Overview of Stray Voltage

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Introduction

There is no such thing as *stray voltage* in a physics sense. It is neither mysterious nor sinister nor stray. What is called stray voltage is a consequence of the laws of physics that apply whenever electrical apparatus is grounded for reasons of safety or fire prevention.[1]

Stray voltage is used in the dairy industry to describe the small voltages that exist at animal contact locations that are related to the delivery and use of electricity on the farm. The term has come into use in a very general sense to describe the wide variety of voltages from both power and non-power sources that may exist at locations that may be contacted by both people and animals in publicly and privately accessible locations. Because of the confusion engendered by casual use of the term, there is an effort in an IEEE committee to develop a more careful definition, including distinguishing between *stray voltage* and something different called *contact voltage*. This work on definitions is ongoing at the present time.

The dairy industry has historically used *stray voltage* to describe voltages that appear in farm locations between objects where voltage would not normally be wanted or expected to be found. These voltages result from normal operation of the electricity delivery and utilization system both on and off the farm. In dairy industry usage, stray voltages can be enhanced by various situations that are

abnormal and correctible, such as poor insulation or wiring errors. It is in this sense that the term *stray voltage* is used in this document (and this is the way it is used in the referenced sources). This concept of stray voltage does not include voltages that occur on an object as the result of an accidental direct connection to an energized electrical conductor, such as a contact between a wire and street light post.

The subject of stray voltage on dairy farms has received considerable attention for the past 30 years or more, especially for its appearance where small contact voltages have been linked to deleterious effects on cow health and milk production.

The subject of stray voltage on dairy farms has received considerable attention for the past 30 years or more, especially for its appearance where small contact voltages have been linked to deleterious effects on cow health and milk production. The response threshold for some cows has been reported to be as low as 1 volt,[2 3] while others have considered contact voltages on the order of 4 volts to be the threshold of harmful effects.[4] Stray voltage has been the subject of symposia sponsored by universities, electric power suppliers, and government agencies.[5] A U. S. Department of Agriculture agricultural handbook is devoted to stray voltage,[6] and other publications dealing with stray voltage and its effects have been issued by universities,[7] utilities,[8] and state government agencies.[9]

In order to be meaningful, the quantity of interest in any discussion of stray voltage is the difference in voltage between two locations, not some arbitrary value without respect to something else. For example the 120-volt difference between the two slots on a wall outlet is a voltage of considerable significance. When current flows in the earth, it may result in a voltage difference between two objects (grounded objects) connected to the earth at different places. When this voltage difference can be contacted by a person or animal, it results in a current flow in the person or animal's body, which might or might not be perceptible.

Step and Touch Voltages

Electric current flows through a person or animal when two parts of the body contact objects at different voltages, thus creating a current flow.

Electric current flows through a person or animal when two parts of the body contact objects at different voltages, thus creating a current flow. If the current is above some threshold, the person or animal will perceive the current and may, in extreme cases, experience a shock. The amount of current that flows through the body depends on the voltage and the nature of the circuit in which the current flows. In situations involving stray voltage on dairy farms, the issue is *perception* of electric current as opposed to potentially injurious situations.

A person may also experience a more serious electric shock by simultaneously touching two things at the same time that have different voltages. This might be a metallic part of a building and a power tool with defective insulation or a defective safety ground. One of these contact points may be the earth; however, good shoes will provide some protection. Fatalities or injuries in swimming pools or bathtubs can occur because one contact is through the water while the person is touching some piece of electrical equipment. Because touch is involved, these are examples of *touch voltages*. A less common—but still real—possibility is contact of each of a person's feet with earth at different voltages. This is called *step voltage* and can be a danger in close proximity to power line faults or lightning strikes.

