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Effects of Electrical Voltage/Current on Farm Animals

How To Detect and Remedy Problems

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Only portions listed below.

2. Sources of Stray Voltage/Current

Pages 2-1 through 2-22
Pages 7-4 through 7-7

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This handbook examines 1) the history of stray voltage/current problems on farms, 2) the physical and electrical sources of stray voltage/current phenomena, 3) the physiological and behavioral bases for losses in milk production, 4) methods for identifying and detecting stray voltage/current problems, 5) methods for mitigating such problems, and 6) areas where further research may be warranted. While the primary emphasis is on cattle and dairy farms, the theories and procedures discussed are completely relevant to all types of livestock and livestock housing facilities. Recommendations are made for action levels and concerning mitigation techniques. The fundamental conclusion of this handbook is that stray voltages/currents can be reduced to acceptable levels.

KEYWORDS: Stray voltage/current, neutral-to-earth voltage, electrical shock, history, sources, physiological effects, behavioral modifications, mitigation, dairy farms, cows.

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There were two primary reasons for publishing this handbook. First, we, as scientists, were distressed that our research results were being misinterpreted and misconstrued in media and in courtrooms. Second, we were disheartened by the animosity that sometimes arose among livestock farmers, dairy equipment manufacturers, and public utilities companies because of a lack of understanding of the causes and effects of stray voltages on farms. For these reasons, we met at Cornell University in May of 1988 to review our opinions and concerns, and to discuss the possibility of publishing a "white paper" on stray voltage. At this meeting, we concluded that there was an excellent possibility that a consensus could be reached, and a second meeting was scheduled for October in Minneapolis.

At the first meeting, the question of funding for future meetings and, if relevant, publication of the "white paper" was raised. Several foundations and agencies funded principally by utilities or dairy cooperatives had offered financial support. However, to eliminate any and all potential for even the appearance of bias, we decided to accept *no* industry funding whatsoever. All travel and meeting expenses were borne by individuals, generally by utilizing university or Government funds.

At the second meeting, a firm consensus was reached that a "white paper" should be published and that it be published as a U.S. Department of Agriculture (USDA) Handbook. The Department was chosen as publisher because it represents an unbiased source of funds to pay for publication, because it has a mechanism for making available publications to the public through the Government Printing Office, and because federal publications are 1) understood by the general population to be unbiased and 2) normally viewed as expert testimony in legal proceedings.

To guarantee that the oral consensus reached at the second meeting was faithfully transferred to paper, we decided on a rather complex procedure for actually writing the manuscript. Chapters were written under the guidance of chapter editors, who then distributed copies of the chapters to all participants for comment. Next, these chapter editors revised their chapters and sent copies to the editor in chief, who assembled and integrated the chapters into a manuscript. The manuscript was distributed to all participants to ensure that all comments had been dealt with satisfactorily by the chapter editors. In addition, as part of the original agreement among contributors, Lloyd B. Craine served as the in-depth reviewer. Remaining problems were addressed to the editor in chief for reconciliation. Subsequently, the USDA's Agricultural Research Service Information Staff and Office of Public Affairs reviewed the manuscript. Ultimately, the edited manuscript was distributed for final approval, and each contributor signed a notice acknowledging that the manuscript was factually correct and a faithful represention.

Alan M. Lefcourt
Editor in chief

Warning

Identification and, particularly, diagnosis of stray voltage problems can require considerable electrical expertise. That is not to say that the input of farmers is not necessary and valuable. Often, the input and observations of people in daily association with a stray voltage/current problem are critically important to its solution. *However, electrical systems can be dangerous. Persons without special training should never attempt investigation of the electrical distribution or farm electrical systems.* For example, persons without special training should never open electrical service panels nor should they even contemplate altering any wiring.

Using a voltage measuring device with well insulated probes to measure voltages between possible points of animal or human contact should not result in a safety hazard with one important exception. Voltages that cause stray voltage/current problems are normally so low that they cannot be detected without special instruments. If an electrical shock can actually be felt or if animals are knocked down, a possible hazard to life exists. The device or electric circuit responsible for the shock should be disconnected by unplugging the device or by deenergizing the circuit at the service panel. The situation should be examined by an electrical professional as soon as possible.

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Contents

2. Sources of Stray Voltage/Current

David Ludington, editor

Summary

Stray voltage is a small voltage (less than 10V) that can be measured between two possible contact points. If these two points are contacted by an animal or person, a current will flow. The amount of current depends on the voltage and the circuit impedance, which includes the source, contact, and body impedances. Animals or persons respond to the resulting current flow and not to the applied voltage. Thus, it is important to determine the current level so that the expected response can be predicted according to data generated by controlled scientific tests. The curent can be reliably estimated by measuring (at the time of contact) the voltage across the contact points and dividing by the sum of the contact and body impedances, in accordance with Ohm's law. Relationships among current levels and types of responses are discussed in chapter 3, "Physiological and Behavioral Effects."

An observed voltage may come from a low-internal-impedance source (such as from current flow through a neutral/grounding system to earth) or a high impedance source (such as from leakage resistance across insulation, or field coupling). It is important to remember that the internal source and the load impedances combine to limit the current that will flow; e.g., a high impedance source will limit current flow regardless of the magnitude of the load impedance.

Low Impedance Sources

A low impedance source is identified as a source whose measured voltage decreases only slightly when a low impedance load is connected in parallel across it. The neutral/grounding system of the distribution line primary and/or the farm secondary system is the usual low-impedance source for stray voltage. Load, leakage, and/or fault currents flowing through the impedances of the neutral, grounding conductors, and earth produce voltages across these impedances. The multiple connections of the neutral/grounding system to earth through ground rods, metallic water lines, or other ground electrodes mean that there will always be voltages to earth. Any metallic structure connected to the neutral or to the grounding system will be at some small voltage to earth. The following are some examples of conditions that produce or increase this neutral/ground system voltage to earth.

- <u>Primary neutral-to-reference-ground voltage</u>: The magnitude of a neutral-to-reference-ground voltage is a function of the currents flowing in the neutral/grounding system and the points between which the voltage is measured. For power-distribution systems with a primary neutral, the primary neutral is part of this neutral/grounding system, and current from the primary neutral can result in the measurement of an excessive voltage between the point of interconnection of the primary and secondary neutrals at the distribution transformer, and a reference ground.

- <u>Unbalanced loads</u>: In a 120/240-volt three-conductor system, the ideal is to keep the 120-volt loads continually balanced between the two hot conductors and the neutral so that no current flows in the neutral. However, the current draw by certain loads, e.g., motors and lights, varies according to such factors as time of day, season, and relative position of the loads along the distribution system. Therefore, it is impossible to completely balance loads. Substantially unbalanced loads will produce high currents (and thus voltages to earth) in the secondary neutral system. The high starting currents associated with motors means that there will often be momentary high currents (and voltages), called transients, on the system.

- <u>Faults</u>: Fault currents result from a low resistance contact between conductors having considerable voltage on them and a metallic (equipment frame) or conducting material (water, earth). The fault may be from the full voltage of the line (if directly from a line conductor) or from some lower voltage, such as a water heater element or a winding on a motor. The fault current may be large enough to cause a circuit breaker or fuse to open, thus preventing any serious effects of the fault or the fault current. The circuit breaker may not operate if an alternate path to ground limits current flow in the neutral or if a high impedance in the circuit limits current flow. Fault currents can produce relatively high stray voltages, which need to be corrected.

- Bad connections: Bad, corroded (high resistance), loose, or broken (open) connections can increase the impedance of an otherwise low impedance circuit. Current flow through the high resistance will increase the chances that the current will take an unintended path, and produce stray voltage/current problems.

- Improper wiring: The interconnection of the neutral (white) conductor and the equipment grounding (green or bare) conductor at each building service entrance (with one exception, see "Voltage Reduction" in chapter4) is required by electrical codes. Compliance with the codes means that the neutral and grounding conductors will be at the same voltage at points of interconnection. All electrical equipment, with the exception of some portable equipment, is required to be grounded. Currents in the grounding conductor will also cause voltages to earth to appear. Improper grounding practices may be of the following types: 1) use of neutral (white wire) also as the grounding conductor and 2) use of a ground rod at the unit instead of a conductor leading back to the service entrance.

High Impedance Sources

A high impedance source is a source whose measured open-circuit voltage decreases greatly when a load is appropriately applied between the two contact points. Two types of high impedance sources may occur on farms.

- Leakage Paths: Leakage paths can result from the presence of moisture and dirt on insulating surfaces, as well as from the presence of damaged, cracked, or broken insulation on conductors, on terminal boards, or in equipment. A leakage path results when one of these conditions provides a path for current to leak to metallic parts or to other conductors. A resistive leakage path often occurs where there are damp, or wet, and dirty conditions, as typically seen in many farm areas. The insulated material from which current leaks will be found to have a measurable voltage relative to some other object. Leakage pathways are usually high resistance pathways, i.e. the measured voltage will drop greatly when a load is applied. Current flow through a high resistance pathway is normally very small.

- Coupled Circuits: An electric field can capacitively couple an alternating voltage to an insulated metallic object, giving it a voltage measurable with a sensitive meter. Tests will usually show that a coupled circuit cannot deliver appreciable current. An alternating magnetic field can also induce a voltage in a circuit; however, conditions to cause induced stray voltage are rare on farms. Proper bonding and/or shielding will prevent or eliminate coupled voltages.

Power Distribution Systems

Electrical distribution systems are divided roughly into two areas, the primary distribution network from the substation to the distribution transformer primary and the secondary service from the transformer secondary to the farmstead. The power utilities' responsibility normally extends into the secondary as far as the power meter.

The most common primary distributions to farms are single-phase and three-phase with wye (Y) and delta (Δ) configurations. A single-phase wye distribution uses one hot conductor and a neutral, while a single-phase delta uses two "hot" conductors with no neutral. A three-phase wye distribution uses four conductors (three hot and a neutral). A three-phase delta distribution uses three "hot" conductors with no neutral. A variant of the delta distribution, the open delta, uses three conductors with one of the three grounded and used as the neutral. Three-phase systems generally start from a substation and are commonly divided into multiple single-phase distributions. The primary neutrals are grounded at intervals along the line (multigrounded) and at each distribution transformer, and they are connected to the secondary neutral and its grounding system at each distribution transformer. The interconnection of neutrals and grounds improves the safety of the power system, but allows interaction of off-farm and on-farm problems. In the absence of a primary neutral, farmsteads are not likely to be affected by off-farm problems; however, the relative impact of on-farm problems may be increased.

As indicated, electrical power is distributed with different phases. In addition, appliances such as motors can alter phase relationships. Therefore, it is important to examine phase relationships among electrical currents when analyzing the impact of electrical loads or faults. The voltage at any point in the neutral/ground system is the resultant (vector sum) of all currents/impedances at that point. The voltage will depend not only on the magnitudes of the currents but also on the phase relationships, i.e., whether the currents are in phase or out of phase. Knowledge of phase relationships is particularly important when attempting to balance electrical loads and/or identify the source(s) of a stray voltage/current problem.

For any suspected stray voltage/current problem, it is important to determine whether the source of the problem is primarily due to any of the previously mentioned on-farm electrical conditions and sources, or is due to the interconnection of the secondary neutral/ground to the primary multi-grounded neutral. Both secondary and primary neutral/ground systems, considered separately, will each have some voltage to earth in normal operation. These voltages are due to normal current flow through the unavoidable impedance of the neutral and grounding resistances of each system. Where the secondary and primary neutrals are connected, current flow in each system will adjust, so there will be the same voltage to earth at the interconnection point.

Caveat
Only if a voltage can be contacted by an animal, and the measured voltage at time of contact exceeds levels of concern, is it *necessary* to continue investigations to determine the actual source of the voltage.

