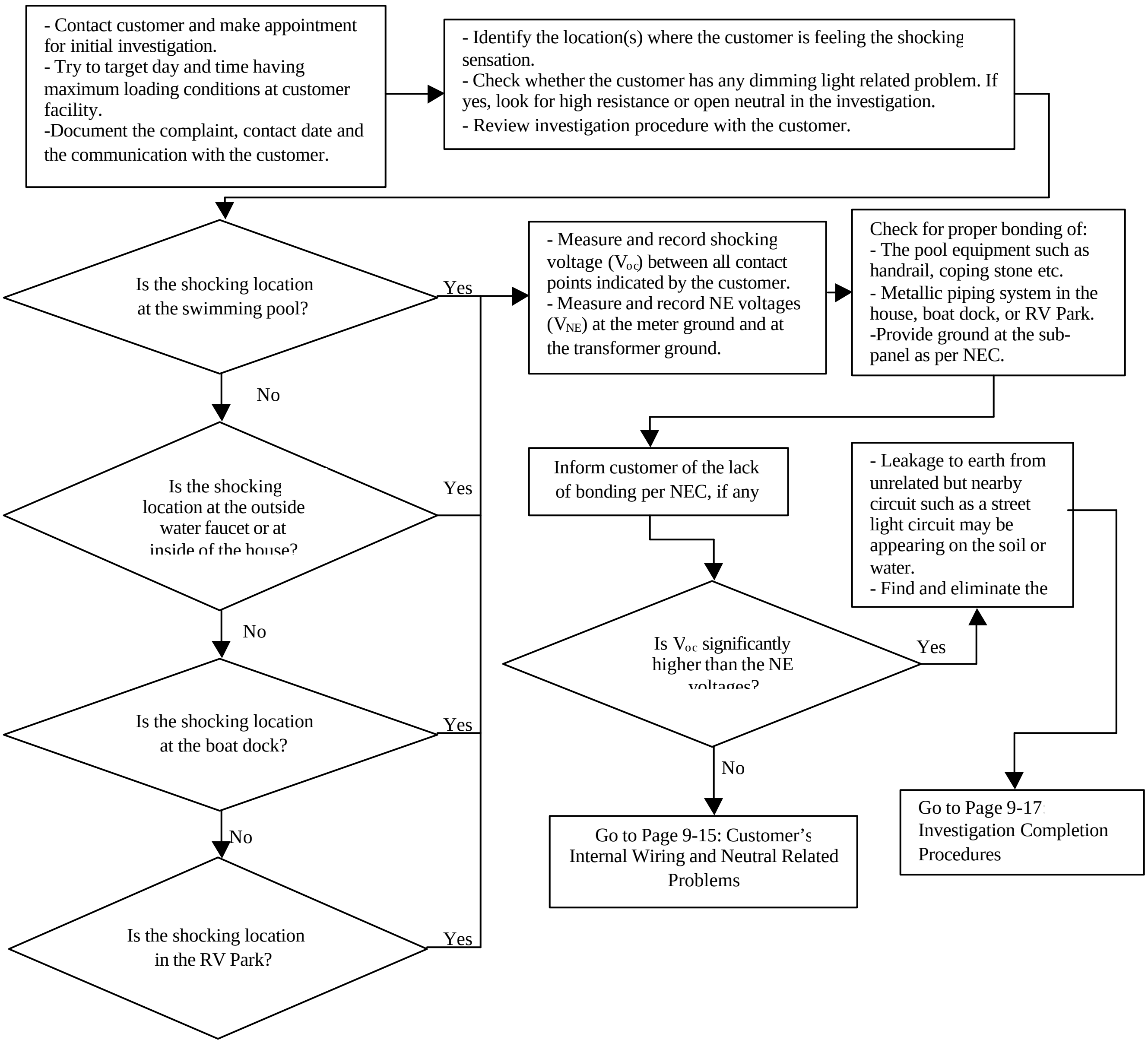
Flowchart using Loadbox Tests – Animal or Poultry Farms (Continued)