In cases of stray voltage on dairy farms, cows can perceive an electric current result-

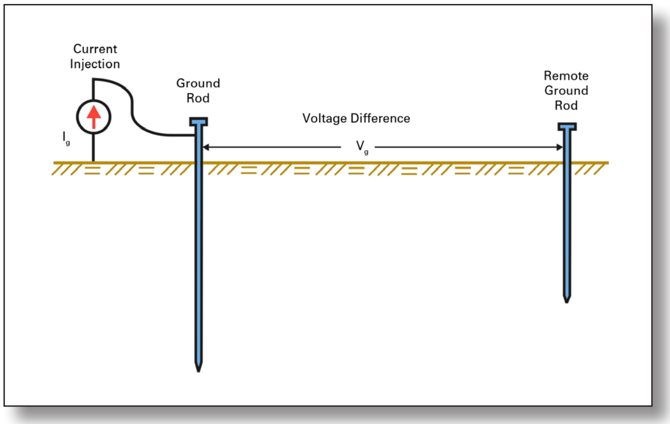

Figure 1. Ground rod voltage

In cases of stray voltage on dairy farms, cows can perceive an electric current resulting from touch or step voltages.

ing from touch or step voltages. Because cows do not wear shoes and often stand on wet earth, they have a better connection to ground than people normally do. Cows can experience an electric current when touching a metallic object at a different voltage from where they are standing. Cows can also perceive an electric current between their front and back hooves if there is current flow in the earth, resulting in a surface potential distribution. An extreme form of step potential for cows is responsible for the death of cows in thunderstorms when lightning strikes the ground (for example, near a tree) close to where the cows are standing.

Ground Connections

The simplest ground electrode is a single driven rod. Because of the finite conductivity of soil, there is a non-zero resistance, called the grounding resistance, between the rod and remote earth.

The simplest ground electrode is a single driven rod. Because of the finite conductivity of soil, there is a non-zero resistance, called the grounding resistance R_g, between the rod and remote earth.[10] If a current I_g flows into the ground rod for whatever reason, the rod takes a voltage $V_g=I_gR_g$, which can be measured by connecting a voltmeter between the ground rod with the injected current and a remote ground rod as shown in Figure 1. (This simplified discussion assumes no induced voltage in the voltmeter connecting leads.)

Aspects of grounding of electricity supply are covered in the National Electrical Code (NEC)[11] and in the National Electrical Safety Code (NESC).[12] Customer service entrance grounding procedures, including application of ground rods and grounding to water supply pipes, are covered by the NEC. These requirements to protect life and property are well established and were mostly in place at the time of the 1913 revision of the NEC.[13] Grounding requirements on the power company's facilities are covered by the NESC.

Mechanisms for Perception of Electric Current

The mechanism of electric current flow in the body is illustrated in Figure 2. Here, a current flowing in the earth causes the voltage of a conducting post mounted in the ground and touched by a person to be different from the point on the earth touched by the person's foot. Current flows in the circuit consisting of the earth, the post, the connections between the person and ground and post, and the person. This creates the possibility of sufficient current flow to be perceptible. The current in the earth in Figure 2 could also produce an electric current in the person without their touching the post if some of it flows up one leg and down the other. The post could also have a different

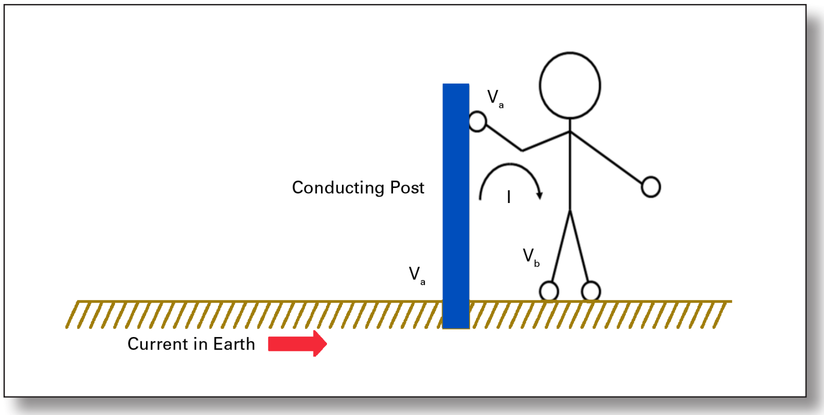

Figure 2. Possible electric current path in the body

voltage from the nearby earth if it were insulated from earth but had an electrical connection to something a distance away.

The voltage differences illustrated in Figure 1 and Figure 2 can appear in several ways:

Transfer of potential (voltage) happens when a conducting path exists from the ground electrode to a location some distance away.