Sources

Stray voltage/currents on farms result from the interactions of multiple variables. The energy basically comes from the electrical power system. Because of the way electricity is distributed and used, there will always be stray voltages/currents. The magnitudes of these stray voltage/currents at different locations depend primarily on conditions on the primary and farm secondary power-distribution systems. The following sections report the various ways in which a stray voltage may occur on a farm and the importance of paths in determining the magnitude of the current that will flow. Generally, the stray voltage that can be measured between two possible animal/person contact points and that arises from currents in the neutral/grounding system is due to a combination of conditions in the secondary and primary systems. Stray voltage from leakage/coupling-type sources may come from either system.

Characteristics of a Source

Source Definition

A source of stray voltage/current has two terminals across which a voltage can be measured; and when a load is applied across the two terminals, current flows from one terminal and returns to the other. Examples of common electrical sources include batteries, alternators, and electrical outlets. All sources have an internal impedance that limits the magnitude of current flow. When a load is applied across the two terminals, this source impedance causes the terminal voltage to be less than the open-circuit source voltage (the voltage measured without the load in place). *A high impedance source is a source whose measured open-circuit voltage decreases greatly when a load is appropriately applied between the two contact points. A low impedance source is identified as a source whose measured voltage decreases only slightly when a low impedance load is connected in parallel across it.*

If the exact terminals of a source are not accessible or well defined, terminals that are accessible can be used for making measurements. If the terminals are remote from the actual electrical source, the total source impedance would include the impedance of the conductive path from the actual source to one terminal and the impedance of the path from the second terminal back to the source. The effective source voltage and its internal impedance at a specific location can be obtained by measurement (see chapter 5, "Detection and Measurement").

Animal Contact and Stray Voltage

Electrical current will flow through an animal if the animal comes in contact with two points/areas (i.e., terminals) that are at different potentials (there is a voltage between the two points). Current flow is what is perceived by the animal and not the voltage differential. The level of perception, or type of response, will depend on the magnitude of current flow and the location of the points of contact. Therefore it is desirable to relate current levels with animal responses by conducting controlled scientific tests. The physiological and behavioral effects of different levels of stray voltage/current are addressed in chapter 3.

Voltage Drop and Impedances

The flow of current (I) in a path or circuit will be impeded or opposed by one or more of the following: 1) resistance (R), 2) capacitive reactance (X_C), and 3) inductive reactance (X_L). Resistance has to do with the physical properties and size of the conductive material. Capacitive reactance concerns conductors separated with a dielectric (insulation). Inductive reactance has to do with the laws of magnetism and inductors or situations which might exhibit inductive characteristics. Impedance (Z) of a path is the complex sum of two or more of these factors which are present in a circuit. Because no path in an outbuilding may be pure, that is, contains only one factor, the term "impedance" which includes all three factors, is often used.

This opposition to current flow is really a load, which produces a voltage drop (E) along the path. The voltage drop can be calculated by using Ohm's Law, which states that the voltage in an electrical path is the product of the current flow and the impedance of that path ($E = I \times Z$). The impedance of a conductor, for example, is dependent on the resistance of the conductor itself (size, material, length) plus the resistance of all connections and any capacitive or inductive reactance.

Example of Source, Path, and Impedance

The term "source voltage" (E_S) in this section is defined as the voltage between two animal contact points/areas measured *without* a shunt resistor in parallel with the meter (fig. 2-1). This measured voltage can also be referred to as the "open circuit voltage" (E_{OC}) (see chapter 5, "Detection and Measurement"). The current passing through the animal contacting these points will depend on the contact voltage (E_C), i.e., the voltage between the two contact points (e.g., water bowl and concrete floor) while the animal is making contact, and the sum of the contact and animal impedances. The contact voltage will be less than the open circuit voltage because of the voltage drops due to the current flow in the circuit impedances.

Important factors in determining the magnitude of the contact voltage are 1) the source impedance (Z_S), 2) the path impedances (Z_{P1}, Z_{P2}), 3) contact impedances (Z_{C1}, Z_{C2}), and 4) the impedance of the animal (Z_A). (Contact impedance (Z_{C1}) could, for example, be between the nose and metal water bowl and (Z_{C2}) between the hoofs and concrete floor. It is possible to include these contact impedances as part of the animal impedance (Z_A), but generally it is better to consider them separately, as they vary with conditions.) These impedances play a major role in controlling the current flow (I_C) through the animal. A high impedance in any single component of the circuit will limit current flow through the animal. However, only when one or more of the impedances Z_S, Z_{P1}, or Z_{P2} is high, will there be a large difference between the open circuit voltage and the contact voltage.

To reiterate, circuit impedance is a function of —

- The source impedance and the impedances of the pathways between the voltage source and the animal contact points.
- The impedances of the contacts themselves, e.g., nose to metal, hooves to concrete, udder to milkline.
- The impedance of the animal between the two points of contact, e.g., mouth to four hooves.

Neutral/Ground System Voltage to Earth

The most common source voltage which results in stray voltage/current problems is an elevated neutral/ground system voltage to earth, i.e., the voltage measured between the neutral/ground point in the service entrance panel of a building and an isolated reference electrode placed in the earth. This neutral-to-reference-ground voltage results from currents flowing through the complex neutral and grounding system of conductive materials (impedances) within the power system.

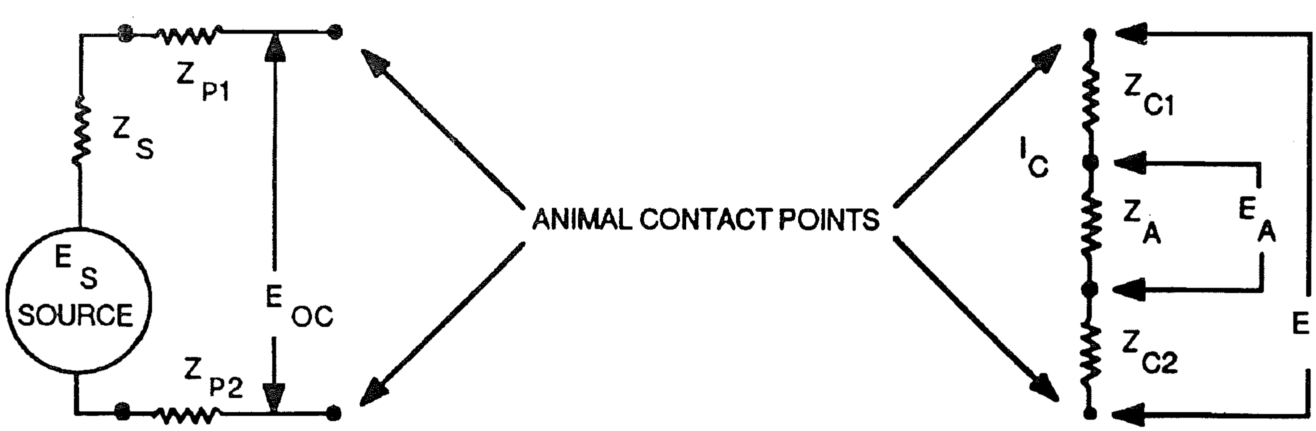


Figure 2-1. Diagram of a path through two animal contact points.

For example, all metal equipment and piping within a structure is bonded to the neutral bus. Grounding is discussed in this chapter under the section heading "Neutral/Ground Bus and Equipment Grounds." The neutral-to-reference ground voltage may be different at various points along the neutral because of interactions among these complex current paths.

A schematic of a suggested model for a current path from neutral/ground bus to earth through two animal contact points is shown in figure 2-2. The current flow through this particular path is labeled I_S and is caused by the voltage between the neutral/ground bus and earth, $E_{N\text{-}E}$. The neutral-to-reference-ground voltage ($E_{N\text{-}RG}$) is also shown in relation to $E_{N\text{-}E}$. The measurable open circuit voltage across the animal contact points is $E_S = E_{OC}$. The path impedance is the sum of Z_1 through Z_3 plus any impedance in the neutral/ground bus.

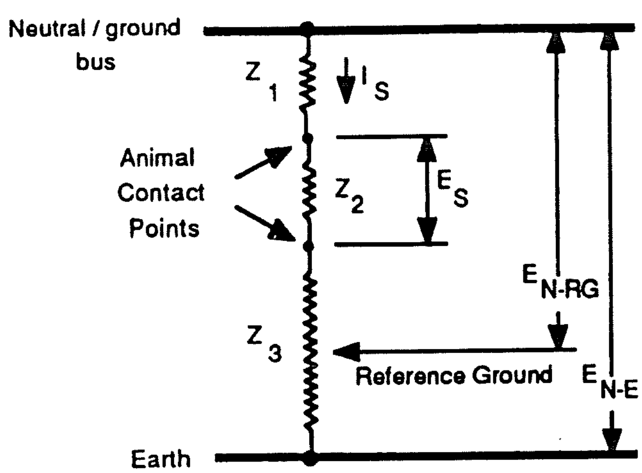


Figure 2-2. Schematic of a model for an electrical path from neutral bus to earth through two animal contact points.

In figure 2-2, Z_1 could represent the impedance between the neutral bus and a water bowl in a stanchion barn. The associated conductive path could be through the bonding conductor to the metal water pipe and/or metal stanchions and to the water bowl. Z_2 would be the impedance of the conductive path between water bowl and the surface of the concrete floor where the animal is standing. This section would include the metal-pipe stanchion frame, the contact between the pipe and concrete, and the concrete itself. Z_3 represents the impedance from the concrete floor surface to earth.

A question could be raised concerning the impedance Z_2. Should this impedance be considered as part of the source impedance or as a load on the circuit along with the animal after contact is made? In this model, Z_2 is considered as a part of the source impedance. If Z_2 were considered to be a load rather than a part of the source impedance, E_S would not be equal to E_{OC}.

As I_S flows through this path, a voltage drop (E_S, which is equivalent to E_{OC} in fig. 2-1) is produced across Z_2. When the animal makes contact with the two contact points, the animal's body and the contact impedances become part of the circuit. With these added shunt impedances, the total impedance of this particular circuit changes; as a result, E_S (or E_{OC}) is reduced (and is now equivalent to E_C in fig. 2-1). The magnitude of this change will depend on the relationship of the various impedances. The current flow through the animal (I_C) is caused by the animal contact voltage (E_C) and is equal to E_C divided by the sum of the contact and animal impedances (fig. 2-1). Because Z_2 was considered part of the source impedance, I_S after contact is not equal to I_C. I_S will equal I_C plus the current flowing through Z_2. If Z_2 is much larger than the sum of the animals' body and contact impedances, which is often the case, I_S after contact will essentially be equal to I_C.

The magnitude of E_C in an outbuilding is generally related both to the voltage between the neutral bus and reference ground and to the circuit impedances. Mitigating animal contact voltage then involves reducing the neutral-to-reference-ground voltage and/or reducing Z_2, the impedance between the two animal contact points. An equipotential plane represents the special case in which $Z_2 = 0$.

Several sources can create the voltage between the neutral/ground system and reference ground:

the voltage drop in the secondary neutral system; currents in the grounding conductor; and load, leakage, or fault currents in the primary or secondary grounding resistances.

Voltage Drop in Secondary Neutral

Voltage drops due to currents in the farm secondary-neutral/grounding systems and the grounding resistances are a source for stray voltages. A schematic of the secondary neutral conductor and earth circuit between the neutral bus in an outbuilding and the center tap of the farm distribution transformer is shown in figure 2-3. Definitions of terms used in figure 2-3 and in subsequent discussions are listed below. Also shown are the equivalent circuit diagrams. The direction of instantaneous current flow and voltage drop is dependent on the neutral-to-reference-ground voltages at the transformer center tap and at the neutral/ground bus point. (The equipment-grounding conductors are not shown in this simplified diagram; it is presumed they are carrying no leakage or fault current, and thus not producing a voltage drop. The grounding system would have a voltage to earth corresponding to the neutral-to-earth voltage at the point of connection.)

The following simplified[1] example applies when the neutral bus has a higher potential than the transformer center tap. The actual current flows and voltages would depend on many factors including other service drops from the transformer and the presence or absence of a primary grounded neutral. The purpose of this example is to illustrate the factors involved, even in a simplistic case, in the division of current at the neutral bus and center tap and the impact of changes in selected circuit impedances.

