

IEEE Guide to Understanding, Diagnosing, and Mitigating Stray and Contact Voltage

IEEE Power and Energy Society

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IEEE Guide to Understanding, Diagnosing, and Mitigating Stray and Contact Voltage

**Transmission and Distribution Committee
of the
IEEE Power and Energy Society**

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Abstract: Voltage conditions that may arise at publicly and privately accessible locations as a result of the delivery and use of electrical energy are addressed in this guide. This guide is not intended for use as a statement of cause and effect. It focuses primarily on the presence of power frequency related voltage conditions and discusses definitions, sources, testing techniques, and strategies that may be available to help reduce those conditions.

Keywords: contact voltage, IEEE 1695™, stray voltage

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Introduction

This introduction is not part of IEEE Std 1695-2016™, IEEE Guide to Understanding, Diagnosing, and Mitigating Stray and Contact Voltage.

For many years the term stray voltage had been primarily used to discuss the power frequency voltages present at animal contact locations in and around animal confinement facilities. With the widespread availability of inexpensive and user friendly voltage measurement and recording devices, there has been a growing awareness that the general public and their pets are also regularly exposed to these voltages at many publicly and privately accessible locations. Until recently there has been little recognition of the important difference between the presence of small voltages related to normal electrical system operation (customer and utility) and the presence of potentially harmful and even lethal voltages related to un-cleared electrical faults. This guide has been created because there are few easy to understand public documents that describe the phenomena, their causes and effects, and actions that may help identify and reduce potentially dangerous voltage conditions.

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1. Overview

1.1 Scope

This guide addresses voltages that exist at publicly and privately accessible locations as a result of the delivery and use of electrical energy. This guide is not intended for use as a statement of cause and effect. It focuses primarily on the presence of power frequency related voltages and discusses definitions, sources, testing techniques, and mitigation strategies.

1.2 Purpose

While some jurisdictions have implemented local rules concerning stray and contact voltage, there is presently no industry-wide guide or standard that describes the variety of publicly and privately accessible voltages resulting from the delivery and use of electrical energy. The purpose of this guide is to provide information regarding the potential for risk and recommend actions taken in respect to the presence of either stray or contact voltage. This guide is also intended to help dispel misinformation surrounding this topic and enhance public safety.

2. Definitions, abbreviations, and acronyms

2.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* can be consulted for terms not defined in this clause.¹

contact impedance: The impedance between any two conductive objects making contact (e.g., test probe and lamp post, cow muzzle and water bowl). Because contact impedance is primarily resistance at extremely low frequency (i.e., 1 Hz to 300 Hz), this term is often referred to as Contact Resistance in stray voltage literature.

contact resistance: Contact impedance with resistive component and no reactive component (*see*: Contact Impedance).

contact voltage: A voltage resulting from electrical faults that may be present between two conductive surfaces that can be simultaneously contacted by members of the general public or animals. Contact voltage can exist at levels that may be hazardous.

earth current: Once electrical current leaves the structure of a grounded object or made electrode to flow within the three dimensional soil structure of the earth itself, it becomes an earth current. (*see also*: Ground Current, Return Current and Neutral Current)

equipotential plane: A grid, sheet, mass, or masses of conducting material that, when bonded together, offer a negligible impedance to current flow and significantly reduce step and touch potentials within the plane.

fault: A partial or total local failure in the insulation or continuity of a conductor.

ground current: Electrical system current that is on a grounding conductor, a grounding electrode, or some other conductive pathway between the neutral (grounded) conductor and the earth. (*see also*: Earth Current, Neutral Current and Return Current).

neutral current: Electrical system current that flows in the neutral conductor. (*see also*: Return Current, Earth Current and Ground Current).

neutral-to-earth voltage (NEV): A voltage measured between the neutral conductor or an extension of the neutral conductor (e.g., primary or secondary grounding conductor, bonded metallic water pipe, or bonded swimming pool water) and remote earth.

qualified reference: A measurement reference point that has been verified to be at zero potential relative to remote earth and have a low impedance pathway to the earth.

reference rod: A metal rod driven into the earth at a remote earth location that is verified to be a low impedance connection to the earth. The reference rod can be used as a common reference point for the measurement of voltages (e.g., neutral-to-earth voltage) on earth-referenced electrical systems.

remote earth: The distant point on the earth's surface where an increase in the distance from a ground electrode will not measurably increase the impedance between that ground electrode and the new distant point.

return current: Electrical system current that returns to its source by way of grounded and grounding conductors, the earth, and any other parallel conductive pathway (e.g., cable messenger) between the location of the load or fault and the current source. (*see also*: Neutral Current, Earth Current and Ground Current).

¹*IEEE Standards Dictionary Online* is available at: <http://ieeexplore.ieee.org/xpls/dictionary.jsp>.

stray voltage: A voltage resulting from the normal delivery or use of electricity that may be present between two conductive surfaces that can be simultaneously contacted by members of the general public or animals. Stray voltage is not related to electrical faults.

2.2 Abbreviations and acronyms

CVD	contact voltage detection
DMM	digital multimeter
DVM	digital voltmeter
ESR	electric-shock report
GFCI	ground-fault circuit interrupter
NEV	neutral-to-earth voltage
PPE	personal protective equipment
THD	total harmonic distortion
VOM	volt-ohm meter

3. General discussion

3.1 The nature of publicly and privately accessible voltages

Every time electricity is used, electric current is present in the device being used. It is also present in the wires of the building where the device is being used, and in the wires that belong to the utilities that deliver the electrical energy to the building. Because the majority of electrical energy is delivered using alternating current (ac), expanding and collapsing electric and magnetic fields surround nearly all of these current carrying conductors. Physical laws dictate that these time varying fields will cause electrical current to be present in all nearby conductive loops (i.e., induced current), and can result in the presence of a voltage on all nearby conductive surfaces (i.e., induced voltage). Because most electrical systems are physically connected to earth for reasons of safety, some amount of electrical current is also present in:

- a) The conductive pathways that exist between the electrical system and the earth (e.g., grounding conductors, water lines).
- b) Many of the parallel conductive pathways connected to the electrical system and/or the earth (e.g., phone and TV cable messengers and shields).
- c) The earth itself.

Wherever electric current flows, voltage exists. As a result, humans and their domesticated animals are often exposed to these manmade voltages. These exposures occur when contact is made between any two conductive surfaces that have a difference of electric potential between them (e.g., metal water faucet and earth). We are generally not aware of these ubiquitous voltage exposures. They are generally imperceptible and far below levels known to cause harm.

This guide will discuss the presence of publicly and privately accessible voltages that can result in conducted current exposures. It will limit discussion to exposures directly related to operation of customer and utility electrical systems.

3.2 Differences between stray voltage and contact voltage

The term “stray voltage” has been historically used to describe the voltages that exist at animal accessible locations in the vicinity of confined livestock. In recent years, however, the term stray voltage has also been used to describe the presence of voltage from a wide variety of sources including unintentionally energized objects in the public right-of-way (e.g., energized lamp posts and hand-hole covers).

This guide is intended for those who have a desire, or a need, for a more complete understanding of the topic. It will provide a comprehensive, understandable, fact-based presentation of:

- a) The causes of publicly and privately accessible voltage.
- b) Levels of voltage that may be of concern.
- c) Remedial actions that can or should be taken.