- Transfer of potential (voltage). This happens when a conducting path exists from the ground electrode to a location some distance away. For example, a pipe with an insulating coating that is grounded at one end can have a voltage with respect to another object that is grounded at a different location.
- Step potential (voltage). Because of the current flow from the grounding electrode into the earth, a voltage distribution occurs on the earth's surface. A person standing with their feet spread apart can bridge a portion of this voltage difference.
- Touch potential (voltage). An example of a touch potential for the situation shown in Figure 2 is a person standing on the earth touching a metal fence. If there is current flowing in the fence ground, the fence would have a different voltage from the earth the person is standing on. Another example is when a person touches two different supposedly grounded objects that are not bonded together and are at different voltages.

These three mechanisms to produce a voltage difference that can result in electric current flow in the body are shown in Figure 3. In each case, the dotted line in the figure shows the path of electric

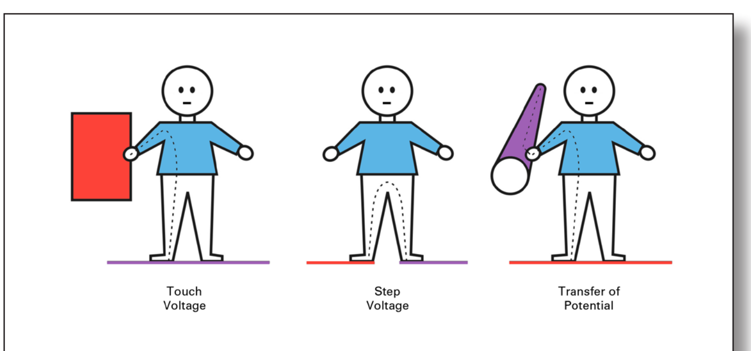

Figure 3. Touch voltage, step voltage, transfer of potential

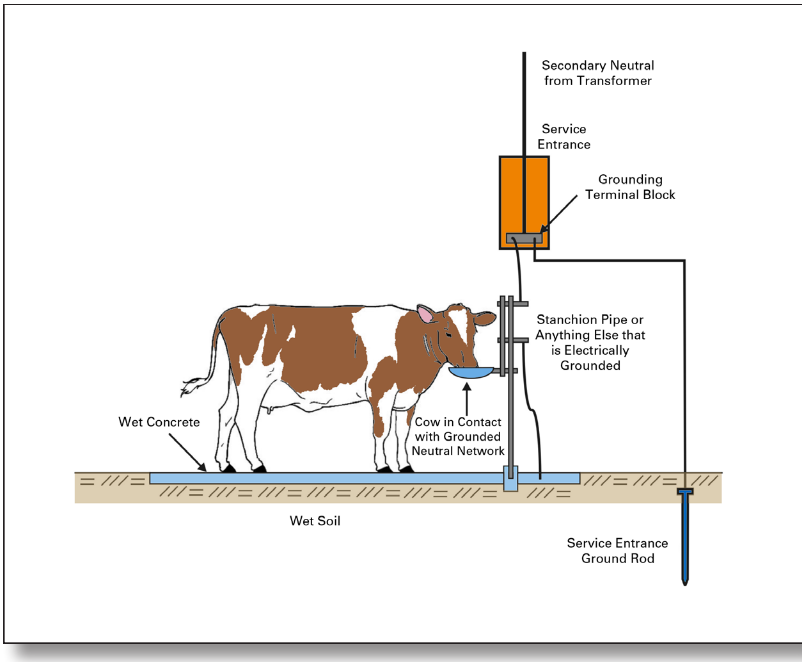

Figure 4 . Electrical contact for a cow

current: hand-to-foot for touch voltage, foot-to-foot for step voltage, and hand-to-foot involving a connection that is a distance away for transfer of potential.

Dairy cows can also experience a voltage in three different ways.

Dairy cows can also experience voltage in each of these three ways. They can be standing on moist earth and touching something metallic, such as a water bowl (touch potential). The water bowl might be energized from something that is a distance away (transfer of potential). This is illustrated in Figure 4, where the water bowl is at a different voltage from the concrete floor due to a connection back to the farm service entrance ground. The cows might have their front hooves on earth at one voltage and their rear hooves on earth at a different voltage (step potential). This has sometimes been observed in cows' reluctance to enter the milking parlor. In each case, what is significant is the contact voltage, whether it involves a person or animal. Because of the complexity of current paths in the earth, contact voltage may be significantly less than voltage from the electrical system neutral to remote earth.