The current, I_T, will divide at the bus into a current flow in the neutral conductor (I_N) and a current flow in the ground (I_G), the magnitude of each being a function of the impedances of the two paths. The current flowing to earth, I_G, is further divided among all the paths to ground, with even further division as the currents proceed toward earth. The magnitudes of some of the currents in these individual paths will be small but they cannot be ignored.

The current, I_G, is the sum of the current flows in all paths from the neutral bus through earth to either 1) the primary neutral via the transformer ground or other primary neutral grounds (wye distribution) or 2) the transformer ground (delta distribution). For simplicity the schematic shows all the ground current returning via the transformer ground. Because of the voltage drops across the impedances, which are shown as resistances R_{NW},

Definitions of terms used in figure 2-3 and in following discussions

R_{NE} = resistance paths to earth at the bus end of the neutral.
R_{TE} = resistance between the transformer center tap and earth.
R_{NW} = resistance of the neutral conductor.
R_{NC} = resistance of all connectors along the neutral conductor.
R_{NP} = total resistance of neutral path.
R_{EP} = total resistance of earth path.
R_{EQ} = equivalent resistance of circuit.
I_T = imbalanced load and fault current returning to neutral bus via the equipment grounds and other bonded equipment or current entering from the primary neutral.
I_G = current flow through earth path.
I_N = current flow through neutral conductor.
$E_{N\text{-}T}$ = voltage between bus and transformer center tap.
$E_{N\text{-}E}$ = voltage between the neutral/ground bus and earth.
$E_{E\text{-}T}$ = voltage between the earth and center tap of the transformer.

R_{NC}, R_{NE}, and R_{TE}, there will be a voltage differential between the bus and the transformer center tap. The magnitudes of individual voltage drops are dependent on current flow and impedances.

To better illustrate many of the concepts needed to understand the cause for stray voltage, values will be given to the variables. (Note: resistances are used in place of impedances so that the example can be followed more easily.) Two cases will be considered:

- Where resistance of neutral connectors, R_{NC}, is zero.
- Where R_{NC} is 0.5 ohms (Ω), because of poor connections.

Assume the following values: I_T = 20 amperes (A), R_{NE} = 3.0 Ω, R_{TE} = 25 Ω, and R_{NW} = 0.076 Ω (150 feet, AWG #4 aluminum). The results of several calculations are shown in table 2-1.

The equivalent resistance (R_{EQ}) of the two parallel circuits between the neutral bus and the transformer's center tap is dominated by the resistance of the neutral conductor path. With the poor connectors in the neutral conductor path, the resistance of the neutral path (R_{NP}) is 0.58 Ω; the resistance of the earth path is 28 Ω. These two resistances in parallel have an equivalent resistance (R_{EQ}) of 0.56 Ω, which is slightly less than R_{NP}. The equivalent resistance of resistances in parallel is always less than the smallest individual resistance. Unless the neutral conductor is open, R_{EQ} will be slightly less than R_{NP}.

Table 2-1. Values of selected parameters for two values of R_{NC}

Value	R_{NC} = 0.0 Ω	R_{NC} = 0.5 Ω
R_{EQ} (Ω)	0.076	0.56
$E_{N\text{-}T}$ (V)	1.52	11.29
I_N (A)	19.95	19.60
I_G (A)	0.05	0.40
$E_{N\text{-}E}$ (V)	0.16	1.21
$E_{E\text{-}T}$ (V)	1.35	10.18

Rules for significant figures have been ignored so that the sum of the parts will more nearly equal the total. There is some rounding error.

With the current flow in the neutral conductor/earth system from the neutral bus to the transformer (I_T) equal to 20 A and the neutral conductor path at the lower resistance, the voltage between the neutral bus and the center tap of the transformer ($E_{N\text{-}T}$) would be about 1.5 volts (V). When the resistance of the poor connectors is added to the resistance of the neutral conductor this voltage increases to 11.3 V. This voltage appears across both paths — neutral conductor and earth — and at the equipment grounding conductor at the neutral/ground bonding point.

[1]The actual farm case will have a multigrounded secondary system with several neutral/ground return conductors, service-entrance grounding points, and ground contacting equipment. The return load and/or leakage/fault currents will divide among the neutral, the grounding conductors, the grounding resistances, and the earth according to their relative admittances (inverse of impedances) to return to the transformer center tap. These form complex current paths and the voltages measured between two different points will generally not be the same. The multigrounded primary neutral has the same problems of neutral conductor impedance, connector resistances, and variable grounding resistances; with load, leakage and fault currents injected at various locations along the primary line. Other secondary systems also may contribute their problems due to secondary-primary neutral interconnections. As any wire, including the primary neutral, has a finite impedance, the resulting current flow gives rise to various voltage drops along the primary neutral conductor and from this conductor to earth. This effect (again simplified) is discussed in detail in the examples in the appendix of chapter 4, "Mitigation". It must be remembered that where the primary and secondary neutrals are connected together at the transformer center tap, the two neutrals at the point of connection are always at the same voltage relative to earth. If there is no primary neutral, or if the primary and secondary neutrals are isolated, the two neutrals can be at different voltages.

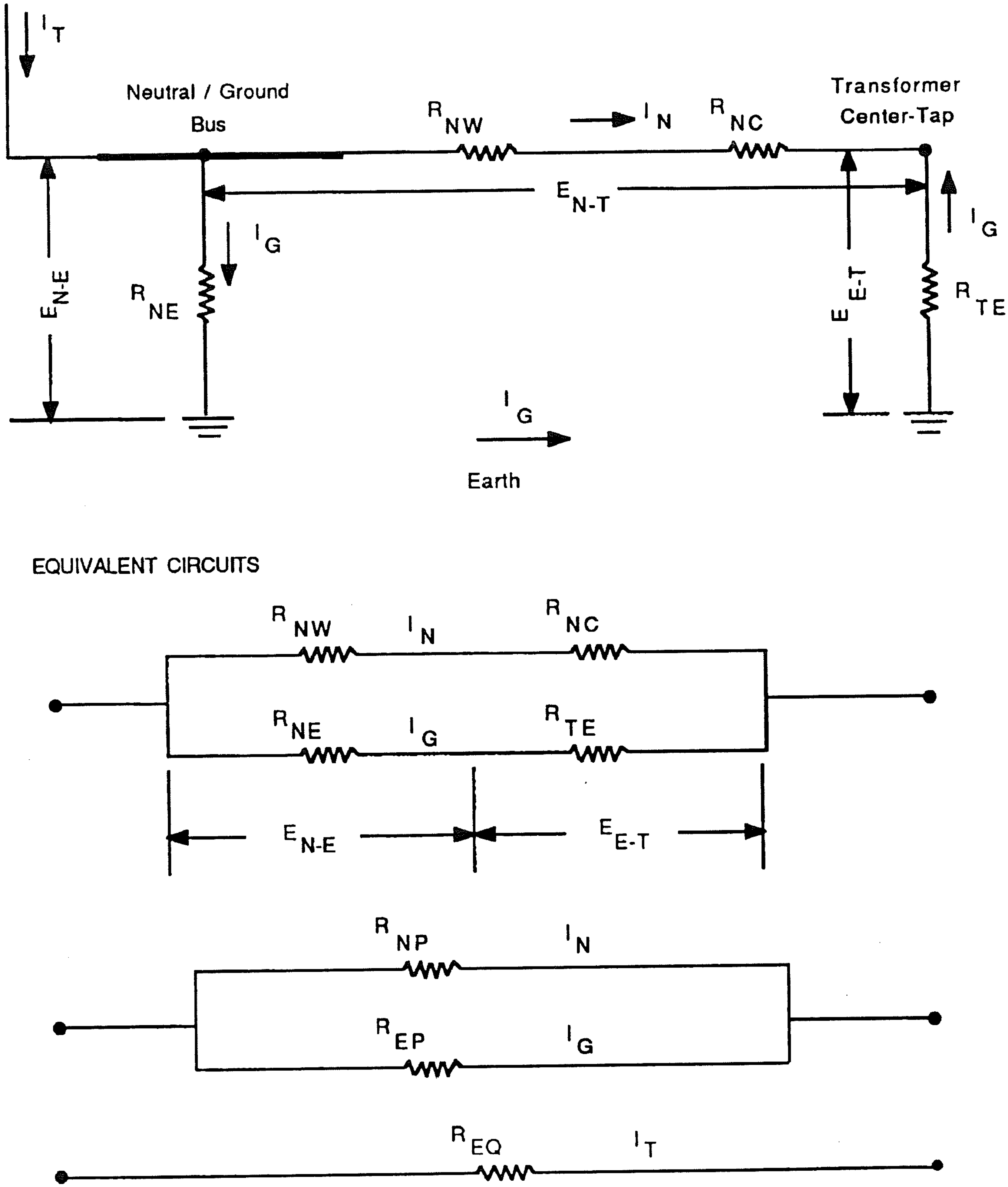


Figure 2-3. Schematics of neutral/ground system between an outbuilding and transformer and of equivalent circuits.

The division of current at the neutral bus is inversely proportional to the resistances of the two paths, i.e., neutral conductor and earth. Most of the current flows through the neutral path where the resistance is much lower: over 19.5 A versus less than 0.5 A. This same relationship between current and resistance will govern the amount of current that will flow through each of the many paths between the neutral bus and earth. We should be reminded of the saying, "Electricity always takes the path of least resistance." This statement is often taken to mean that all the current takes the path of least resistance. This is wrong. "More current will take the path of lower resistance" is more accurate.

The total voltage difference between the neutral bus and transformer (E_{N-T}) will be divided between the neutral-to-earth connection (R_{NE}) and transformer-to-earth connection (R_{TE}). The E_{N-E} voltage produced by conditions on the secondary side of the transformer is a function of the following factors:

- Current flow (imbalance, fault, other) in the neutral/earth system.
- Impedance of the neutral/earth circuit.
- Relationship between the impedances of the neutral-to-earth connection and the transformer-to-earth connection.

The voltage along the neutral bus to the transformer increased from 1.5 V to 11.3 V when the connector impedance was added. These voltages are the same irrespective of path, i.e., across the neutral conductor or the earth. In the earth path, about 10 percent (3/28) of the total voltage change occurs at the neutral-to-earth connection because the impedance at this point is about one-tenth (3 vs. 25 Ω) of the impedance at the transformer center tap. As a result of the poor connection, the E_{N-E} voltage increased over seven times, from about 0.16 V to about 1.2 V. The magnitude of this increase vividly demonstrates how one simple problem in the electrical distribution system has the possibility of creating a stray voltage/current problem. A sevenfold increase in the E_{N-E} will produce a sevenfold increase in any contact voltage whose source is the E_{N-E}.

The above example clearly demonstrates that problems with the secondary neutral conductor can easily produce a stray voltage/current problem. It is important to keep the resistance of the secondary neutral as low as feasible. It is also important to keep current flow in this conductor as low as possible to reduce the chance of producing a stray voltage/current problem should the resistance of the conductor increase over time. In the example, the increase in resistance resulted from failure of a connector. Such increases are common with corroded connectors.

Neutral/Ground Bus and Equipment Grounds

The neutral/ground bus at the farm service entrance is the junction for all parts of the grounded neutral system of the secondary. In the wiring system for a farmstead, as stipulated in the National Electrical Code of 1990, Section 250-50 (a), the equipment grounding conductors must be bonded to the neutral and to the grounding electrode conductor at the main service-entrance panel. The neutral and equipment grounding conductor must also be grounded at other building panels on the farm and at the distribution transformer. The electrical system and supply equipment must be grounded according to the National Electrical Code, section 250-42. (Separation of grounding and neutral conductors at a building panel is sometimes allowed accrding to a specific exception for agricultural buildings; see below.)