To better understand the issue of publicly accessible voltage exposures it is important to note that some amount of measurable voltage will always be present between conductive surfaces that are near operating electrical systems. This is true regardless of whether the system is operated by an individual property owner (i.e., electric customer) or an electric utility. It is also true regardless of the type of electrical system, its operating voltage, or how it is grounded. Under normal operating conditions, with a code compliant electrical system, publicly accessible voltages are usually imperceptible to both people and their animals. Special circumstances (e.g., confined livestock) or special exposure conditions (e.g., barefoot in an outdoor shower) can however result in perceptible exposures even when the electrical systems, utility and customer, are operating as intended. As defined in this guide this type of accessible voltage is termed “stray voltage”.

Publically accessible voltages that are the result of an existing fault condition (i.e., a short-circuit or an unintended open-circuit), are referred to in this guide as “contact voltage”. Understanding the difference between publicly accessible voltage exposures related to normal system operation (i.e., stray voltage), and potentially harmful exposures related to contact voltage is important to an understanding of this topic. To aid in this understanding, stray and contact voltage are defined and discussed separately in [Clause 5](#) and [Clause 6](#), respectively.

The organization of this document treats stray and contact voltage scenarios separately and distinctly. When a publicly accessible elevated voltage is found, it is either stray voltage, contact voltage, or both. A thorough understanding of all material contained in this guide will help the investigator choose appropriate techniques and procedures to safely and accurately identify the type of voltage present and its source(s).

Some jurisdictions have implemented local rules concerning stray and contact voltage. The investigator should be aware of these rules and make certain the instrumentation and methodology used in the investigation achieves the minimum requirement of the local rule.

3.3 The difficulty of stating a level of harm in terms of voltage

One of the difficulties of stray and contact voltage exposure assessment becomes apparent when you try to answer the question, “What level of voltage is harmful?” The voltage that we may make contact with at a publicly accessible location should not, in and of itself, be harmful. The voltage is merely the force that pushes the electric current through our conductive bodies. We feel and react to the current flow once it has reached a perceptible level. In general, once perception has been reached, increasing amounts of conducted current have increasingly negative consequences for both people and animals.

The amount of current that will flow through the person or animal (i.e., the amount of current in the exposure circuit) is dependent not only on the stray or contact voltage present at the point of contact (i.e., the exposure voltage), but on all elements of the exposure circuit (e.g., source impedance, contact impedance, and body impedance). In addition, the level of perception varies from one species to the next and even among individuals

within a species. Because the impedances of the exposure circuit are different at every exposure location and can vary with time, the amount of voltage required to create a perceptible current exposure may also be different at each exposure location and for each exposure.

Because contact voltage is fault related and can easily go from an imperceptible level to a dangerous level in a short period of time, a determination of the voltage source should be made. When the voltage present is determined to be due to a system defect (i.e., contact voltage), the existing or potential hazard should be isolated from the public and/or mitigated as soon as practical.

The science behind human and animal exposure to electricity is well established. It has been ongoing for more than a hundred years. What we now know about human and animal exposure to conducted current, including levels of perception and levels of harm, is discussed in detail in [Clause 4](#) of this guide. How to make meaningful exposure and diagnostic measurements, how to interpret findings, and how to mitigate stray and contact voltage sources are topics discussed in [Clause 5](#) and [Clause 6](#).

3.4 Safety

The annexes of this guide discuss procedures and methods for field investigations to locate and, if necessary, mitigate stray and contact voltages. Since many of these investigations will involve electrical systems with existing faults, strict adherence to current electrical industry working methods and safety procedures is paramount. Lethal voltages may be present on normally safe surfaces and equipment. Only qualified personnel with adequate personal protective equipment (PPE) should investigate locations with abnormal voltages. Possible contact voltages present can be considered and planned for so that the correct PPE is available on-site.

4. Human and animal electrical sensitivity

In this clause, results from previous research on human and animal electrical sensitivity to 50/60 Hz ac current and voltage are reviewed. Current flow through the human or animal body can cause a number of effects ranging from a slight tingling sensation at low current to muscle contraction at high current. These effects are only experienced if the current exceeds a perception threshold so that sensory neurons (producing sensations) and muscle neurons (producing muscle contractions) are activated (Reinemann [B39]²). The level of current flowing through the human or animal depends on the voltage applied and the impedance of the current path through the body. For stray voltage exposure scenarios where a long-term or repeated low voltage exposure may be of concern, an understanding of the body impedance of humans and animals is necessary for determining whether or not a perceptible exposure exists. In comparison, for fault related contact voltage scenarios knowing a person or animal's body impedance is not necessary because the objective is to identify and then mitigate the electrical fault that is the source of the contact voltage.

4.1 Impedance of the human body

Research shows that the shock severity is proportional to current flow through the body rather than the voltage imposed on the body when the shock occurs. As a result, threshold values are generally depicted in terms of current and not in terms of voltage.

IEEE Std 80-2013 [B27] gives recommended values for body impedance, which are based on research conducted by Dalziel, 1946 [B5], Dalziel, 1972 [B7], Dalziel and Lee, 1969 [B8], Geddes and Baker [B17], Geiges [B18], Kiselev [B30], and Osypka [B37]. According to these studies, the internal body impedance is approximately 300 Ω and the total body impedance, including the impedance of the skin, ranges from 500- Ω to 3000 Ω . For example, Dalziel and Massogilia [B10] determined experimentally that the hand-to-hand body impedance for saltwater wet conditions is 2330 Ω and the hand-to-feet body impedance for saltwater wet conditions is 1130 Ω . Based on Dalziel's and Massogilia's research, IEEE Std 80-2013 uses 1000 Ω for

²The numbers in brackets correspond to those of the bibliography in [Annex G](#).

hand-to-hand and hand-to-feet body impedances, which is stated to be a conservatively low value that neglects hand and foot contact impedances and the impedance of gloves/shoes. Dalziel states that often a comparably low impedance of 500 Ω is used as a conservative value for the body impedance between major extremities to estimate shock currents during industrial accidents, but does not mention the research this impedance value is based on.

It should be noted that due to the physiological variability in humans, however, it is difficult to establish a firm value for the body resistance to alternating current, particularly at higher exposure voltage levels. As mentioned above, 1000 Ω is a widely accepted resistance value in the United States. Initially, this resistance value became an acceptable standard due to its recommendation by IEEE Std 80-2013 for substation ground grid designs where typical exposure voltage levels are expected to be much higher. As the need in other areas of electrical exposure evolved, the 1000 Ω value started being accepted for those areas also.

4.2 Current thresholds for humans

Many studies use current thresholds based on the research of Charles Dalziel. The current thresholds listed in Table 1 were published by Dalziel in 1956 [B10] and are widely used in the industry today for quantifying shock hazards. Dalziel based the non-lethal thresholds on shock experiments conducted on humans. Let-go thresholds are determined from experiments with 134 male and 28 female adults (Dalziel, 1968 [B9]). Perception thresholds are determined from experiments with 167 adult men (Dalziel, 1972 [B5]) and Thompson's experiments on 40 adult men and women (Thompson [B43]). The lethal thresholds (ventricular fibrillation possible/certain) are based on experiments conducted on sheep, calves, pigs, and dogs, whose chest dimensions, body weights, heart weights, and heart rates are comparable to humans. None of Dalziel's experiments were conducted on children. Instead, it was assumed that the thresholds for children are half of the thresholds for an adult male.