Investigation Completion Procedures



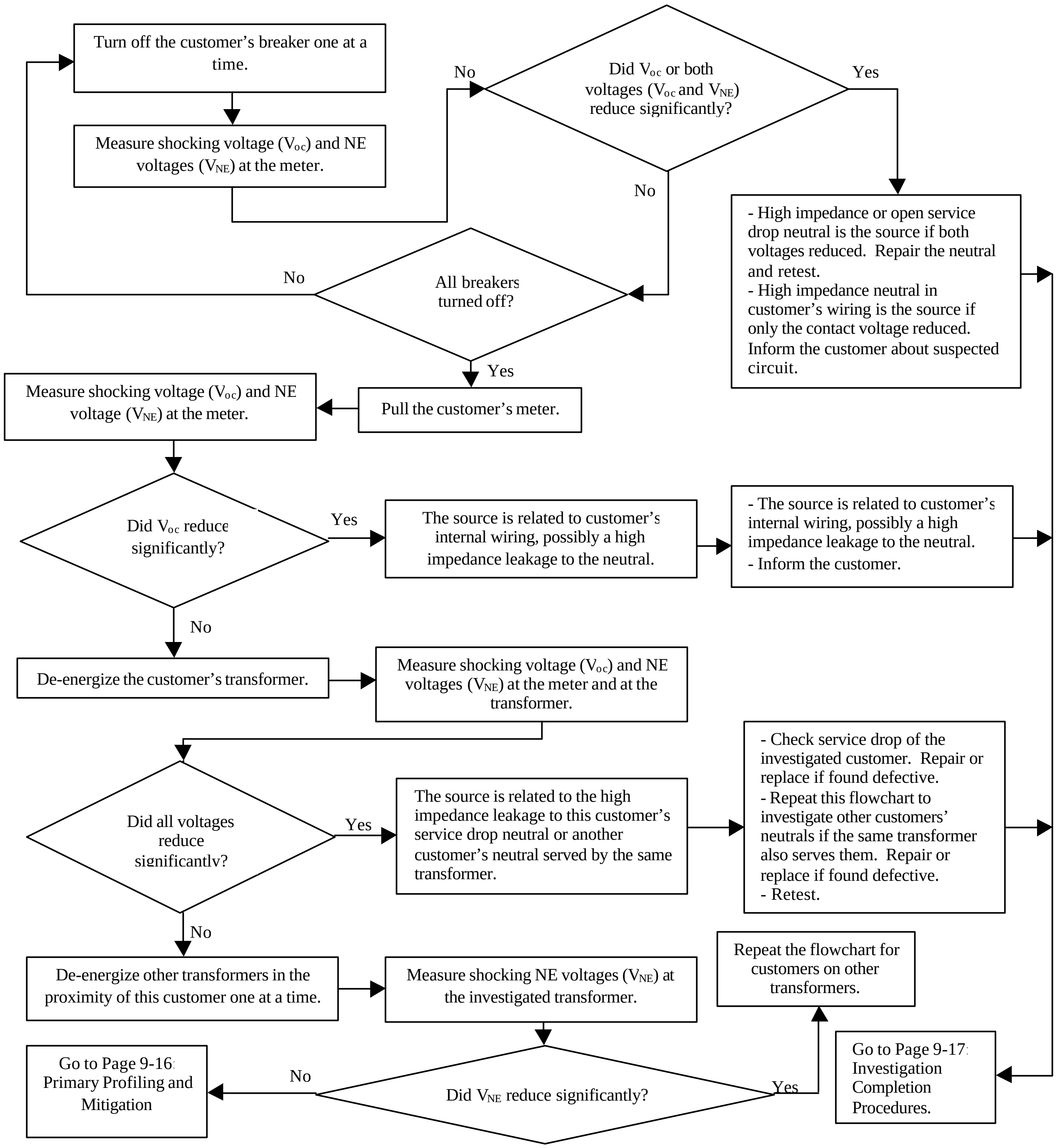
Investigation Flowchart – Shocking Incidents Involving Humans (Based on EPRI TR-113566[29])