A separate wire (conductor) should be used for equipment grounding, although under certain circumstances, a metal sheath of a cable or a metal raceway (such as a rigid steel conduit) may be used as the equipment grounding conductor. In any case, the grounding conductors are connected to the grounded neutral conductor and the grounding electrode at the building service entrance. The equipment grounds are intended to carry small capacitively coupled or leakage currents or heavy current only in the event of a fault. (Some localities may permit/require separation of neutral and grounding conductors at the outbuilding service entrance or subpanel. Thus, these conductors remain separate and are carried independently to the main service entrance, where they *are* bonded; see chapter 4, "Mitigation.")

Figure 2-4 illustrates a neutral/ground bus in a building service entrance showing the many parts that are joined together at the bus. The secondary neutral conductor is joined to the white (neutral conductor) current carrying conductors for the 120-V circuits; the grounding electrode conductor; equipment grounding conductors (green or bare wires); and bonding conductors to water pipes, panel boxes, and other metal objects. The path from the neutral/ground bus to earth will be via the grounding electrode; the bondings to water pipes, etc.; and some of the electrical equipment grounds, such as those going to motors on the gutter cleaner and electrically heated stock waterers. These several paths, with individual impedances, are in parallel. The neutral-to-earth resistance (R_{NE}) in figure 2-3 represents the equivalent impedance of all these parallel paths.

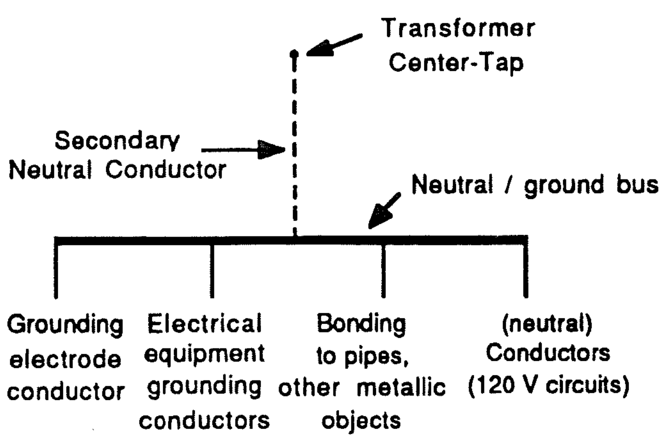


Figure 2-4. Schematic of neutral/ground bus with attached conductors and bonds.

Voltage Drop in Equipment Grounds

Equipment grounds (green or bare wires) are required to prevent shocks due to faults in electrical equipment. Equipment grounds are intended to provide a low-resistance return path for fault current, thus causing an overcurrent device to trip/open and prevent a voltage from developing between exposed metal parts of electrical equipment and earth. Equipment grounding conductors are supposed to carry current only when there is a fault. Figure 2-5 shows a branch circuit with a properly installed equipment ground. The equipment grounding conductor is shown attached to the neutral/ground bus at the service entrance panel. The National Electrical Code requires that equipment grounding conductors (green or bare) and the neutral (white) conductor be separated at all points beyond the breaker panel of the main service entrance in an outbuilding.

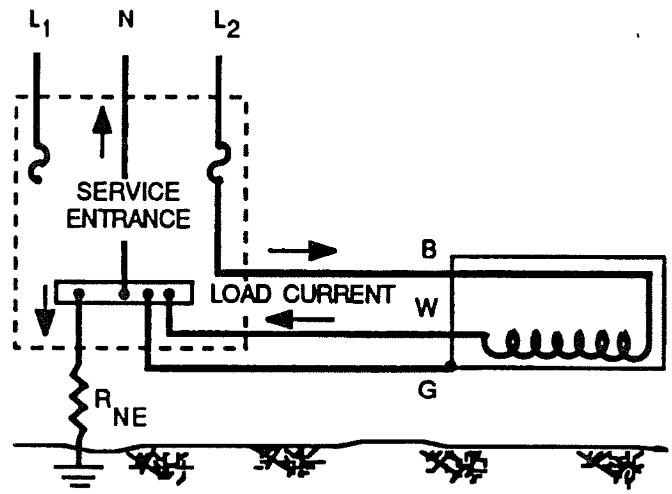


Figure 2-5. A branch circuit with power conductors (B&W) and equipment ground (G) properly connected.

The frame of the electric equipment in figure 2-5 is shown as being isolated from earth. If the equipment frame and earth were the two animal contact points, the value of the impedance Z_2 in figure 2-2, would be very high. Under normal conditions, there would be essentially no current flow in the equipment grounding conductor and the frame would take on the same potential with respect to earth as the neutral bus. Due to a low value of the resistance of the equipment grounding conductor, the animal contact voltage (E_C) would be nearly equal to the neutral-to-earth voltage if the animal's feet were at earth potential (i.e., $Z_3 = 0$). If the animal were standing on concrete or a wooden floor (Z_3 greater than 0 but less than infinity), the contact voltage would be less than the neutral-to-reference-ground voltage because of the voltage drop across Z_3.

Often the frame of electrical equipment is not isolated from earth, and there is a current path to ground/earth. Such equipment would include a gutter cleaner, condensing units on a milk tank, a milk pump, and a domestic water pump.
Figure 2-6 illustrates such a situation. The impedance of this path is shown as R_G. Referring to figure 2-2, Z_2 can be low.

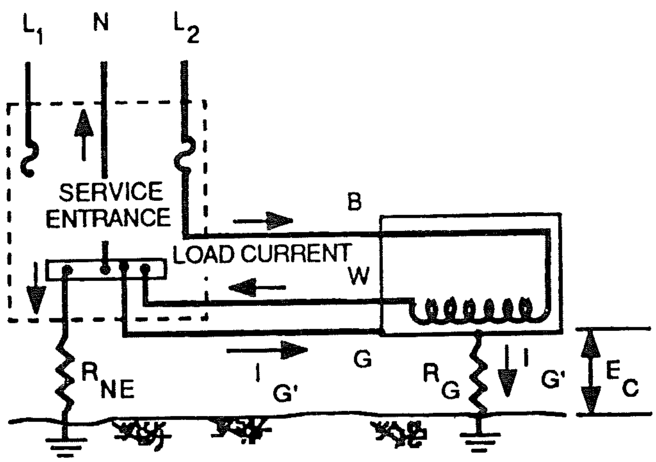


Figure 2-6. A branch circuit with power conductors (B&W) and equipment ground (G) properly connected. A connection (R_G) between the equipment and earth exists.

With the equipment ground conductor connected to the neutral/ground bus and to the equipment frame, and with a path to earth, there will be a current flow (shown as $I_{G'}$ in fig. 2-6) whenever there is a neutral-to-reference-ground voltage. This current flow will be accompanied by a voltage drop that will be divided between the equipment grounding conductor and the drop across R_G. The voltage drop across R_G would equal the open circuit voltage (E_{OC}). There could be little voltage drop along the equipment ground conductor.

Figures 2-5 and 2-6 show proper wiring and no faults. Even so, a possible animal-contact voltage directly proportional to the neutral-to-reference-ground voltage does exist between the equipment and ground. A stray voltage/current problem will exist only if animals can come into contact with the equipment and the magnitude of the resulting current is sufficient to cause a response.

Leakage or Fault Current on an Equipment Ground

Leakage or fault currents will produce a voltage drop along the equipment grounding conductor. For example, a 10-A fault current in 50 feet of #12 copper conductor will result in a voltage drop of 0.9 V. It is important to maintain low-resistance equipment grounds. Corrosive environments in livestock facilities can deteriorate electrical connections. Such deterioration can cause excessive voltage drops along the grounding conductor and increase the chances of establishing a stray voltage/current problem. *Periodic inspections and maintenance are essential to preserve the integrity of electrical systems.*

Figure 2-7 illustrates the effect of a piece of equipment with an electrical fault. The equipment is in contact with the earth. Part of the fault current, I_{F1}, is shown returning to the neutral bus via the equipment grounding conductor. The remaining fault current, I_{F2}, returns via an earth path. Differences in current magnitudes affect the voltage drop between the equipment frame and the neutral bus.

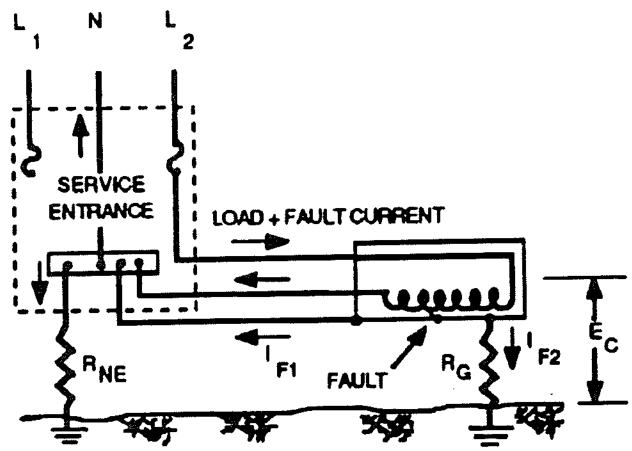
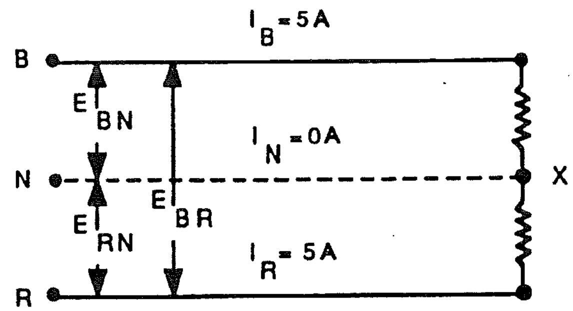


Figure 2-7. Fault in properly wired equipment causes fault current to flow toward transformer.

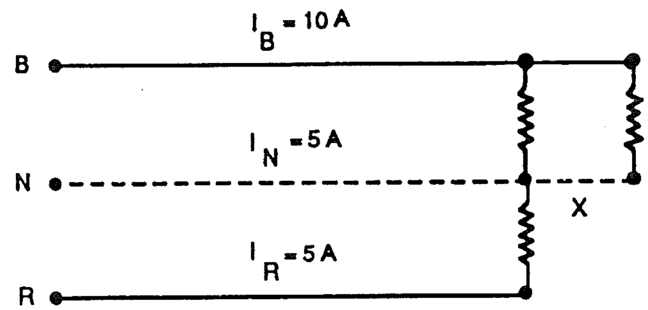
Considered by itself, this voltage drop in the equipment grounding conductor would raise the open circuit voltage, E_{OC}. However, this voltage drop together with the changes in the secondary neutral current (discussed earlier) may result in an increase or decrease of the open circuit voltage, depending on their relative magnitudes and phase relationships. The resulting open circuit voltage will appear as a voltage (E_{NE}) between the faulty equipment and earth and could be accessed by animals through any conductive path to the faulty equipment. The lower contact voltage (E_C) would be measured on animal contact.



(A) Balanced Load

Excessive Secondary Neutral Current

Excessive current, I_T, flowing in the secondary neutral system of a service drop can result from several factors, including 1) imbalance of the 120-V electric loads in the outbuilding, 2) the phase relationship between the various currents, e.g., imbalance, fault, and primary neutral (fig. 2-3), 3) electrical faults, and 4) improper wiring.



(B) Unbalanced Load

Figure 2-8. Three-conductor 120/240-V secondary distributions with balanced (A) and unbalanced (B) loads. Each load is 600 W.

Unbalanced 120-V Loads

Unbalanced 120-V loads in an outbuilding can have a major effect on the voltage measured between the neutral bus and a reference ground. A three-conductor service drop to a farmstead is illustrated in figure 2-8. The two ungrounded conductors are labeled B and R, and the neutral conductor is N. The voltages E_{BN} and E_{RN} are 120 V and E_{BR} is 240 V. Figure 2-8A shows two 600-W resistive loads, one across E_{BN} and one across E_{RN}. Both loads are on at the same time. The current flow in conductors B and R is at 5.0 A, and that in conductor N is 0.0 A. The reason the current in the neutral is 0.0 A instead of 10.0 A is that voltages E_{BN} and E_{RN}, and thus the currents I_B and I_R, are out of phase by 180 degrees. Therefore the two current flows of 5.0 A, which meet at point X, cancel each other rather than add together. This is an example of balanced loads, i.e., no neutral current flow. If one load had an inductive or capacitive component, there would have been a phase shift in the current. As a result, the two currents I_B and I_R would not have canceled completely, and the neutral conductor would have carried a small current, I_N.