The criteria for the perception of electric current for people are related to the electric current flow in the body.

The criteria for the perception of electric current for people are related to the electric current flow in the body. Threshold levels for human perception of 60-Hz contact currents are shown in Table 1.[14] Although cow threshold levels of perception are also related to current, the threshold levels for cow response are normally specified in terms of contact voltage, usually in the range of 1–4 volts.[3, 4]

Table 1. Human perception of electric current

Description	Women	Men
Touch perception for 1% of subjects	0.09 mA	0.13 mA
Grip perception for 1% of subjects	0.33 mA	0.49 mA
Touch perception for 50% of subjects	0.24 mA	0.36 mA
Grip perception for 50% of subjects	0.73 mA	1.10 mA

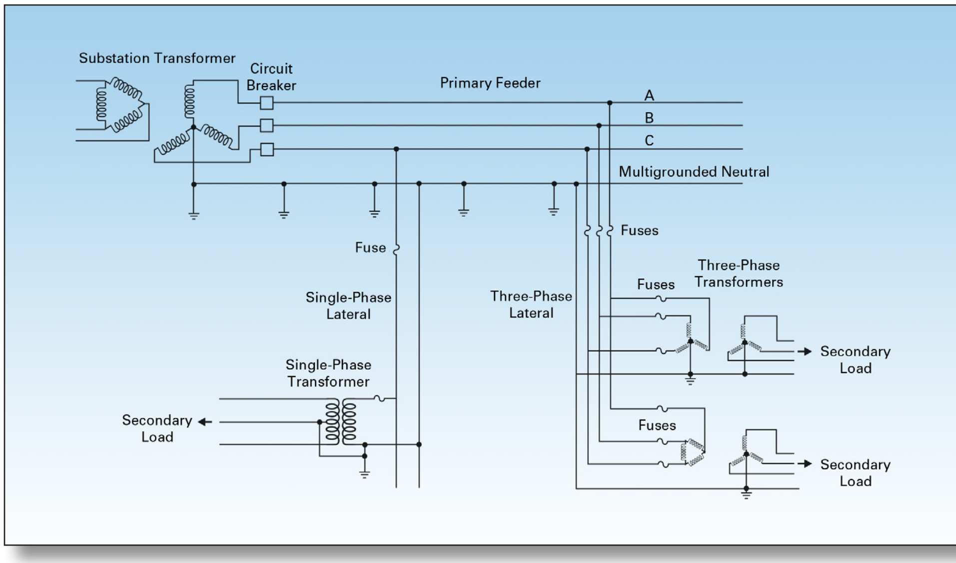

Figure 5. Multigrounded neutral feeder

The Multi-Grounded Distribution Feeder

The most common type of distribution feeder in the United States is the four-wire multigrounded feeder.

The most common type of distribution feeder in the United States is the four-wire multigrounded feeder, which is illustrated in Figure 5.[15] The multigrounded system has a number of advantages, including safety and cost. The feeder circuit consists of the three primary phase wires and a neutral wire. The neutral wire is grounded at numerous locations including at transformers that are supplying customers. The neutral wire serves as a safety ground and carries unbalanced phase current. Single-phase loads are supplied between one of the primary wires and the neutral wire with current return in the neutral. An attempt is made to connect single-phase loads equally to the different primary phases to balance the loads, but some unbalance current continues to flow in the neutral wire. The amount of this neutral current is affected by the conductor size and the presence of harmonics in the load current.

Current flowing in the neutral circuit divides between the neutral wire and earth with some current flowing in the wire and some in the earth.

Because the neutral wire is connected to earth at numerous locations, current flowing in the neutral circuit divides between the neutral wire and earth with some current flowing in the wire and some in the earth. This splitting of the current through different paths results in current flowing to earth in the ground rods or other ground connections. Current flowing in the various ground connections causes the neutral voltage not to be exactly zero at a customer's service entrance, which is the location where the user takes electricity from the utility including the main circuit breaker panel board (Figure 6). This neutral voltage may appear in ways similar to that shown in Figure 1.