Dalziel and Lee [B8] derived the so-called "electrocution equation" from electrocution data documented by Lee [B31]. The electrocutions occurred in England and Wales during the years 1962–1963. Of the electrocutions, 166 occurred on voltages less than 250 V (50 Hz), 30% of the victims were female, and 26% were persons under 20 years of age. This equation specifies the current threshold I_{fib} at which ventricular fibrillation can occur. The actual average weight of the electrocution victims was estimated to be less than 70 kg, but, for conservatism, Dalziel and Lee chose to use this equation for adults of 50 kg of weight. The empirically derived electrocution equation is given below and is applicable for shock durations ranging from 8.3 ms to 5 s.

$$I_{fib} = \frac{0.116 \text{ to } 0.185 \text{ A}}{\sqrt{t}} \quad (1)$$

where

t is 8.3 ms to 5 s

I_{fib} is the current threshold in amperes at which ventricular fibrillation is possible

t is the shock duration in seconds

IEEE Std 80-2013 adopts this equation with a value of 0.157 in the numerator and for adults with 70 kg body weight. Dalziel and Lee extrapolated the data, which was only obtained from adults, to derive the following electrocution equation that is applicable to children.

$$I_{fib, \text{ children}} = \frac{0.052 \text{ to } 0.069 \text{ A}}{\sqrt{t}} \quad (2)$$

where

t is 8.3 ms to 5 s

Table 1—Effects of 60 Hz electric current on the human body

Effect	Current threshold for men (mA, rms)	Current threshold for women (mA, rms)
Perception threshold (slight tingling)	1.1	0.7
Painful shock	9.0	6.0
Let-go threshold	16.0	10.5
Painful and severe shock, muscle contract, breathing difficult	23.0	15.0
Ventricular fibrillation possible, short exposure (0.03 s)	1000	1000
Ventricular fibrillation possible, long exposure (3 s)	100	100
Certain death from ventricular fibrillation, short exposure (0.03 s)	2750	2750
Certain death from ventricular fibrillation, long exposure (3 s)	275	275

Relying on the research of Dalziel and others, Whitaker of Underwriters' Laboratories (UL) established a maximum uninterrupted 60 Hz ac current of 5 mA as the safe let-go current for a two-year-old child. He did this by extrapolating the ventricular fibrillation data of an animal having a body and heart weight proportional to that of a two-year-old child (Hammam and Baishiki [B23]). This value is still used by UL as the maximum continuous safe current for the general population.

4.3 Animal electrical sensitivity

The following sub-clauses document previous research on the electrical sensitivity of animals.

4.3.1 Dairy cows

Table 2 documents the electrical sensitivities of dairy cows (ASAE EP473.2 2001 [B3]).

Table 2—Electrical sensitivities of dairy cows

Effect	Cattle group	Current threshold	Voltage threshold	Comment
Mild behavioral modification	Most sensitive cows	2 mA	1–2 V	Documented for dairy cows. Similar levels for beef cattle expected.
	50% of all cows	5 mA	2.5–5 V	
	Least sensitive cows	8 mA	4–8 V	
Short term avoidance behavior (may result in depression of milk production)	Most sensitive cows	3 mA	1.5–3 V	Depression of milk production only expected if the water source with high electrical potential is the only water source.
	50% of all cows	7.5 mA	3.8–7.5 V	
	Least sensitive cows	12 mA	6–12 V	

The voltage threshold levels are based on contact resistance of 500 Ω at poorly drained, wet locations surrounding watering devices and on contact resistance of 1000 Ω in well designed, constructed, and managed facilities. While these levels have been well documented for dairy cows, they may also apply to beef cattle (Reinemann [B39]).

4.3.2 Swine

Table 3 documents the electrical sensitivities of swine (Godcharles, Matte, and Marineau [B19], Gustafson, 1986 [B21], Kennedy [B29], Reinemann [B39], Robert, Matte, and Martineau, 1996 [B41], Robert, Matte,

and Bertin-Mahieux, 1992 [B42]). Research suggests that swine adapt to voltage exposure in a similar way as cattle (Matte et al. [B32] and Reinenmann [B39]).

Table 3—Electrical sensitivities of swine

Effect	Current threshold	Voltage threshold	Comment
Drinking behavior changes	3 mA	5 V	Continuous exposure to 5 V with intermittent exposure to 8 V produced behavioral changes, but did not change water intake.
Short term reduction in water intake	4 mA	8 V	Exposure up to 8 V did not impair welfare, reproductive performance, or health of sows and suckling pigs.

4.3.3 Sheep

Ewes avoided electrified feed bowls when exposure levels exceeded 5.5 V. Lambs showed the same behavior if exposure levels exceeded 5 V. Research suggests that current sensitivity for sheep is lower and body resistance is higher compared to cows (Duvaux-Ponter, Roussel, and Deschamps, 2005 [B12] and Duvaux-Ponter, et al., 2006 [B13]).

4.3.4 Poultry

Exposures to voltages as high as 18 V had no effect on the production and behavior of hens. This is likely due to the very high electrical resistance of poultry (between 350 kΩ and 544 kΩ) (Reinemann [B39]).

5. Contact voltage

Contact voltage is a voltage resulting from electrical faults which may be present between two conductive surfaces that can be simultaneously contacted by members of the general public or animals. Contact voltage can exist at levels that may be hazardous.

5.1 Background

Contact voltages can arise from two distinct types of faults on electrical systems; phase conductor faults and neutral conductor faults. Contact voltage often results from damaged insulation on phase conductors or damaged or faulted neutral conductors. Improperly connected customer or utility equipment can also cause contact voltage. Since contact voltage often involves phase conductors, it should be treated carefully because a low voltage level can rise to full line voltage as the impedance of the conductive fault pathway changes.

Contact voltage is not a traditional step and touch potential problem. Step and touch potentials are usually discussed in terms of the accessible voltages present during a short duration electrical system fault event. The risk of contact voltage is not just from the momentary voltage associated with a short duration fault, but rather the presence of an electrical fault in customer or utility wiring that has not cleared (i.e., the protection device, if present, has not operated). As such, the fault can result in a long term publicly accessible voltage that may, under specific exposure conditions, reach harmful levels. Based on utility experience, in the majority of cases the voltage measured at the time of investigation is in excess of 5 V, but many cases are reported below 5 V (New York State Public Service Commission [B35]). Multiple voltage measurements recorded at different times of day or on different days often yield different results due to the variations in the fault conditions such as changes in temperature, fault impedances, and moisture levels in the soil.

In bodies of water contact voltage cases often result from un-cleared faults in vessel wiring or dock electrical systems. Voltage values near metal objects proximate to the source of the fault may be near line voltage, while the conductivity of the water may result in low voltages at nearby grounded objects.

When considering contact voltage it is important to understand voltage levels sourced by a fault and appearing on an accessible surface are rarely constant. For example a measurement of as little as 1 V_{ac} at one point in time could rise to full line voltage as environmental conditions change or as the insulation continues to degrade. While this complicates the detection and mitigation process, effective contact voltage detection (CVD) and mitigation can be accomplished with proper understanding and techniques.