Figure 2-8B shows the same circuit arrangement except with three 600-W loads, two across E_{BN} and one across E_{RN}. The current flows have changed. Now current flow is 5.0 A in conductor R but 10.0 A in conductor B and 5.0 A in N. The current flow in conductor B is now only partially canceled by the current in R, with the remainder flowing in conductor N. This circuit is unbalanced. The current flow in the neutral conductor is 5.0 A, the difference between the current in conductors I_B and I_R. Balancing 120-V loads as nearly as possible, including the times they are on, will reduce the secondary neutral current and the resulting voltage drop.

Phase Relationships

The phase relationship between the secondary neutral current and the primary neutral current has a direct bearing on the voltage between the neutral bus and a reference ground for a single-phase service. When primary and secondary are both single-phase systems, these two currents can be in phase or 180 degrees out of phase; thus, the voltage drop in the secondary neutral can be in phase or 180 degrees out of phase with the primary neutral. In reality, these relationships are more complicated than this statement suggests. The use of inductive loads, such as motors and high intensity discharge lamps (mercury vapor or high pressure sodium), causes phase shifts between current and voltage that are less than 180 degrees. These shifted voltages do not directly add or subtract.

When two or more currents or voltage drops combine at a junction, the resulting current or voltage is always the vector sum of the components. If two voltage drops are involved and are in phase, they will add, and the voltage between the neutral bus and a reference ground will increase. If the two are 180 degrees out of phase, the vector sum will be smaller than the larger component and perhaps smaller than both components. If the two voltages are out of phase by less than 180 degrees, the vector sum will lie between these two extremes. The high starting currents associated with motors mean that there will often be momentary high currents (and voltages), called transients, on the system.

A true delta primary distribution has no primary neutral conductor and, thus, no primary neutral current. Therefore the secondary neutral current (voltage drop) is independent of primary distribution and occurs because of conditions on the farmstead.

Fault or Leakage Currents

Undesired current will occasionally flow when a conductor -- hot (black or red) wire, neutral (white) wire, or electrical equipment (e.g., a heating element in a water heater) -- makes electrical contact with an object which is at a lower potential. The contact may be the result of a fault (i.e., direct contact) or leakage, e.g., via dirt and moisture. Leakage may also result from capacitive coupling. Coupling is discussed in this chapter under the heading "Coupled Voltage/Current." In general, a conductive pathway to an area of lower potential must exist before any current can flow. This path may be another wire or a grounded material which is in direct contact with the defect. Alternatively, moisture and dirt around the defect may provide a conductive path to earth. Common causes of fault or leakage currents are old equipment, improper wiring, and poor maintenance of electrical equipment. In addition, water heaters, buried cables or equipment, and submersible water pumps are especially susceptible to damage which results in current leakage or faults.

The severity of the problem, i.e., the amount of current flow, depends on the impedance of the path and location of the problem. A "dead short" would have a very low impedance and would most likely trigger protective fuses or circuit breakers. In contrast, a crack in insulation surrounded by moist cobwebs could have a high impedance to earth and result in a small current flow.

The location of the problem within a piece of equipment is also important. In a 120-V electric heater, for example, a fault involving the black (hot) wire would be more serious than the same kind of fault involving the white neutral wire. This is because the black wire is never grounded, which means that the voltage in the black wire relative to earth approaches 120 V. The voltage in the white wire relative to earth will be similar to the neutral-to-reference-ground voltage at the service entrance, because the white wire *is* the neutral conductor.

Fault or leakage currents must return to the center tap of the distribution transformer. Depending on the phase relationship between these currents and any secondary-neutral imbalance current, the secondary-neutral voltage drop may be increased or decreased. In other words, fault or leakage currents can improve or worsen the current balance on the secondary neutral and, thus, the voltage between the neutral bus and a reference ground. It is best to minimize leakage currents.

Fault Current to Earth: If a fault to earth occurs, the leakage or fault current will return to the transformer's center tap via the grounding conductors and also via the secondary and primary

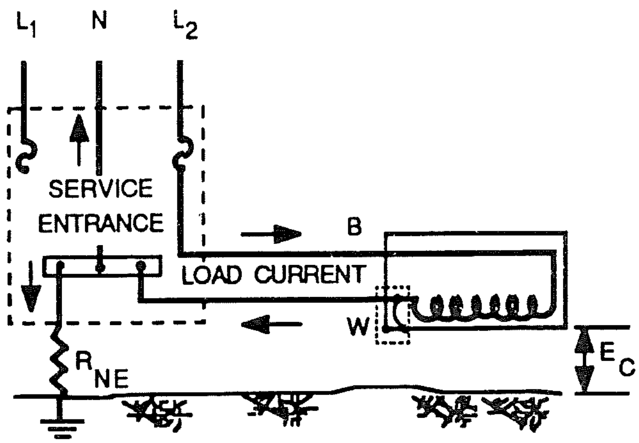


Figure 2-9. Improper use of the white conductor (neutral) as an equipment grounding conductor. Frame should not be bonded to neutral.

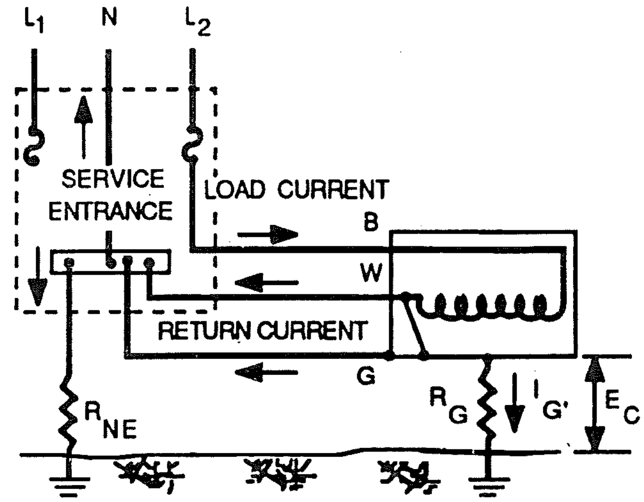


Figure 2-10. Improper interconnection of white conductor (neutral) and the equipment grounding conductor (G). These conductors must be separated.

neutrals. If the equipment is improperly wired, as in figures 2-9 and 2-10, the fault current may return on the white conductor. In either of the cases depicted in these figures, the added current flow on the neutral system may result in a net increase or decrease in current flow, again depending on phase relationships. *For safety reasons, all faults must be corrected as soon as possible.*

Fault location will be one determinant of the magnitude of the voltage gradient and, thus, leakage current. If the fault occurs in an electrical load such as a motor or heater, the position within the load relative to the neutral is important. Figure 2-7 shows a fault near the middle of the load. (This would provide a source of about 60 V and with a low impedance grounding conductor should cause the circuit breaker/fuse to open. A fault closer to the neutral might not result in sufficient current flow to operate the line protection. This current flow could then be a source for a stray voltage.) In a buried cable, a leakage from a fault occurring in a hot conductor will be greater than that from a similar fault occurring in the white conductor, because of the greater potential across the fault (fig. 2-11).

Even when all wiring is done according to the National Electrical Code, the occurrence of a fault can create a stray voltage/current problem. The magnitude of the problem will depend on the location and impedance of the fault within the system, the impedances of the various paths to the transformer's center tap, and the phase relationships; i.e., the fault current will be divided among

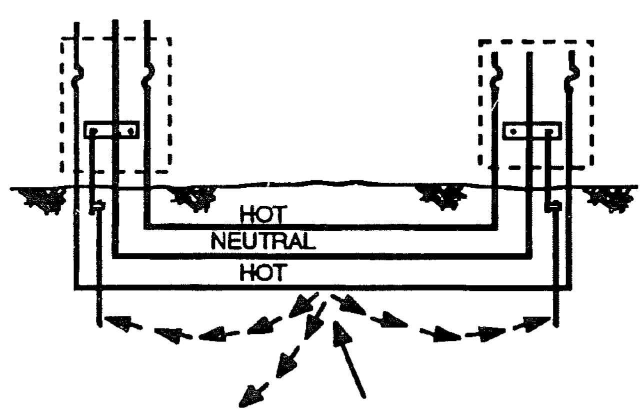


Figure 2-11. Leakage current to earth from an energized buried electric cable.

the several paths in relation to the impedances of these paths.

Improper Wiring

Interconnection of Neutral and Equipment Ground: Interconnection of the neutral (white) conductor and the equipment grounding conductor (green or bare) beyond ("downstream from") the service entrance violates the National Electrical Code. The neutral and equipment grounding conductors must be separate in all feeders and branch circuits beyond the building service entrance. This requirement is not always adhered to, particularly where the code is not enforced.

One violation of this rule is the bonding of the white conductor to the equipment frame, as shown in figure 2-9. The white current carrying conductor now doubles as the equipment grounding conductor. The voltage between the frame of this equipment and earth will be the neutral-to-reference-ground voltage plus or minus the voltage drop in the branch-circuit neutral conductor from the neutral bus to the equipment frame. The increase or decrease depends on the phase relationship between the two currents. As stated earlier the voltage drop depends on the resistance of the neutral conductor and the magnitude of current. The current flow is a function of the electric load, assuming no faults. Installing a proper equipment-grounding conductor may raise or lower the possible animal contact voltage, depending on the change in magnitudes and actual phase relationship of the currents.

The voltage drop in the neutral could be particularly high during the start of 120-V motors. Should a problem occur in the white conductor, such as a loose connection, the animal contact voltage would be further increased by the voltage drop across the high impedance connection. A hazardous condition could exist.

Another improper interconnection is shown in figure 2-10. Here a jumper wire is used to bond the neutral (white) conductor and the equipment grounding conductor. This is a violation of the National Electrical Code. These conductors must be separated. The equipment grounding conductor is not to be used to carry load current. The potential animal-contact voltage at the equipment under normal operating conditions may be slightly less than that for the circuit shown in figure 2-9 because both conductors (white and green/bare) are carrying the return current in parallel to the neutral bus.

If there is a path to earth from the equipment frame, part of the load current (shown as $I_{G'}$) will flow to earth. This situation is not significant as long as the neutral and equipment ground are intact. Should there be a problem with these conductors, the path to earth would be forced to carry all the load current. This situation could increase the potential contact voltage to a dangerous level.

Using Ground Rods in Place of Equipment Grounding: Grounding electrodes may be used to supplement, but should not be used to replace, the equipment grounding conductor. For remote equipment, such as stock waterers or heaters, ground rods have been used in place of equipment grounding conductors to save money, because a two-conductor cable can be used instead of a three-conductor cable (fig. 2-12).

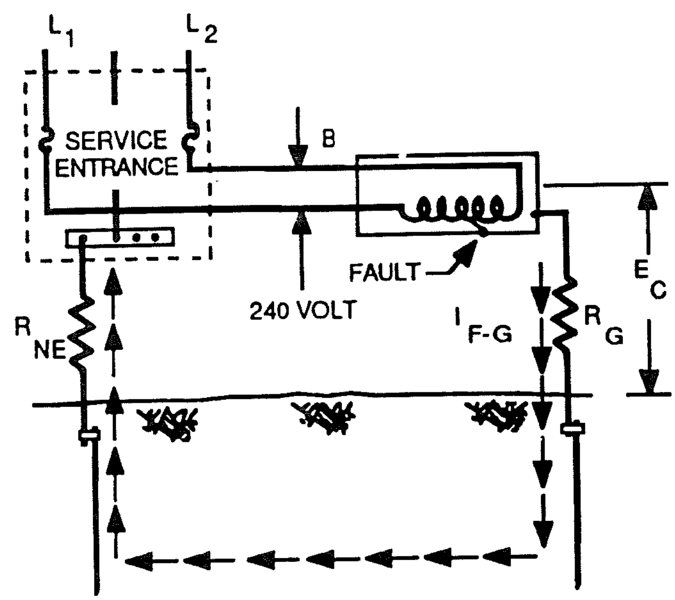


Figure 2-12. Improper grounding of remote equipment with ground rod.