Service Entrance Grounding

Most electricity customers take what is called *secondary service* because they are connected to the low voltage or secondary side of the power company's supply transformer. Large users might connect to the high voltage or primary side of the power company feeder, but secondary service is much more common. A typical single-phase secondary supply in the United States is a three-wire 120/240 volt connection that consists of two energized (hot) wires and a neutral wire. Between either of the hot

Figure 6. Electrical Panel showing the ground lead at the upper left

wires and the neutral is 120 volts, and it exists in such a way that 240 volts exists between the two hot wires.

Several forms of three-phase service are available; the most common in the U.S. is a 120/208-volt four-wire service consisting of three hot wires and a neutral wire. Between any hot wire and the neutral wire is 120 volts, and 208 volts exists between any pair of hot wires. The neutral wire is required to be grounded at the customer service entrance for either single- or three-phase service. Figure 6 shows a typical electrical panel with the ground connection at the upper left.

Current flows in the neutral wire due to unbalance in the current on the hot wires.

Current flows in the neutral wire due to unbalance in the current on the hot wires. For example, current in a 120-volt light bulb returns in the neutral wire unless cancelled by a current from the other hot wire(s). Some of this neutral current might flow to earth in the service entrance ground

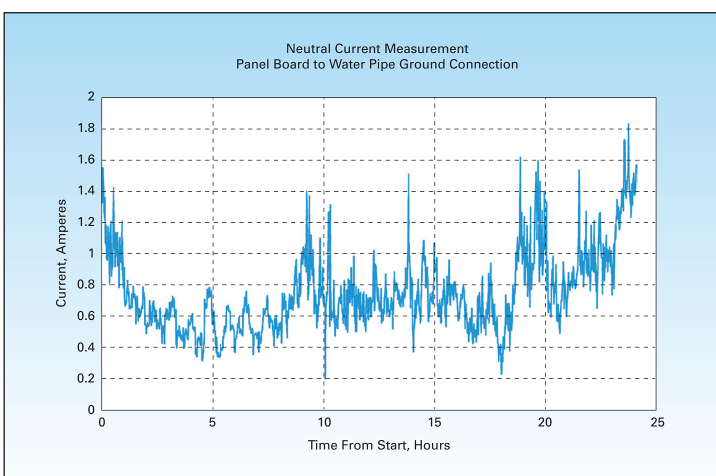

Figure 7. Current from the electrical panel to ground

depending on a number of factors, including the neutral wire size and the resistances to earth in the ground connections. When supplied by a multigrounded primary feeder, an NESC provision calls for the primary and secondary neutral grounds to be connected together for safety reasons.

A consequence of this is that the primary side can, in effect, be partially grounded by the earth connection on the secondary side. Current flowing in the primary neutral wire can go to earth at the customer's service entrance, thus raising the local service entrance neutral circuit to remote earth voltage. Figure 7 shows a measurement of current in the ground lead that was shown in Figure 6 over a 24-hour period starting in the evening. Most of this current is from the primary feeder.

Paths for Electric Current to Enter Earth

In addition to the deliberate safety grounds at the customer service entrance and on the primary feeder, there may be other ground connections where equipment metallic housings are themselves connected to ground in one way or another as shown in Figure 8. These additional ground connections provide parallel paths for current to enter the earth. There are also ways for the load current to return in the earth rather than in the neutral wire as it is supposed to. The two most common are wiring errors and defective insulation.

In addition to the deliberate safety grounds at the customer service entrance and on the primary feeder, there may be other ground connections where equipment metallic housings are themselves connected to ground in one way or another.