5.2 Identification of contact voltage

When voltage is found on a surface or structure, it is important to determine whether or not it is contact voltage. Specifically, the characterization and troubleshooting process can be aided, and the investigation can be performed more safely, by first determining if the source of the voltage is a fault in either a nearby phase conductor or a neutral conductor. In addition to measuring voltage magnitude during the test process, a measurement of total harmonic distortion (THD) may be beneficial.

Determining whether or not the exposure voltage is contact voltage is often possible by measuring the THD of the voltage waveform. In cases where the THD is low, the voltage could be sourced by either a fault on the phase conductor or a fault on a neutral that is connected to a linear load or a load with harmonic suppression. If it is, the voltage is likely contact voltage. In cases where there is a higher level of harmonic distortion the voltage is likely being sourced from the neutral (or return side of the circuit) and is therefore stray voltage. It can be noted that harmonic measurements alone do not provide adequate information to differentiate between stray voltage and contact voltage. The final determination of stray voltage requires confirmation that no defects are present in the system, and thus the voltage is the result of a “normally operating electric system.”

5.2.1 Contact voltages from line-side sources

To distinguish between contact voltage caused by phase conductor faults and faults in the neutral conductor, the harmonic content of the measured voltage can be utilized to suggest the source. The power quality standard IEEE Std 519-2014, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, recommends that utilities deliver voltages that are ≤ 1 kV with $< 5\%$ THD. Since the earth, metallic objects, and other conductive surfaces of concern behave like resistive (linear) loads, voltage resulting from phase conductor faults has the same THD as the source (phase) voltage. A contact voltage caused by a phase conductor fault will almost always have a relatively low harmonic 60 Hz sinusoidal waveform, just like the voltage of its phase conductor source.

The important concept here is that the harmonic content of the source and the harmonic content of an inadvertently energized object will have exactly the same THD percentages, but may not have exactly the same voltage levels. The reason for the voltage difference between the source and the inadvertently energized object stems from the fact that the voltage measured on the energized object is a function of the series resistance of the connection between the phase conductor and the energized surface. This series resistance is typically referred to as the fault impedance, see [Equation \(3\)](#). [Figure 1](#) shows a simplified version of the measurement schematic.

$$V_{object} = \frac{V_{source} (Z_{earth})}{(Z_{fault} + Z_{earth})} \quad (3)$$

where:

V_{object}	is the voltage measure on the energized surface
V_{source}	is the source voltage (typically 120 V in the US)
Z_{fault}	is the impedance between the source conductor and the energized object

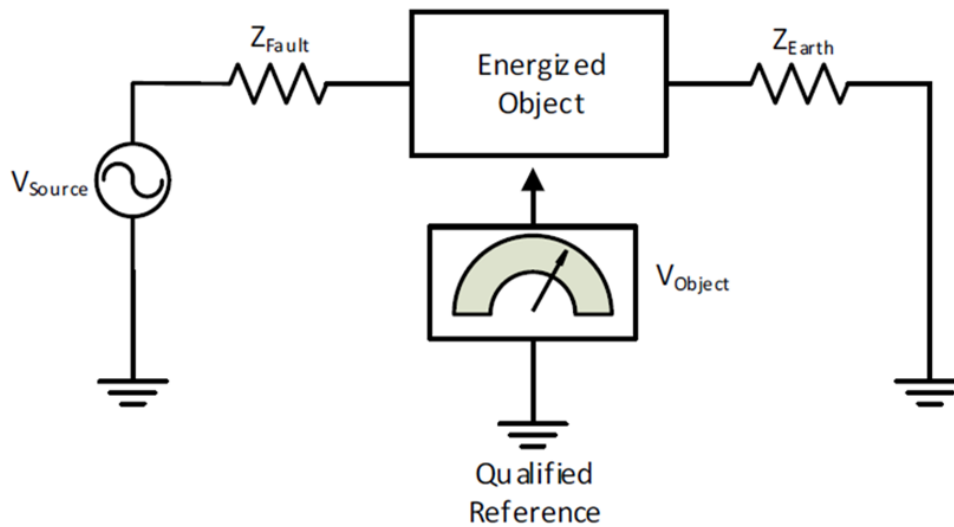


Figure 1—Phase conductor contact voltage source

Z_{earth} is the impedance of the earth return path

The previous equation suggests that the voltage level on the conductive surface may change as fault impedance (i.e., the series resistance components) changes due to environmental factors such as moisture, humidity, soil, or concrete resistivity. Since contact voltage is often the result of damaged insulation, the voltage can vary from low levels (less than a few volts) to full line voltage levels.

Figure 2 depicts a typical contact voltage waveform resulting from damaged insulation on a phase conductor. Figure 3 is a histogram representation from the waveform example shown in Figure 2.

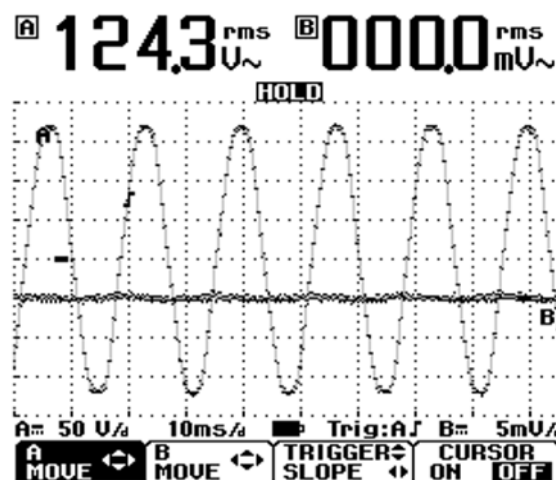


Figure 2—Contact voltage waveform resulting from damaged insulation on a phase conductor

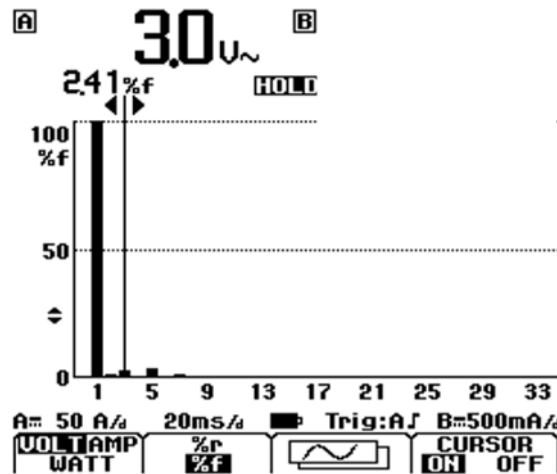


Figure 3—Contact voltage histogram resulting from damaged insulation on a phase conductor

Contact voltage from phase conductor sources will almost always show the fundamental frequency (i.e., 50/60 Hz) sinusoidal waveform with low distortion. It has been found that contact voltages from phase conductor sources have a THD typically less than 5% and rarely exceeding 10% by contact measurement with probes. These contact voltages result from a variety of conditions including; deterioration of conductors, faulted equipment, aged equipment, exposure to the elements, and various secondary wiring related issues. These fault related voltages should not exist on normally operating electric facilities and need to be mitigated to help prevent harm to the public and maintain system reliability. Some contact voltages associated with neutral conductor faults may also exhibit less than 10% THD. This can occur when the load is predominately a linear load.