Such a use of ground rods does not meet National Electrical Code requirements and can lead to hazardous contact voltages — up to 120 V — for both animals and humans should a fault occur. The seriousness of the problem will depend on the location and impedance of the fault and the impedance of the earth path. Fault current will flow in the earth, where it may cause serious touch or step voltages for animals and humans at the waterer. In addition, because of the grounding resistance, fuses or circuit breakers may fail to operate.

Coupled Voltage/Current

Conductive materials which are electrically isolated from ground can acquire a voltage with respect to a reference ground. This voltage can appear as a result of capacitive or inductive coupling. It can also appear as a result of a high-resistance leakage path from the power lines, or, for example, from a pulsating high-voltage source, such as a cow trainer or electrified fence. Cow trainers consist of a single wire; thus, the electric field around the wire is much higher than that around a 120- or 240-V branch circuit cable. Branch circuit cables have two conductors in close proximity. Because the "out" and "back" current flow through the two conductors, the magnetic field of one conductor cancels most of the magnetic field of the other conductor. Thus, the resultant magnetic field around the cables is low.

Voltages can be capacitively coupled when a single conductor carrying an alternating or pulsating voltage runs parallel to electrically isolated conductive materials. For example, voltage might be induced in an isolated stainless steel milk pipeline which is parallel with a cow trainer located above the cows in a stanchion barn.

Because the voltage is the result of coupling rather than direct contact with an electrical supply, the source impedance for the milk pipeline, for example, would be very high. Therefore the capabilities of producing current levels sufficient to cause problems are rare. Depending on the capacitance of the item in question and its level of isolation, there may be enough stored energy to cause a problem when an animal shorts or discharges the energy from the item to ground. There would, however, be little sustained current flow.

Step Potentials

Current flowing through the resistance of the earth can set up a potential (voltage) gradient across the earth surface. The potential is highest near the contact point where the current enters the earth. The voltage between two points (as from front to rear hooves of an animal) depends on the current and resistance of the path between those points (the hooves). The resistance increases with increasing distance between points of contact. Normally a heavy current such as might originate from a power fault or lightning strike and close proximity of an animal to the current source are needed to result in the flow of a dangerous current through the animal. The step potential decreases rapidly away from the earth-current contact point. This decrease is the basis for designs of step-potential gradient zones commonly used with equipotential planes.

Caveat

Only if a voltage which the animal contacts (E_C) is sufficient to produce a current at a level of concern, is it then *necessary* to make the appropriate measurements to determine the source(s) and devise a mitigation process.

Power Delivery Systems

Another origin of stray voltage/current problems is an elevated voltage between the primary neutral and earth. "Neutral-to-earth" voltage is the name given to the voltage measured between the multigrounded neutral system (generally the neutral bus at the service entrance) and earth. This voltage is estimated by measuring the voltage between the neutral/ground bus and a reference (isolated) ground rod. The accuracy of the estimate depends on the location of the reference ground and the measurement system. "Neutral-to-reference ground voltage" is a more accurate

Items in a delivery system for electric power

- Generation
- Transmission
- Substation
- Primary distribution (three- and single-phase)
- Customer's transformer
- Secondary distribution
  - Utility service drop (three- and single-phase)
  - Meter
  - Feeders to buildings
  - Service entrance conductors
  - Service equipment/distribution panel (location of secondary neutral/ground bus)
  - Branch circuits and feeders
  - Appliance/load

name for what is being measured and will therefore be used for the remainder of this section.

Stray voltage should not be equated with neutral-to-reference-ground voltage. The reason is that animals would not normally make simultaneous contact with the primary multigrounded neutral system and the reference ground. The actual contact voltage is generally a fraction of the neutral-to-reference-ground voltage and depends on the impedances of the current paths between the animal, the neutral/grounding bus, and earth.

To understand the causes of elevated neutral-to-reference-ground voltages, relations among the electric-power distribution system and the farmstead electrical system must be understood. The delivery system which brings electric power from the generation plant to the customer's appliance is made up of many components. Not all systems have the same components, but the following list contains most of the major items.

The words "primary" and "secondary" are used in discussing distribution of electric power. The implication is that primary voltages are higher than secondary voltages, which are usually on the customer's side of the transformer. Distribution transformers commonly have a high-voltage (primary) side and a low-voltage (secondary) side. The earlier parts of this chapter have dealt with the secondary system.

Power Generation and Transmission

Nearly all the commercial production of ac electricity is accomplished with three-phase synchronous alternators. These alternators produce three single-phase currents with 120 degrees between each phase. Most power used worldwide has a sinusoidal waveform of 50 or 60 hertz (Hz) (cycles per second). This generated power is transmitted at high voltages (up to and over 700 kilovolts (kV)) to substations, where the voltage is reduced for either subtransmission to a second substation or primary distribution. Voltages of primary distribution lines are usually less than 35 kV phase to phase.

Primary Distribution

Primary distribution lines deliver power from the substation to the customer's transformer. These lines are normally owned by public or private utility companies. Three-phase wye (Y), three-phase delta (Δ), and single phase are the most common configurations used for primary distribution of electric power. From the substation, a three-phase primary could go directly 1) to a large customer, 2) to supply single-phase power to smaller customers, or 3) to serve as a feed to single-phase primary-distribution branches.

Wye Distribution

A three-phase wye primary distribution with a multigrounded neutral system uses four conductors (fig. 2-13). Three of the conductors (A, B, and C) are ungrounded phase (hot) conductors. The fourth conductor (N) is a grounded neutral conductor. This primary neutral is grounded at intervals along the distribution line and at each transformer. A single-phase primary distribution with two conductors, one ungrounded (B) and one grounded (N), is shown branching from the three-phase line. Other single-phase branches could be taken from conductor A, B, or C and N. To reduce current flow in the neutral, the utility will try to balance the load on the three ungrounded conductors by choosing which ungrounded conductor to use for individual service drops or for single-phase

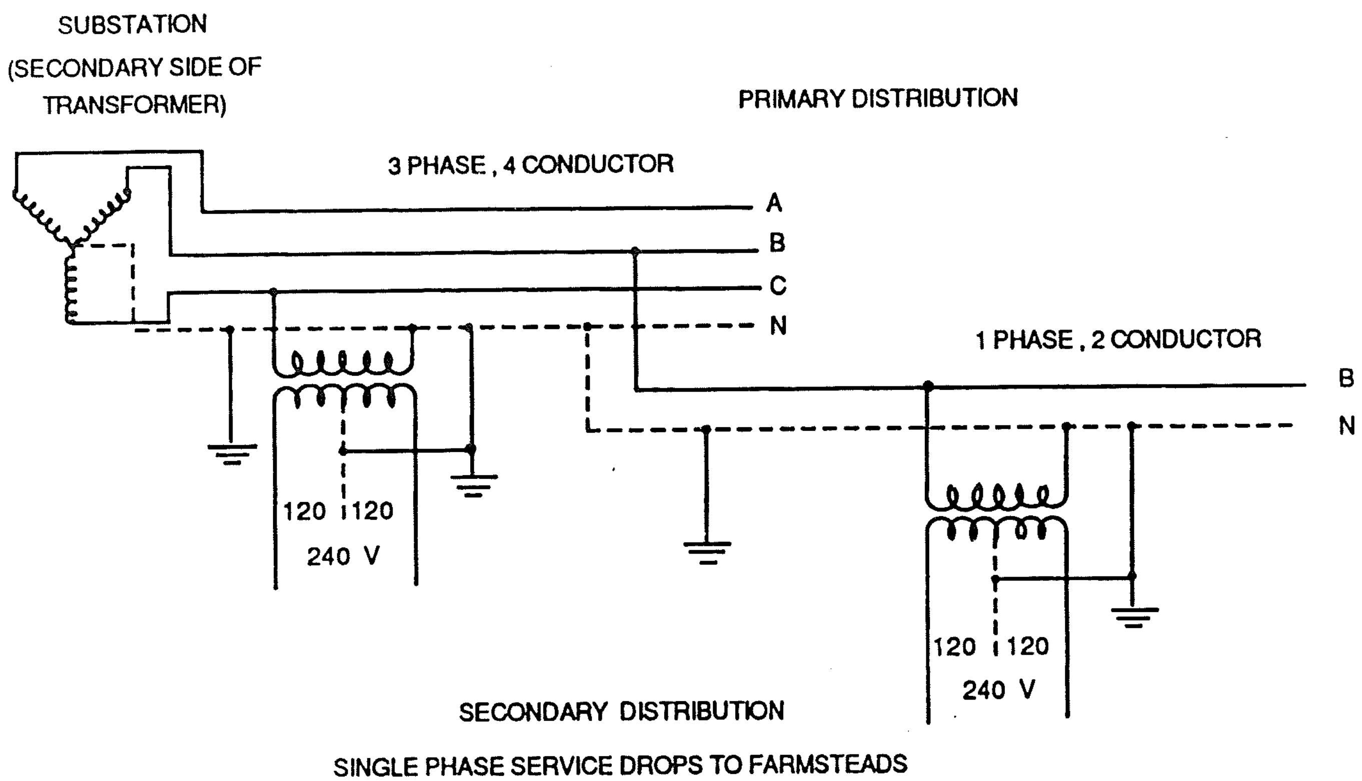


Figure 2-13. Multigrounded neutral distribution system (wye).

branches. From a practical standpoint, it is impossible to cancel (balance) all neutral currents. Variations in use of electricity by time of day, differences in phases of loads at individual user sites, and the variable spacing of users along the distribution mean that there will be different neutral currents along the neutral.

Delta Distribution

A true three-phase delta (Δ) primary system uses three conductors (fig. 2-14). All of the conductors are ungrounded (hot) conductors. There is no grounded primary neutral. A single-phase primary distribution branch attached to conductors A and C is also shown. Again, the utility will try to balance loads on the three primary-phase conductors by choosing the appropriate pair of conductors for all single-phase lines and services.

Open Delta Distribution

A third, less common, type of three-phase primary distribution is the open delta, or V phase, which has two ungrounded phase conductors and a grounded primary neutral (fig. 2-15). The secondary consists of a single-phase service drop (B,N,C 120/240 V) which uses a single transformer and three conductors. A single-phase service drop (C,N,B 120/240 V) and a three-phase service drop (A,C,B 120/240 V) can be provided by using two transformers and four conductors. There may or may not be bonding between the primary and secondary neutrals.