As an example of wiring errors, single-phase 120-volt branch circuits (the user's individual circuits connected to their own fuses or circuit breakers) contain both a neutral (white) wire and a safety ground (green) wire, which are to be connected only at the electrical panel. The white wire connects to the longer blade on an electrical outlet, and the green wire goes to the round connection on the outlet. When something is plugged in, the current comes from the panel board to the outlet in the hot (black) wire and returns to the panel board in the white wire. It is not uncommon to find wiring errors that result in current returning in the green wire and/or in parallel conducting paths such as building steel, reinforcing rods, or the earth itself, instead of just in the white wire as is supposed to happen. There are also occasions where the neutral wire has been deliberately used as part of the

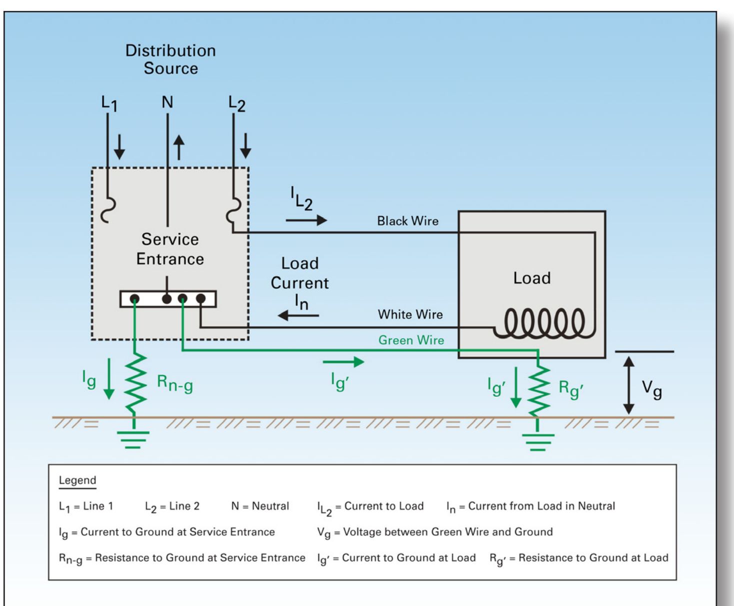

Figure 8. Multiple ground connections

safety grounding, which was allowed in older codes or code exceptions. While not strictly a wiring error, the effect is the same in that current flows in the safety grounding wires where it is not normally wanted.

A related situation might be the use of an insufficiently large neutral wire to carry the current without an excessive voltage drop that might appear as a voltage difference between two supposedly grounded objects. The possibility of a too small neutral wire has increased with the proliferation of computers, energy efficient lighting, and other applications that cause significant harmonic s in the line current that, in some cases, may increase the current in the neutral wire beyond its original design capacity.

An electric motor with faulty insulation is an example of defective equipment that could cause current to flow in the earth or metallic objects not intended to be part of the electrical circuit. Sufficient current may flow to ground through the motor housing to cause a voltage drop in the ground connection, but not sufficient current to operate the circuit protective device.

Any of these mechanisms may result in current getting into the earth by different paths, resulting in voltage differences between objects grounded in different locations that could give rise to situations that could or would lead to stray voltage. These ground connections may be either deliberate, as with a driven rod, or accidental, such as through a motor housing and whatever the motor is mounted on. Many so-called stray voltage problems on dairy farms can be traced to multiple grounds, wiring errors, or defective insulation.

An additional consideration, especially in farms, is corroded or poorly conducting connections in the neutral or ground current path that may increase the electrical resistance of the path.

An additional consideration, especially in farms, is corroded or poorly conducting connections in the neutral or ground current path that may increase the electrical resistance of the path. Moisture on farms can lead to corrosion and inadequate electrical conductivity and result in current being diverted into the earth.

Where Unexpected Voltages May Appear

The important consideration in dealing with unexpected voltages is not the voltage at one location, but the contact voltage that can be experienced by a person or animal contacting two things at once. Voltage is really a meaningful concept only as the difference of potential between two locations. The entire body can be at a high voltage without any perception of electric current if the entire body is at the same voltage. What is important is the difference in voltage between two locations on the body that results in a current flow in the body, such as the step and touch potentials described earlier.

Voltages can appear between different objects that are supposedly grounded as a result of current flowing to ground in various places through their individual grounding resistances. Figure 9 shows a 24-hour measurement, starting in the evening, of the voltage difference between the panel board ground wire shown in Figure 6 and a ground rod about 40 feet (12.2 m) away. No current was flowing in the remote ground rod. If current had also been flowing in this rod, the measured voltage could have been considerably higher.