5.2.2 Contact voltages from neutral conductor sources

The higher level of harmonics in faults associated with neutral conductors is a result of the characteristic of the current on the neutral conductor. Static power converters utilize power semiconductor devices for power conversion. These devices constitute the largest category of nonlinear loads connected to the electric power system. Static power converters are used in a variety of applications including: computers, television sets, compact fluorescent lighting, motor speed controllers, pump flow controllers, and other electronic equipment. Unless equipped with harmonic suppression devices, static power converters often draw non-linear currents and return them onto the neutral. If the load is purely linear then the resultant voltage will have a harmonic content that matches the harmonic content of the power system.

Contact voltages caused by neutral conductor sources are a simple extension of Ohm's Law where the return currents from the loads create a voltage drop as they pass through the impedance of the return path, see Equation (4).

$$V = Z \sqrt{(I_{h1}^2 + I_{h2}^2 + I_{h3}^2 + \dots I_{hn}^2)} \quad (4)$$

where

- V is the voltage
- Z is the impedance of the conductive path
- I_{h1} is the current at fundamental frequency
- I_{h2} is the current at second harmonic frequency

I_{h3} is the current at third harmonic frequency

I_{hn} is the current at n^{th} harmonic frequency

If return-path impedance is high (e.g., a high impedance neutral connection), the voltage drop can be large. Because the voltage drop is directly proportional to the total current (fundamental and the harmonics), we can expect the resulting contact voltage will have the same harmonic components. The THD is dependent on the amount of non-linear load on the circuit of interest. It follows from this discussion that when the measured voltage on an inadvertently energized object has a high harmonic content it is almost always going to be caused by system return current on a neutral return path. There are always exceptions such as when a circuit has only motor or heater load, but the majority of the circuits feeding residential, commercial, or industrial facilities have neutral return current with at least a 10% or greater harmonic current content.

Figure 4 depicts an example of a contact voltage waveform from a neutral conductor source. Figure 5 is a histogram representation from the example shown in Figure 4.

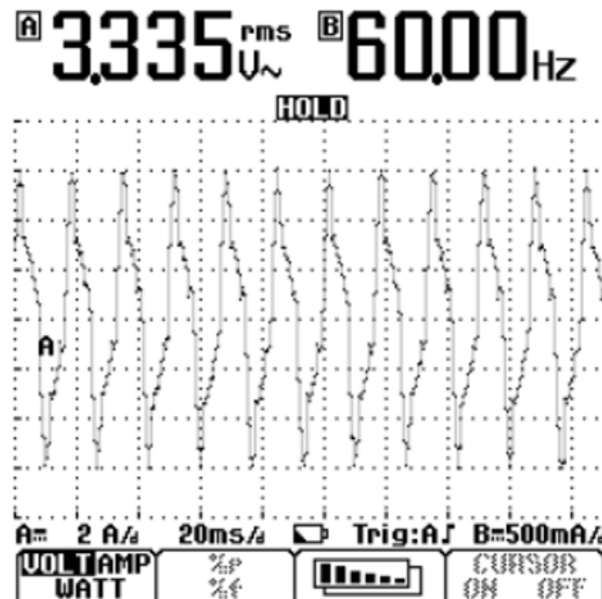


Figure 4—Contact voltage waveform from a neutral conductor source

In cases where the THD of the measured voltage is greater than 10%, it is often not clear whether the source of the voltage is normal return current or a faulted neutral conductor (open or nearly open neutral). In these cases, investigators can examine the circuit to determine whether the voltage is the result of normal power system operations or defective equipment. If the voltage is the result of normally operating equipment, the voltage would be considered a stray voltage (see Clause 6). Harmonic level measurements alone cannot determine the voltage source, a visual inspection is needed to determine if the source is stray or contact voltage. If the cause is defective equipment, it would be classified as contact voltage and the area should be safeguarded until repairs can be made.

5.3 Causes of contact voltage

A fault can occur where the electric system breaks down from mechanical, thermal, chemical, or electrical stress. The fault (i.e., a shorted-phase conductor or an open neutral conductor) can be a high-impedance fault

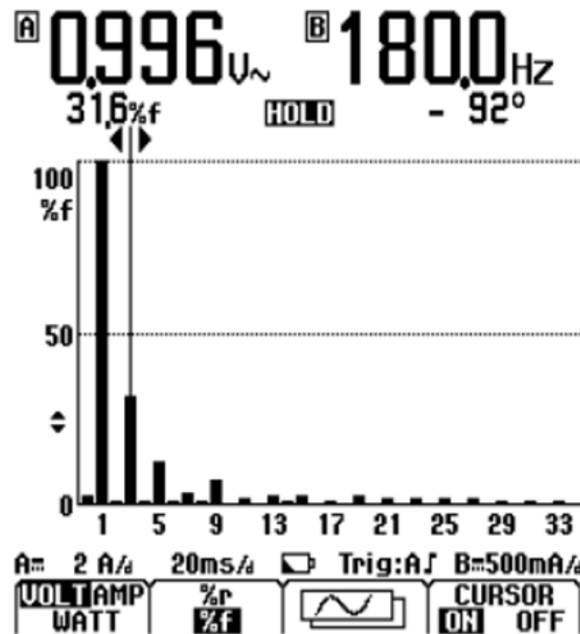


Figure 5—Contact voltage harmonics histogram from a neutral conductor source

which can go unnoticed by the customer or utility responsible for maintaining the asset until reported by a member of the public or identified through some kind of testing process. Experience has shown that any conductive structure in the vicinity of an electrical fault may become energized and pose a hazard to the public. The high impedance faults that cause contact voltage can be attributed to one or more of a list of causes, including, but not limited to:

- Environment:* Environmental factors (e.g., moisture, freeze thaw cycles, corrosive atmosphere, vibration, and lightning) can cause electrical insulation to fail on cables, connectors and other energized system components. Corrosion can also reduce the mechanical strength of conductors, conduits, supports, cable jackets, and mechanical connections, all of which can initiate damage to insulation and compromise neutral return paths.
- Design:* Issues related to system design can lead to insulation failure and result in an electrical fault. Damaged wires can occur due to improper rating, insufficient protection (both physical and electrical), inadequate mechanical support, improper weatherproofing, and other design related issues.
- Installation:* Incorrect installation can result in an electrical system fault that may become a hazard to the public. Specific examples include insulation damage from pinched wires, improper installation of hand taped insulation, accidentally reversing polarity, failure to properly tighten connections, and insufficient mechanical protection of energized conductors. On an operating electrical system, customer or utility, all components should be installed in accordance with the manufacturer's instructions, and appropriate codes (NEC, NESC, etc.). Such components are tested and qualified by the manufacturer based on the assumption that they will be installed in accordance with the instructions provided. If they are not, the product cannot be expected to perform as intended.
- Accidents:* Accidental damage to an operating electrical system can occur in a variety of ways (e.g., vehicular accidents, dig-ins, and fires). The damage may result in an immediate or future electrical fault condition resulting in conductive surfaces near the fault becoming energized.
- Animal damage:* Animals such as insects, birds, squirrels, mice, gophers, moles, rabbits, and raccoons have been known to damage insulation and connections.