Single-Phase Service Drops

Service drops take power from the secondary side of the transformer to the electric meter. Single-phase (120/240-V) power can be obtained from either a three-phase or single-phase primary. In

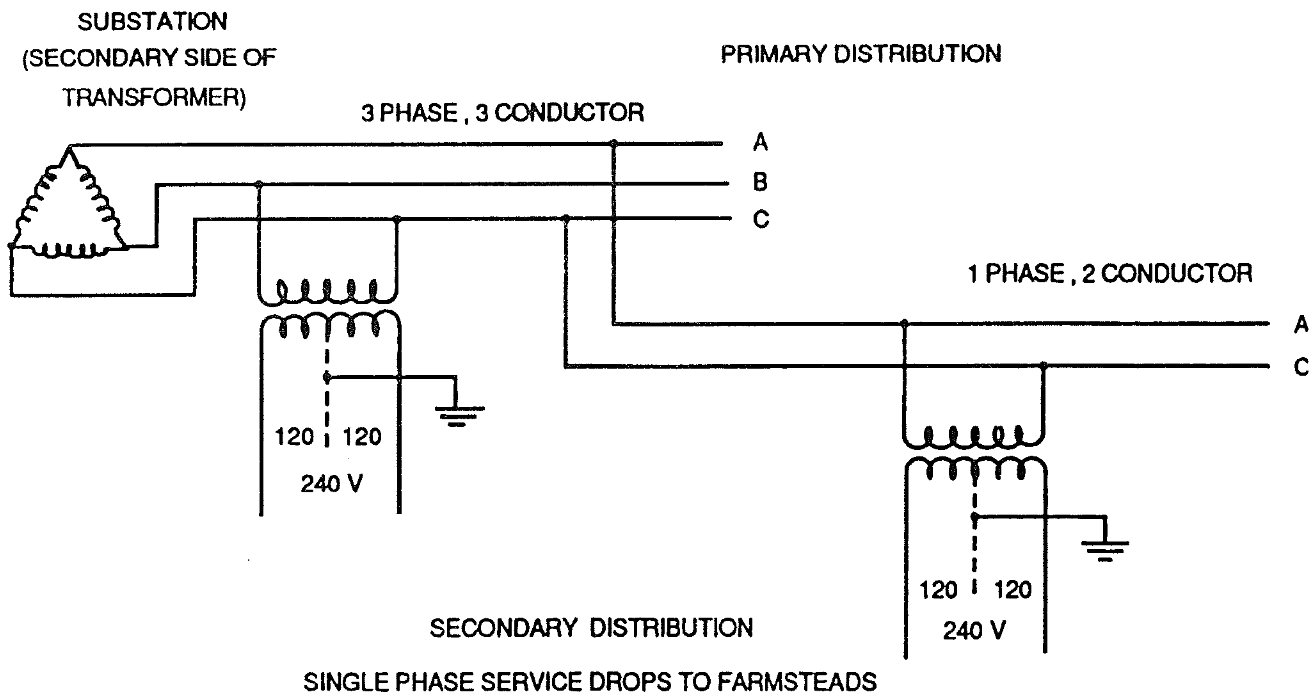


Figure 2-14. Delta distribution system.

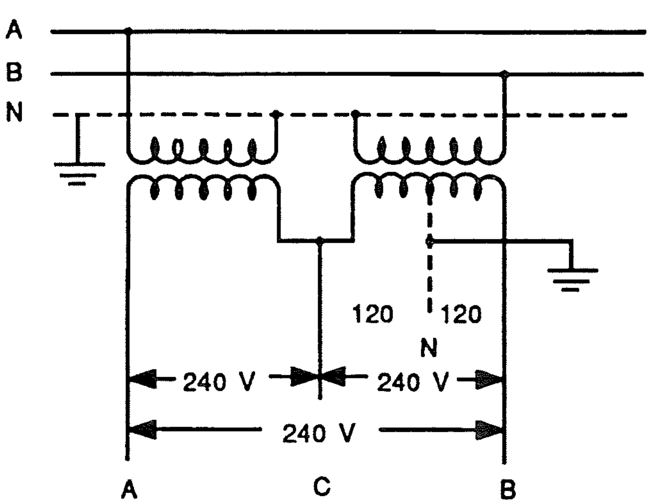


Figure 2-15. Open delta distribution system.

either case, a step-down transformer with a secondary center tap is used for the service drop.

Wye Primary
Two single-phase service drops to separate farmsteads are shown with center-tap step-down transformers in figure 2-13. One service drop is taken from conductors C and N of the three-phase primary distribution. The second service drop shown is taken from the single-phase primary distribution conductors B and N. Other service drops could be taken from conductors A, B, or C along with N.

For the multigrounded primary system shown in figure 2-13, there is a continuous neutral system with grounds at intervals along the primary distribution and at building service entrances. Note the bond between the primary grounded neutral and the secondary neutral in the service drops. The source of power for the farmstead is the transformer; but the path of the return current, including unbalanced and fault currents, involves both the primary and secondary neutral/grounding systems and earth. The farmstead distribution system is not isolated from the primary distribution. Neutral load or fault currents to neutral or ground at an adjacent farmstead(s) can affect the neutral-to-ground voltage of a farmstead. The primary and secondary neutrals will have the same voltage to reference ground at the point where they are bonded.

The earth is a return current path in parallel with the neutral conductor paths. These paths are not only in parallel but also interconnected at many points via the multiple grounds. According to the National Electrical Code, the neutral on a farmstead must be grounded at the transformer, main service (meter), and generally at the outbuilding service entrances for safety reasons. The amount of current flowing in each of these paths — earth and neutral conductor paths — will depend on their relative impedances. (The higher the relative impedance, the lower the current.) Under the excepted condition in which the primary and secondary neutrals are disconnected, the use of an approved surge protection device is required.

Voltage Between the Primary Neutral and a Reference Ground

The magnitude of the voltage between the primary neutral and a reference ground is dependent on the voltage drop in the neutral system. Because the primary/secondary neutral is grounded at each distribution transformer and the primary at intervals at distribution poles, some current passes through the grounding resistances. Thus there is an expected, usual, voltage to earth all along the line. This voltage will be different at various locations and will change constantly, depending on load changes and seasonal changes in earth resistance. The impedance of the neutral conductor depends both on the size of the conductor (resistive component) and the spacing from the other power conductor(s) (reactive component); thus there is a reasonable limit to a lowest impedance for the neutral.

The National Electrical Code and National Electrical Safety Code require that the primary and secondary neutrals be interconnected at the distribution transformer for safety. (There is an exception whereby if an approved surge arrester is used, this requirement is waived.) One consequence is that at the point of interconnection, the neutral to earth voltage for the primary and secondary neutrals will be the same, i.e., the load, leakage, and fault currents, and the impedances in the primary and secondary neutrals; the secondary equipment-grounding system; and the grounding resistances, together, determine the observed voltage at the interconnection point. Any change in current in either system is likely to produce a change in this voltage. For example, changes in load at another farm or at a factory or residence may produce a change in the neutral-to-earth voltage at a given farm. Thus, there can be secondary to secondary system effects due to interconnections with the primary neutral, as well as effects from primary system changes. Depending on phase relationships of the currents, the neutral-to-earth voltage may increase or decrease. These interactions are discussed in detail in chapter 4, "Mitigation."

Consequences of interconnecting primary and secondary neutrals in three-phase distribution systems are similar to those for single-phase distributions. However, it is possible on a three-phase line (but not on a single-phase line) to rotate the different single-phase loads to different phases. The neutral currents will tend to balance and thus reduce the magnitude of the neutral-to-earth voltage along the line. (A balanced three-phase load does not contribute appreciably to neutral current.)

To solve difficult stray voltage problems at a farm, it is sometimes useful to temporarily disconnect the primary and secondary neutrals. This must be done *only* by the utility; a stray voltage expert should be present to interpret the electrical measurements made. The procedures for detecting and correcting problems are discussed in the chapters on measurements and detection, and on mitigation.

Delta Primary

Two single-phase service drops (120/240 V) for farmsteads are shown in figure 2-14. They are shown originating from the three-phase and single-phase primary distribution lines. These drops begin on the secondary side of the transformer and are the start of the secondary distribution network.

For the delta ungrounded primary system, the transformer isolates the farmstead distribution from the primary distribution system. There are no direct connections (bonding) of conductors. The transformer secondary windings become the power source for the farmstead, and therefore all imbalance and fault currents must return to the transformer directly via the secondary grounded neutral and earth system. The farmstead is not impacted by off-farm loads or faults except through changes in line voltages or through changes in effective impedances to earth. However, because system grounding is restricted to the farmstead, faults or unbalanced loads at the farmstead are likely to have a greater effect on the neutral-to-reference-ground voltage for this distribution system than for one in which the primary neutral is bonded to the secondary neutral.

Three-Phase Service Drops

Some large farms use three-phase, four-wire service drops. These can be taken from either a three-phase primary wye or delta distribution system. Most commonly three transformers are used, one for each phase. The transformer windings are connected to form a wye. The three secondaries are also connected to form a wye, with the center point used for the neutral, thus yielding 120/208 V (fig. 2-16). Two or three transformers can also be connected to form an open or closed delta (fig. 2-16). One transformer has a center tap on the secondary side. The secondary neutral originates at this center tap and is bonded to the primary grounded neutral; both are grounded at the transformer pole. This service would provide single-phase 120/240 V, and three-phase 240 V. In combined single- and three-phase systems, a larger transformer is needed to accommodate the added single-phase 120/240-V load.

Additional Sources of Information

For additional information, see Surbrook and Reese (1981), Cloud et al. (1987), and Ludington et al. (1987).

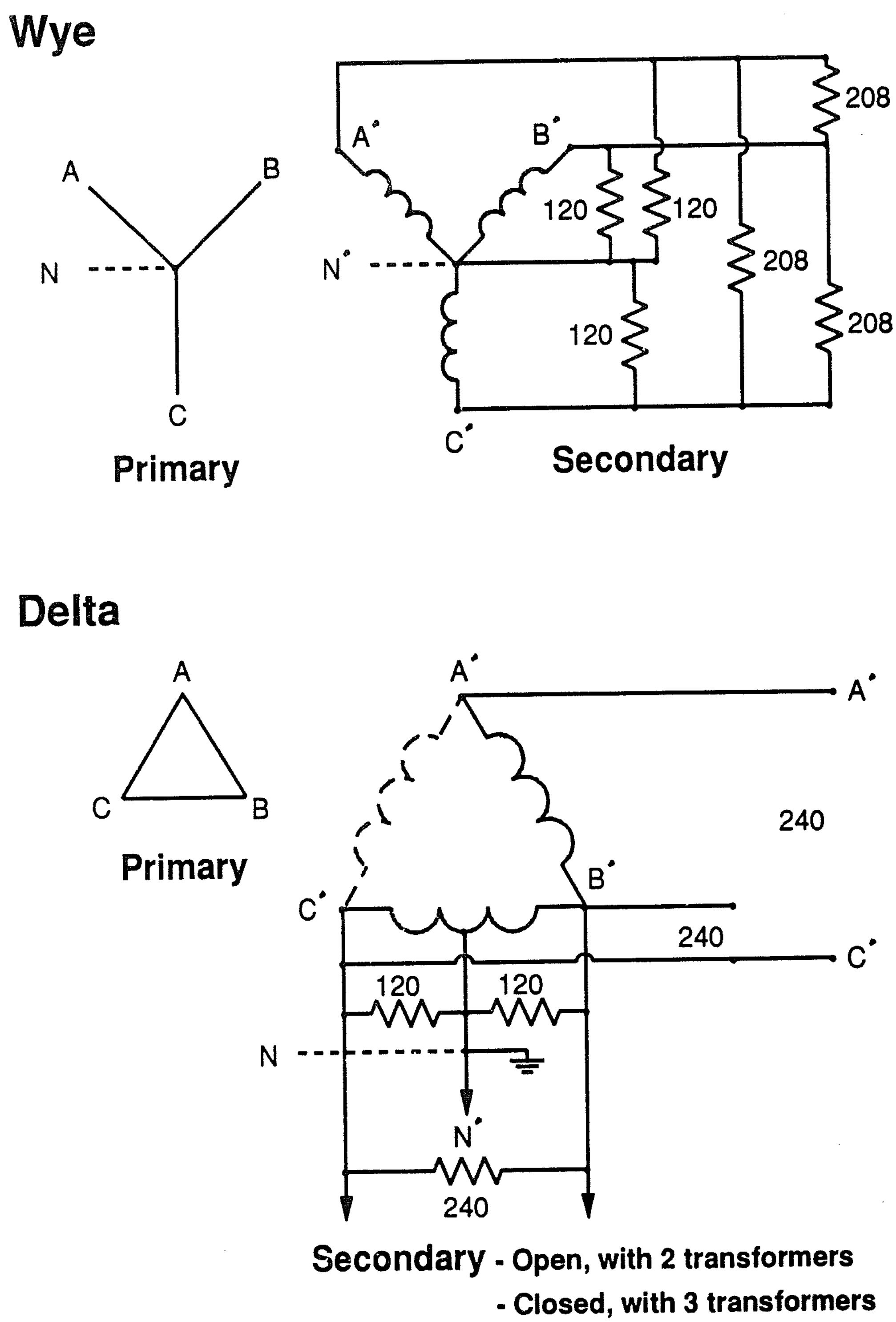


Figure 2-16. Single- and three-phase secondaries derived from (top) a wye distribution and (bottom) a delta distribution. If the delta distribution is an open-delta distribution, the third transformer shown with dashed lines is not used; hence the term "open."