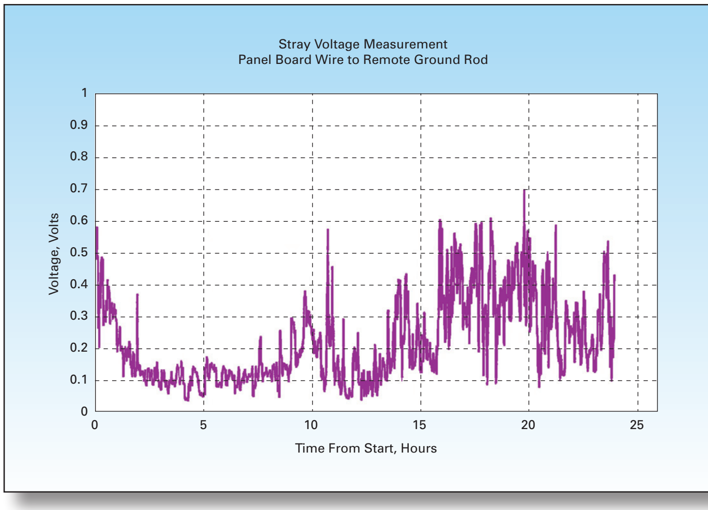

Figure 9. Voltage between electrical panel neutral and remote ground rod

Voltages can appear between different objects that are supposedly grounded as a result of current flowing to ground in various places through their individual grounding resistances.

An example similar to the situation described in Figure 9 with much higher voltages occurred in a residence many years ago. In this case, the problem was seriously annoying levels of electric current that were felt while the customer was in the shower. Service entrances have historically been grounded to metallic water pipes where they enter the building, and since 1965, also to one or more additional ground electrodes.

In this situation, the service entrance was properly grounded, but for some unusual reasons, an abnormal amount of primary feeder neutral current was flowing to earth in this customer's service entrance ground. This amount of current resulted in an abnormally high voltage difference between the water pipe to the residence and remote ground—in this case, the drain pipe. The shower drain was connected to the septic tank through a pipe that was not electrically connected to the water supply line. The resulting effect was that the voltage at the service entrance ground showed up as a voltage difference between the shower head and the drain.

In a dairy farm, the important voltages are the voltages that a cow can contact at the same time.

In a dairy farm, the important voltages are the voltages that a cow can contact at the same time. These voltages include the voltage difference between a water bowl and the ground where the cow is standing and the voltage difference between the milking machine and the milking parlor floor. As previously mentioned, step voltages have been observed as having an effect on a cow's willingness to enter the milking parlor.

Power Transmission, Distribution, and Utilization

The stray voltage issue as it relates to normal operation of the electricity supply system is one of currents in the distribution circuit paths through the earth and parallel conducting paths. These currents can arise from

normal primary and secondary neutral currents because the neutrals are grounded according to code, or they can arise from wiring errors or defective equipment on the customer side.

Stray voltage is not normally a power transmission issue because transmission line structure grounds are not generally connected to the distribution line grounds.

Stray voltage is not normally a power transmission issue because transmission line structure grounds are not generally connected to the distribution line grounds, and little current flows in transmission structure grounds except during faults. The rare exception to this general observation is where transmission and distribution lines run parallel for long distances. When there is a long parallel, it is possible that the transmission line induces current in the distribution line neutral wire. It is also possible that current flow in the earth, resulting from normal transmission line operation, may also partially flow in the distribution line neutral wire. If this distribution line serves a farm, it is possible that the resulting neutral voltage could cause a stray voltage problem on the farm, but this would be a very uncommon situation.

Measuring Stray Voltage on the Farm

The procedure for detecting and measuring stray voltage is well documented.[16] Care must be applied in making measurements in order to obtain valid results and to ensure the safety of the individual taking the measurements.

Actual cow contact voltage is often less than the simple voltage between neutral and remote earth.

Actual cow contact voltage is often less than the simple voltage between neutral and remote earth for two reasons. First, the electrical circuit for contact voltage can be more complicated than simply the local neutral or local ground voltage with respect to other locations or remote earth. Parallel metallic structures, such as fences or piping, can carry some of the current, for example, and reduce the contact voltage. For this reason, it is important to take stray voltage measurements that are representative of the voltage difference between two points that the cow may actually contact.