- f) *Vandalism/theft*: Vandals can damage or remove access covers, resulting in exposed wires and the introduction of debris into electrical structures or streetlight bases. Thieves can create hazards that prevent the proper operation of protective devices by removing neutral and ground conductors. Unauthorized connections to supply circuits may be made using unapproved components or work practices prone to failure.
- g) *Life-cycle events*: Workers may pierce or remove insulation to test for voltage on an underground supply cable. If not properly re-insulated, this can leave a path for current leakage to cable supports, duct work, and other normally non-energized surfaces.
- h) *Temporary connections*: Temporary power connected for emergency restoration or seasonal lighting can create electrical hazards. This can occur if not properly installed or adequately safeguarded from the elements and from unauthorized access.

5.4 Contact voltage detection (CVD)

Identifying a need to repair a defect or fault begins with detection of voltage on a surface or structure not intentionally energized. The discovery process comes about through some form of detection.

Contact voltage can be detected in four ways: a) Direct detection—a managed program of testing specific assets or geographical areas for contact voltage, b) Incidental detection—discovery of energized structures during routine maintenance work or through abnormalities noticed during visual inspections, c) Publicly reported shock—a member of the public or a pet receives and reports an electrical shock, and d) Public report of concern—reports from the public who have not been shocked, but have noticed a cause for concern. All public reports should be investigated.

- a) *Direct detection*: An electrical system asset owner or an electric utility may periodically test for contact voltage. The goal of such a program is to locate un-cleared electrical faults by detecting voltage on nearby conductive surfaces within reach of the public. Once detected a series of tests can be performed to determine whether the voltage is related to a fault condition and/or whether a potential hazard exists. Test results can also be used to make informed decisions about repairs, if they are necessary. In a managed direct detection program it is advisable to use the most sensitive means available to detect energized surfaces. Using the most sensitive means available will help identify the potentially hazardous locations. Once identified, a more rigorous diagnostic process can be used to rule out conditions which do not come from a fault and therefore are not likely to become hazardous. A sensitive detection process can accomplish the goals of proactively finding faults, minimizing the number of contact voltage incidents, and improving the safety and reliability of the system. Insensitive detection processes may allow possible hazards to be filtered out before any diagnostics can be performed.
- b) *Incidental detection*: Detection of contact voltage can also occur during regularly scheduled repair and maintenance work. The addition of pre and post-work tests for contact voltage can enhance the incidental detection process, and improve both public and worker safety.
- c) *Public report of shock*: Reports of shock should be investigated as soon as practical. First responders investigating a reported shock site should assume a fault condition exists and treat surfaces as energized until proven otherwise. Structures determined to be energized as a result of an existing fault should be barricaded until the fault (customer or utility owned) can be de-energized and repaired.
- d) *Public report of concern*: These are reports from the public by those who have not been shocked, but have noticed a cause for concern. Some examples include missing streetlight access covers, broken equipment, and code violations. These deficiencies might result in a voltage finding in the area or lead to one in the future.

5.4.1 Equipment for detecting contact voltage

This section describes existing test equipment that may be useful for detecting inadvertently energized objects and surfaces. There are a number of methods and hardware options available for this task. The two most commonly used methods are mobile detection and handheld detection.

There is no single technology or test method that works for all scenarios; therefore, it is important to understand the capabilities and limitations of the equipment being used and the test being performed. The investigator can conduct individual field trials and review test reports and manufacturers specifications to ensure that the selected devices perform as required for the objectives of the given test program and as expected in the given application.

5.4.1.1 Mobile electric field detection

Mobile electric field detection relies on a capacitive sensor which measures the ambient electric field and detects small changes in the field as the sensor passes by energized objects and surfaces. An example of such a system is shown in [Figure 6](#). A mobile electric field detection vehicle can scan an area quickly providing a positive indication of objects or surfaces that are energized at the time of testing. A mobile detection vehicle can simultaneously detect the presence of voltage on all surfaces within range of the sensor. These surfaces include, but are not limited to: streetlights, manholes, fences, hand-hole covers, roadways, and sidewalks. Since mobile electric field detection identifies all energized objects and surfaces within the range of the detector rather than specific assets, it is the most inclusive detection method currently available.

Mobile electric field detection systems work well for underground distribution and some mixed overhead/underground systems. However, electric field levels from overhead medium and high voltage lines (distribution and transmission) typically mask contact voltage signals in their immediate proximity. Therefore mobile detection is not generally suitable in areas under or very near these overhead conductors.

5.4.1.2 Handheld detection

There are three types of handheld detectors currently in use for detecting inadvertently energized objects and surfaces. These include:

- a) Probe-based (test lead) voltmeters
- b) Physical contact based handheld capacitive or “pen” testers (as shown in [Figure 7](#))
- c) Non-contact based electric field strength indicators

For surveys of contact voltage in areas influenced by overhead primary distribution and transmission lines, one or more of the direct contact handheld measurement devices may be considered.

5.4.1.2.1 Probe-based voltmeters

Probe-based voltmeters and their uses are additionally described elsewhere in this document ([5.5](#), [6.5](#), [Annex C](#), and [Annex D](#)). These meters provide not only an accurate indication of an energized object, but they can additionally discern the precise voltage level on the object with decimal place accuracy. Getting a positive indication and obtaining the voltage parameters with a single measurement is convenient, but the trade-offs in efficiencies are the amount of time it takes to test individual assets and the need to identify a qualified reference (See [5.5.1.3](#)).

5.4.1.2.2 Physical contact pen testers

Contact based pen testers are capacitively coupled detectors that provide visible or audio indication the object under test is energized at a voltage above the detector’s specified voltage threshold. The pen testers operate assuming the user is capacitively coupled to the earth and at zero potential, and therefore do not require a test



Figure 6—Example of a mobile detection system



Figure 7—CVD using a pen tester

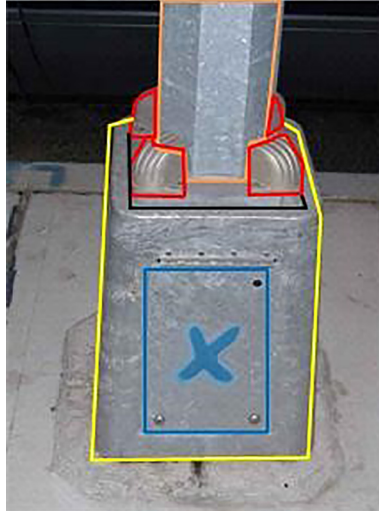


Figure 8—Physical contact is not electrical contact. Test each part of a lamp separately (e.g., pole, base, access door, bolt covers, mounting flange)

lead connected to a qualified reference in order to make the measurement. Physical contact pen testers may provide erroneous results when the user is unknowingly standing on energized earth and the pen tester is no longer provided with a ground reference at or near zero potential. Independent laboratory tests have documented the most commonly used pen testers can detect voltage as small as 5 V in the laboratory environment.

Pen testers are often used for asset list-based test programs. Typically these test programs target a specific list of assets such as traffic signals, street lights and other targeted metal apparatuses. The asset list-based detection process works well for inventory items, but is not intended to test for underground faults, which may energize sidewalks or other surfaces that do not appear on an asset list. Handheld pen testers are far more practical for testing a large number of assets than a traditional voltmeter because pass/fail criteria is indicated by a light, an audible alarm or both. These devices are not as sensitive as the voltmeter and may not identify a potential hazard that is energized below the minimum voltage threshold of the device.