History

While some knowledge of stray voltage has existed for many years, it was not until about 1982 that the national and worldwide nature of this phenomenon was recognized. Even when livestock problems were recognized, early solutions were not always fully effective and/or were not always satisfactory to both farmers and power suppliers. One of the challenges to solving stray voltage/current problems has been in persuading everyone involved to work as a team in diagnosing and solving the problems on the basis of a rational understanding of the factors involved. In the past these problems often caused frustration, since many, if not most, livestock farmers have little understanding of electrical distribution and farmstead wiring systems. At the same time, few electrical workers understood the behavioral and physiological responses of animals to small electrical currents. Furthermore, the importance of the farmers' reactions to these problems was not generally appreciated; i.e., their reaction to livestock behavioral changes associated with stray voltages/currents may create even more serious problems.

In 1948 an Australian researcher implied that current resulting from electrical equipment in the milking area may have affected cows negatively. Similar statements were published some years later in New Zealand. The first cases of stray voltage/current problems on the North American continent were reported in Washington State in 1969 and in Canada in 1975. These cases were assumed to be unusual and primarily a localized problem; thus, they received little attention and publicity in the popular press and trade journals. By 1982, numerous articles and news releases concerning stray voltage had been published. For example, Hoard's Dairyman — a popular magazine that most dairy farmers receive — published at least 12 articles, notes, or references related to the subject between 1980 and 1983. This period marked the beginning of national and worldwide recognition of stray voltage.

In the 1980's, physiological and behavioral responses of dairy cattle to electrical currents were quantified, and appropriate diagnostic and mitigation procedures were developed and adopted. Many dairy groups, including university Extension Services, conducted training sessions for persons with electrical expertise, held information sessions for producers and others providing support and assistance to dairy farmers, and established more uniform procedures for diagnosis and mitigation.

This handbook, prepared by many researchers with expertise in the field of stray voltage/current, consolidates this body of information.

Sources

Power in North America is distributed as alternating current at 60 cycles per second (Hz). In some parts of the world, electricity is distributed at 50 Hz. In terms of stray voltage, 50- and 60-Hz currents are essentially equivalent. In this text voltage (V) is assumed to be Vac (volts of alternating current) and measured as a root-mean-square (rms) value.

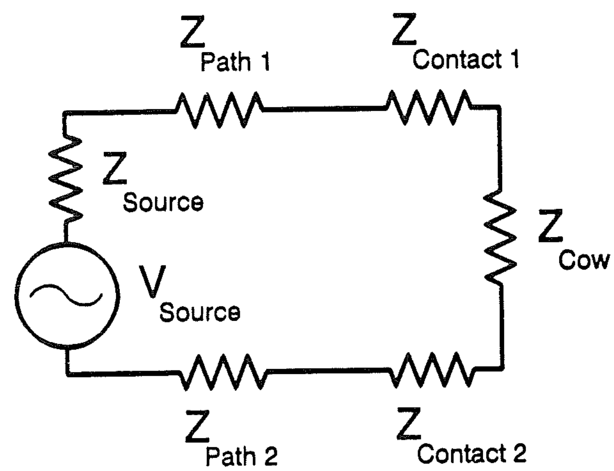
The most common source of stray voltage is an elevated neutral-to-earth voltage at the service panel, i.e., an elevated voltage on the neutral bus when that voltage is measured relative to an electrode placed in the earth. Neutral-to-earth voltages are a direct and unavoidable consequence of the mechanisms used to distribute electrical power. Even when no violations of the electrical codes exist, neutral-to-earth voltages may be sufficiently high as to be sources for stray voltages. Other possible sources include improper or faulty wiring, faulty electrical equipment, induced or coupled voltages, and static (capacitive) discharges. Often, these other sources result in increased neutral-to-earth voltages; and the elevated neutral-to-earth voltages, in turn, are then the sources for stray voltages. *Regardless of the voltage source, a conductive path between the voltage source and an animal must exist before a possible problem can become a real stray voltage/current concern.*

Animal Contact

Stray voltage exists only when a voltage appears across two points that an animal can contact, i.e., the animal must become part of an electrical circuit that conducts sufficient electrical current to cause a deleterious response by the animal. The circuit consists of the voltage source, a conductive path from the voltage source to the animal, contact between this path and the animal, the animal, contact between the animal and a return path, and the return path from the animal back to the voltage source. Each component of the circuit has its own impedance. The sum of these impedances, i.e., the impedance of the circuit, determines the amount of electrical current that will result from a given source voltage. The current is calculated by use of Ohm's law, which states that current (I) equals the voltage (V) divided by the total circuit impedance (resistance) (Z). In the example above (fig. 7-1), the total circuit impedance is the sum of all the individual circuit impedances. It is important to determine current because animals respond to the current generated by a voltage and not to that voltage directly: the higher the impedance of the circuit (and the higher any individual impedance, as total impedance is the sum of individual impedances), the lower the current and the less likely that the animal will be affected.

Cicuit Impedances

The most common stray voltage/current problem is the presence of a voltage relative to earth on a metallic object, such as a bar on a stanchion. The return path is the earth itself, and a circuit is completed when the animal touches both the object and the floor (earth). The impedances of the pathways to and from the animal vary considerably depending upon individual circumstance. The contact impedance between the animal and the floor is likely to be low if the floor is wet and covered with manure. The impedance of cows varies from cow to cow and depends on the points of contact. Estimations of cow contact plus body impedances depend on how measurements were made; estimates range from 250 to 3,000 ohms (table 7-1).



Series Impedance =

$$Z_{Source} + Z_{Paths} + Z_{Contacts} + Z_{Cow}$$

Figure 7-1. An equivalent electrical circuit showing the elements that must be in place for a stray voltage problem to exist. V is the voltage source and Z's are circuit impedances. Current equals V divided by series impedance.

The contact impedance between the electrified object and the animal will also vary. This contact impedance plays a very important role in determining the impact of the stray voltage/current problem. Consider for a moment a person standing barefoot in manure and grabbing a bare wire carrying 120 V relative to earth. The funeral is next Monday. If that person had been wearing dry, insulating rubber gloves, he/she would still be alive today. Even if the person had been wearing such gloves, a circuit would have been completed when the wire was grabbed; however, the high impedance of the gloves would have limited the current flowing through the body to a safe level. Thus, even if an animal contacts an electrified object, a problem will exist only if the contact impedance is low enough to allow a significant current to flow through the animal. The contact impedance between dry hair and an electrified object can be quite high. In contrast, the contact impedance between the tongue and a metal watering bowl is low.

Table 7-1. Resistances of various electrical pathways through the cow[1]

Pathway	n[2]	Resistance Mean (ohms)	Resistance Range (ohms)	Current Frequency (Hz)	References
Mouth to all hooves	70	350	324-393	60	Craine et al. 1970
	28	361	244-525[3]	60	Norell et al. 1983
Mouth to rear hooves	28	475	345-776[3]	60	Norell et al. 1983
Mouth to front hooves	28	624	420-851	60	Norell et al. 1983
Front leg to rear leg	5	300	250-405	60	Lefcourt, 1982
	13	362	302-412	60	Lefcourt et al. 1985
Front to rear hooves	28	734	496-1152[3]	60	Norell et al. 1983
Rump to all hooves	7	680	420-1220	50	Whittlestone et al. 1975
Chest to all hooves	5	980	700-1230	50	Whittlestone et al. 1975
	?	1000	?	50	Woolford, 1972
Teat to mouth	28	433	294-713[3]	60	Norell et al. 1983
Teat to all hooves	28	594	402-953	60	Norell et al. 1983
	4	880	640-1150	50	Whittlestone et al. 1975
Teat to rear hooves	28	594	402-953[3]	60	Norell et al. 1983
Teat to front hooves	28	874	593-1508	60	Norell et al. 1983
All teats to all hooves[4]	6	1320	860-1960	50	Whittestone et al. 1975
	?	1000	?	50	Phillips et al. 1963
Udder to all hooves	12	1700	650-3000	60	Henke Drenkard et al. 1985

[1] Adapted from Appleman and Gustafson (1985b).
[2] Number of animals.
[3] Ranges given are for 10-90% percentile, or percent of cows with measured resistance between the reported limit.
[4] Measured during milk flow.

It is impossible to quantify the total circuit impedance for all conditions and situations. For evaluation purposes, it is often sufficient to consider the worst case impedance, i.e., the lowest circuit impedance possible, and a more realistic impedance, i.e., the lowest circuit impedance likely to be encountered. For the worst case circuit impedance, the assumption is made that the source and all path impedances are zero, an extremely unlikely occurrence. The worst case impedance then becomes the sum of the contact and animal impedances. From experimental tests and field experience, we consider 500 ohms to be a very conservative estimate of this worst case impedance.

Table 7-2. Estimates of worst case and realistic circuit impedances for translating currents to voltages

	Impedances (ohms) Path + Source	Contact + Animal	Total
Worst case	0	500	500
Realistic	500	500	1000

We also consider 500 ohms to be a conservative estimate of total source and path impedances. Adding these two impedances results in an estimate of 1,000 ohms for the more realistic impedance (table 7-2).

Neutral-to-Earth Voltages

Neutral-to-earth voltages are a consequence of the mechanisms used to distribute electrical power, notably, the periodic connection of specific wires with the earth (ground) to allow electric faults and lightning strikes to be dissipated in the earth with minimal harm. Excessive neutral-to-earth voltages can result from normal interactions in the electrical power distribution system, as well as from flaws in the electrical system. Neutral-to-earth voltages approach zero only under unusual circumstances.

Factors which normally affect neutral-to-earth voltages on a specific farm are voltages and phases in distribution lines, type of distribution transformer(s), load balance along the distribution lines and within farms, impedance of the earth, and impedances of wires and connectors within the electrical distribution system. Because of the complexity of the interaction of these variables, it is tempting to try to classify problems as "on-farm" or "off-farm." Unfortunately, this is not really possible. Often problems are the result of interactions between on-farm and off-farm factors. However, in the majority of cases, excessive neutral-to-earth voltages are the result of flaws in the electrical system which can be either off-farm, e.g., a high-impedance distribution neutral wire, or on-farm, e.g., an electrical fault on the farm (or on an adjacent farm).

Determining the actual source(s) of an elevated neutral-to-earth voltage requires specific knowledge of local on-farm and off-farm electrical systems as well as a thorough understanding of electrical power distribution systems in general.

Leakage or Coupled Sources

Because it is usually moist and dirty, the farm environment often leads to the development of leakage paths across normally insulating structures. These leakage paths almost always have a high resistance; however, a meter with a high input impedance may measure voltages across these paths. Capacitive coupling between circuits and/or structures may also lead to the existence of measurable voltages. To differentiate between a true problem voltage and a high resistance leakage/coupling source, it is necessary to place an electrical load across the two points of contact. A 1-kohm resistor is an appropriate load (chapter 5, "Detection and Measurement").

Physiological and Behavioral Effects

Cows and humans appear to be equally sensitive to electric current; i.e., both respond similarly to similar current levels flowing through their respective bodies. However, cows are much more susceptible to stray voltages because the body impedances (resistances) of cows are much lower than those of humans. In accordance with Ohm's law, therefore, a given voltage across a lower body impedance results in a larger current.

One critical problem faced by stray voltage researchers was to determine the current levels that can be perceived by cows and, more importantly, the levels that cause irritation and economically significant physiological or behavioral responses.

Because cows cannot tell a researcher when they perceive a current, researchers looked at responses they could measure, such as physiological responses or changes in behavior. They found that the magnitude of current needed to elicit minimal behavioral responses in cows is very similar to the lowest currents that can be perceived by humans. The lowest current which causes a detectable change in behavior varies from cow to cow and depends to a lesser degree on the points of contact, e.g., mouth to four hooves or front leg to rear hock. Similar variations are found for perception in humans.

The voltage needed to deliver these currents depends on the body impedance of the cow, the contact impedances between the cow and the con-