The second reason that the cow voltage is often less than the simple voltage between neutral and remote earth is the effect of the electrical resistance of the cow itself on the contact voltage. To correctly account for the impact of the cow on the electrical circuit stray voltage, measurements are commonly taken with a 500-ohm resistor in parallel with the voltmeter.

Mitigation Methods

Several methods can be applied to mitigate stray voltage concerns on dairy farms:

1. Replacement of defective equipment and correction of wiring errors is paramount.
2. Improved grounding using more ground rods and ones that are longer can reduce voltages on grounded objects.
3. Bonding of metallic structures can be used to form equipotential surfaces to reduce possible contact voltages.

4. In some cases, the primary and secondary neutral circuits are separated at the supply transformer. This separation reduces the effect of primary neutral current on stray voltage, but it requires special equipment to meet code requirements for safety.
5. Special equipment is sometimes applied for injection of current into the ground using an active system to cancel the current causing the stray voltage.

6. Increasing the neutral wire size either on the farm itself or on the power company's supply wiring can occasionally direct a larger fraction of current from earth into the neutral wire and reduce stray voltage.

Summary and Conclusions

Stray voltage on dairy farms is primarily related to electrical current in wiring on the farm and the power company's distribution system that supplies the farm. Very rarely is it found to be caused by the power company's transmission system.

Stray voltage, as understood in the dairy industry, is a consequence of physics. It is not mysterious. It is a natural result of current flowing in ground paths and voltage drop in the resistance of grounding electrodes and wiring. While this ground current may be enhanced by wiring errors or defective equipment, it can also be found in cases of good equipment and wiring that is fully up to code as a natural consequence of proper operation of the electrical system. Mitigating methods are available, but they need to be carefully applied on a case-by-case basis.

Stray voltage on dairy farms is primarily related to electrical current in wiring on the farm and the power company's distribution system that supplies the farm. Very rarely is it found to be caused by the power company's transmission system.

For further information see:

- Doug Dorr and Bill Howe, "Understanding Nuisance Shocking," EPRI *PQ Tech Watch*, March 2005.
- "Shocking Circumstances," EPRI *Distribution Dispatch*, 1019565, Third Quarter 2009.

Glossary

branch circuit—Wiring in a residence or on a farm fed through an individual fuse or circuit breaker that supplies lights, outlets, and connected appliances.

contact voltage—Voltage experienced by a person or animal that is contacting two different objects at the same time.

hot wire—The energized wire, usually black or red, that is supplying an outlet, light, or connected appliance.

multigrounded system—The common power company distribution circuit design where the neutral wire is grounded at multiple locations, usually at least at each transformer.

neutral—The part of the electrical system connected to ground that is used as part of circuits on both the customer's and power company's facilities.

neutral voltage—A voltage difference between neutral wires and the neutral connections at the panel board and remote earth that results from current flow in the neutral wiring, earth, and parallel electrically conducting paths.

neutral wire—On the customer's property, the white wire that carries current from outlets, lights, and connected appliances back to the panel board; on the power company side, a singly or multiply grounded wire that is part of the feeder circuit.

panel board—The box containing fuses or circuit breakers and its contents and wiring.

phase—An energized wire where the alternating (ac) voltage has a particular time relationship to some reference. Primary feeders and service to customers may be either single or three phase.

primary feeder—The high-voltage portion of the distribution system that supplies the transformers at load locations.

remote earth—A location far enough from the point where a voltage is being measured where the reference voltage can be considered to be zero.

safety ground wire—The green wire that is not intended to normally carry current that connects the panel board to outlets, lights, and connected appliances.

secondary service—Electrical connection to a customer at low voltage (under 600 volts).

service entrance—The connection of a customer to the power company, including the meter, panel board, and ground electrodes.

Stray voltage, as used in the dairy industry, is a term that is loosely applied to describe a voltage difference between objects where a voltage would normally not be expected to be found and/or is not wanted.

stray voltage—As used in the dairy industry, a term that is loosely applied to describe a voltage difference between objects where a voltage would normally not be expected to be found and/or is not wanted. These voltages result from normal operation of the electrical system and can be enhanced by defective insulation or wiring errors. Stray voltage does not include voltages that occur on an object as a result of an accidental direct connection to an energized electrical conductor.

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Stray voltage as understood in the dairy industry is a consequence of physics. It is not mysterious.

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