Variations from user to user can affect the reliability of detection with a pen tester. Therefore standard practices are to be encouraged to ensure repeatable measurements are obtained:

- a) Keep all body parts as far away from the object being tested as possible. Since the tester's body is the "ground reference" for the test, wearing thick gloves or boots may prevent a voltage indication from occurring.
- b) Make solid metal-to-metal contact with each surface tested. Paint can insulate energized surfaces from detection with a contact device.
- c) Test all metal parts of an object separately. Metal surfaces in physical contact are not necessarily in electrical contact, especially if painted or corroded (see [Figure 8](#)).
- d) The investigator should follow all written test procedures and manufactures instructions (e.g., hold the detector at arms' length).
- e) Verify if gloved hands are recommended by the manufacturer, some detectors require bare hand use. Grip these detectors firmly with a full hand.
- f) The investigator should conduct multiple measurements from alternate locations to reduce the chance of standing on energized ground.

- g) Verify the detector to a known reference often as battery performance may change due to environmental conditions (cold weather) and the batteries age.

5.4.1.2.3 Non-contact electric-field detectors (see also 5.5.1.5)

Handheld electric-field detectors are also capacitively coupled sensors that measure electric fields. They are similar to mobile electric-field detectors, without a mobile platform and with less sophisticated computer-based processing. These handheld detectors can be used to locate a specific energized object or surface following a positive indication from a mobile scan, or when investigating an incidental detection (e.g., an ESR from the public). They may also be used in areas where a mobile platform is difficult to deploy (e.g., foot traffic only areas), and can be useful when identifying a qualified reference (see 5.5.1.5).

The sensitivity of handheld electric-field detectors can vary greatly based on their intended application. For example, some handheld electric-field detectors are designed for measuring human exposures to electric fields. In these devices the field strengths may be several orders of magnitude larger than those associated with contact voltages. Care is needed in selecting a detector that has the requisite sensitivity. Some of these testers may also have directional sensitivity to help the investigator find and validate the energized object among multiple objects that may be energized. As a result of the high sensitivity needed to detect small amounts of contact voltage, handheld electric-field detectors are also subject to false readings that may be caused by a variety of electrical noise sources. Similar to mobile electric-field detectors, handheld detectors may be affected by electric fields from nearby overhead distribution and transmission lines (Consolidated Edison Co. of NY, Inc. [B40]).

5.5 Verification and measurement of contact voltage

5.5.1 Contact voltage measurement equipment

5.5.1.1 True rms digital voltmeter (DVM)

A true rms digital voltmeter (DVM) can be used as a means of quantifying the voltage once it has been detected. Voltage measurements require several steps, often including the use of a shunt resistor (see 5.5.1.4). Measurement of voltage on objects should commence anytime a detection by any of the previously described methods occurs. The meter can be outfitted with test leads which are long enough to access the object under investigation and qualified reference points.

5.5.1.2 True rms ammeter

A true rms ammeter or clamp-on ammeter can be used to determine the presence of ground faults by quantifying the net current in a circuit. DVMs with a built-in clamp-on ammeter are available and provide the user with the same functionality as using a separate current clamp. Care can be taken to ensure the proper measurement range of the meter is selected to provide accurate current measurement.

5.5.1.3 Qualified reference

Accurate measurements of contact voltage levels require the use of a qualified reference. A qualified reference is a measurement reference location that has been verified to be at zero potential relative to remote earth and have a low impedance connection to the earth. A qualified reference is selected from available nearby candidates that include fire hydrants, fence and sign posts, and other conductive metal objects in intimate contact with earth. A temporary ground rod may be used, but the investigator should ensure that it is of adequate length to provide a low impedance pathway to the earth. A confirmation process, detailed in Annex A, describes the process for qualifying a candidate reference for use in the contact voltage measurement process. All voltage measurements should be made via the qualified reference.

5.5.1.4 Shunt resistor

After measuring voltage on an energized structure or surface with a high impedance voltmeter, it is often helpful to perform measurements with the addition of a shunt resistor to the measurement circuit. Measurements with a properly sized shunt resistor can help eliminate false readings. The application of proper measurement procedures will result in more accurate measurements that are repeatable from user to user. This reduces confusion at all levels of the process and aids the investigator in discerning the difference between hazardous energizations that are caused by faults and energizations that are caused by other sources

Measureable voltage can be present on ungrounded, isolated metal objects due to the influence of nearby high voltage sources such as power lines, lighting ballasts, or unshielded power cords. This phenomenon is known as capacitive coupling, although other terms have been used to describe it, including “phantom voltage.” In these cases, the object under test has a measurable voltage present, but no physical connection to a current source exists. Elimination of capacitively coupled voltages is the primary purpose of a shunt resistor when making contact voltage measurements.

An example of a shunt resistor is shown in Figure 9. The momentary push button allows the resistor to be inserted into the circuit without the need to reposition the test probes. By maintaining constant contact with the probes the introduction of additional measurement error into the circuit can be avoided. The push button also allows the investigator performing the test to compare the open circuit and shunt voltages quickly to determine if the voltage at the selected reference point has a low impedance source.

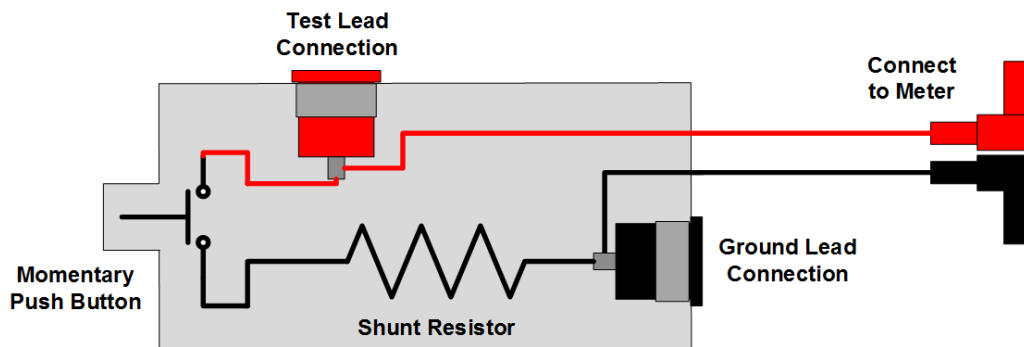


Figure 9—Push button shunt resistor schematic

When a high input impedance voltmeter is used to make contact voltage measurements from an energized surface to a qualified reference, placing a small known load, or shunt resistor, in parallel with the input of the voltmeter is an effective methodology to eliminate capacitively coupled voltages. If current flows from the object under test through the shunt resistor to earth, the voltage collapses to nearly zero, eliminating false positive voltages due to capacitive coupling. The voltage on objects energized by an actual low impedance current source will not collapse to zero, but may be reduced from the un-shunted open circuit voltage value (V_{OC}) according to Ohm’s Law [see Equation (5)].

$$V_{SHUNT} \approx V_{OC} \left(\frac{Z_{SHUNT}}{Z_{SOURCE} + Z_{SHUNT}} \right) \quad (5)$$

where

V_{SHUNT} is the voltage measured with the shunt resistor in parallel with voltmeter
 V_{OC} is the voltage measured without the shunt resistor
 Z_{SHUNT} is the impedance of the shunt resistor
 Z_{SOURCE} is the source Impedance

V_{SHUNT} collapses to nearly zero in cases where voltage is sourced via capacitive coupling, as $Z_{SOURCE} \gg Z_{SHUNT}$. This equation assumes zero contact impedance and ground impedance. The schematic shown in Figure 10 captures the circuit elements in the measurement circuit. Analysis of this circuit allows selection of an appropriate value of shunt resistance for the task at hand.