Initiation of Investigation and Identifying Shocking Locations



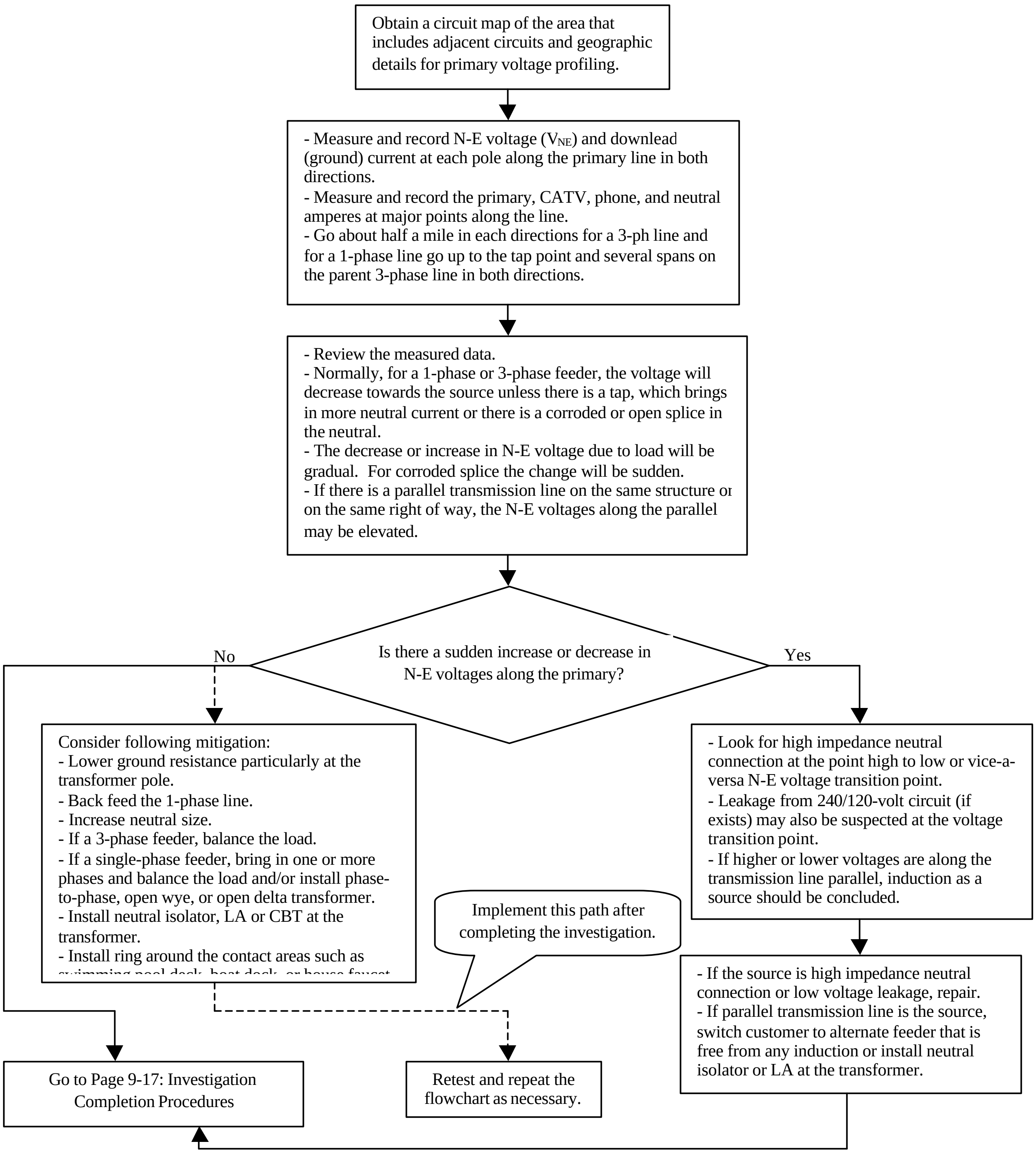
Investigation Flowchart – Shocking Incidents Involving Humans (Continued)

Customer's Internal Wiring and Neutral Related Problems



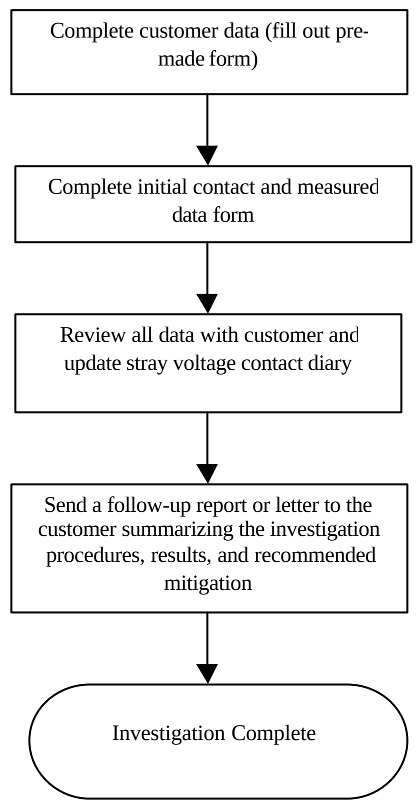
Flowchart – Shocking Incidents Involving Humans (Continued)

Primary Profiling and Mitigation



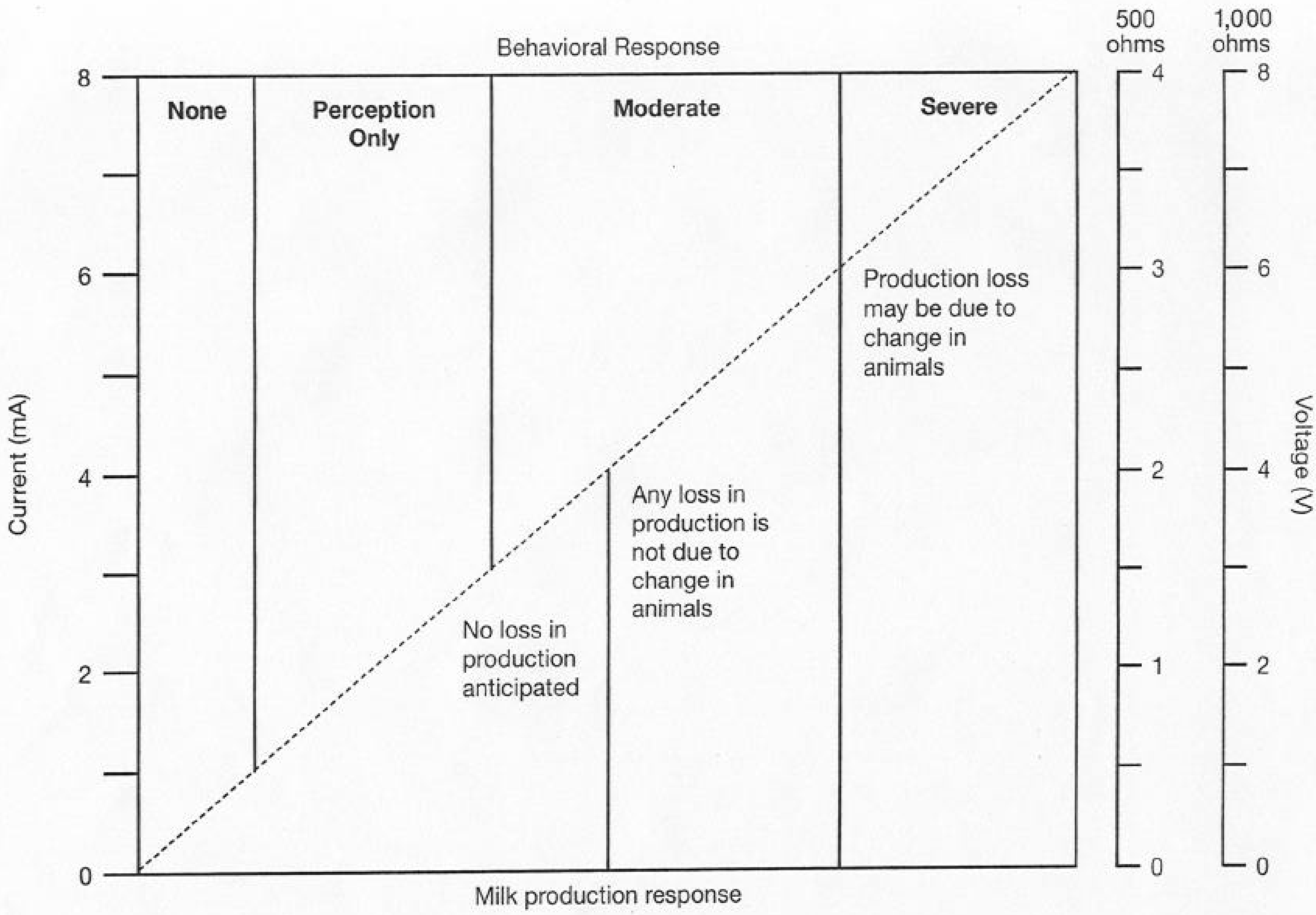
Flowchart – Shocking Incidents Involving Humans (Continued)

Investigation Completion Procedures



Appendix-B

Cows’ Behavioral and Milk Production Responses to Increasing Current Levels
(A Graph from USDA Handbook 696)



Behavioral and milk production responses to increasing current levels. Voltages (right vertical axis) were estimated using a worst-case circuit impedance (500 ohms) and a more realistic impedance (1,000 ohms). From USDA 696.