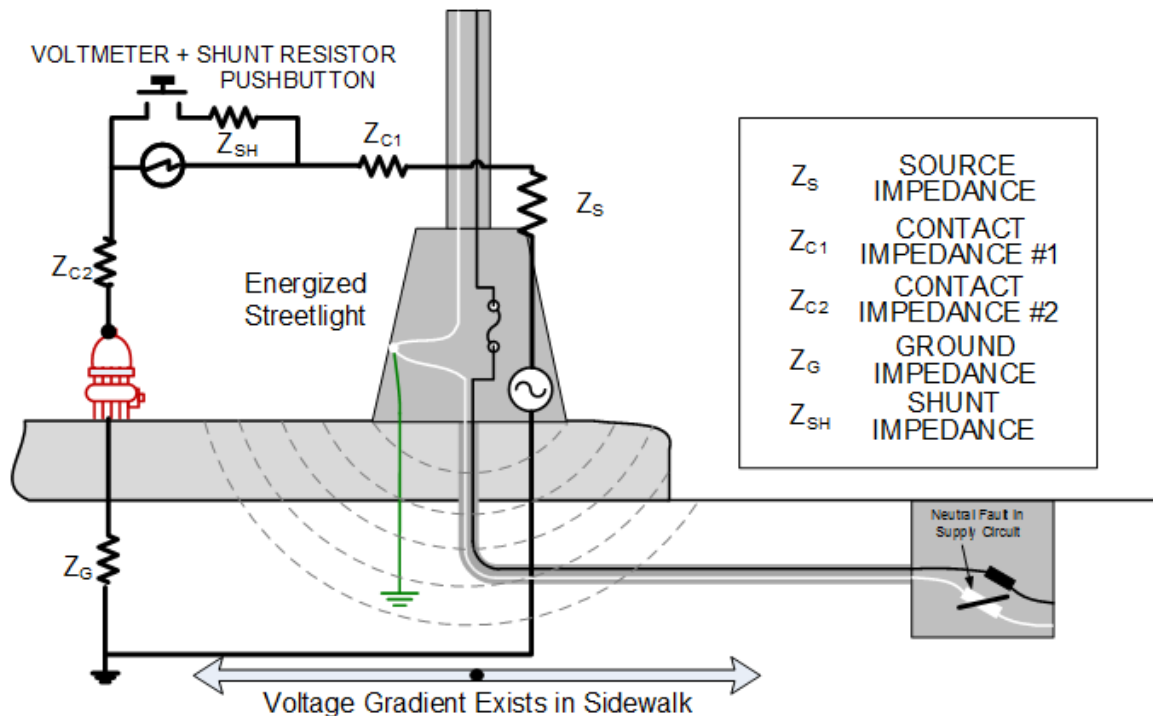


Figure 10—Measurement circuit including various circuit impedances

Errors due to contact and ground impedance can complicate the troubleshooting process. By observing and minimizing the change in voltage that occurs when a shunt resistor is introduced into the circuit, the investigator can minimize contact and ground impedances and get accurate readings that are repeatable from person to person. This positive feedback activity calls for a shunt resistor that can be quickly engaged and disengaged, without disconnecting or moving the test leads. It also calls for a shunt with resistance low enough to collapse the voltage from a capacitively coupled source, but high enough to minimize measurement error.

Historically, in farm investigations of stray voltage, a shunt resistance of 500 Ω was chosen as it represents a conservative estimate of a cow's body and contact resistance in real world conditions (Patel [B38]). By using this value for field measurements, it is possible to assess the amount of current that could flow through a cow making contact with the energized surface being investigated.

Contact voltage measurements bring their own unique set of measurement requirements. The measurements are performed to guide the investigator to a fault or defect so it can be repaired. The shunt resistor value selec-

tion is not guided by human or animal impedances as the measurement is not intended to be a measurement of exposure. Selection of a shunt resistor value for contact voltage measurements is guided by the need for accurate repeatable measurements. Shunt resistor values of 500 Ω , 3000 Ω , and 10000 Ω have been used in contact voltage investigations, but a higher resistance shunt is more likely to result in accurate and repeatable measurements.

Measurement error is a function of the impedances in the measurement circuit (see Equation (6), Equation (7) and Equation (8)). Ideally, the variability in measurements as a result of typical error values in the field is less than 10%. Table 4 shows shunt voltage variability for a 20 Ω source impedance, low total (ground and contact) impedances (50 Ω), and a more realistic value (250 Ω), using 500 Ω , 3000 Ω , and 10000 Ω shunt resistors. It is easy to see how a lower value of shunt impedance results in large measurement variability which can cause confusion and miscommunication between multiple diagnostic or repair crews that may make connection to different qualified references. The equations below show that the measurement error of the shunt voltage is a function of the ground and contact impedances in the measurement circuit.

$$\epsilon = \frac{Z_{SHUNT} + Z_{SOURCE}}{Z_{SHUNT} + Z_{SOURCE} + Z_{CONTACT} + Z_{GROUND}} \quad (6)$$

where:

ϵ is the measurement accuracy
 Z_{SHUNT} is the impedance of the shunt resistor
 Z_{SOURCE} is the source impedance
 $Z_{CONTACT}$ is the contact impedance
 Z_{GROUND} is the ground impedance

$$V_{SHUNT} = V_{OC} \times \left(\frac{Z_{SHUNT}}{Z_{SOURCE} + Z_{SHUNT}} \right) \times \epsilon \quad (7)$$

where:

V_{SHUNT} is the voltage measured with the shunt resistor in parallel with the voltmeter
 V_{OC} is the voltage measured without the shunt resistor
 Z_{SHUNT} is the impedance of the shunt resistor
 Z_{SOURCE} is the source impedance
 ϵ is the measurement accuracy

$$\text{Measurement Error}(\%) = (1 - \epsilon) \times 100 \quad (8)$$

From Table 4, we see that error in measurements utilizing a 500- Ω shunt is only low when ground and contact impedances are very low. When typical values of ground and contact impedance are considered, measurement error increases rapidly. The importance of measurement accuracy and appropriately large shunt resistances was noted as early as 1984 (Gustafson, 1984 [B22]).

Table 4—Examples of measurement error for various shunt resistor values

	Ideal measurement conditions		Typical measurement conditions		
$Z_{SHUNT} (\Omega)$	500	3000	500	3000	10000
$Z_S (\Omega)$	20	20	20	20	20
$Z_G + Z_C (\Omega)$	50	50	250	250	250
V_{SHUNT}	$0.88 \times V_{OC}$	$0.98 \times V_{OC}$	$0.65 \times V_{OC}$	$0.92 \times V_{OC}$	$0.98 \times V_{OC}$
Error (%)	9%	2%	32%	8%	2%
ε	0.91	0.98	0.68	0.92	0.98

The importance of shunt resistor value selection is illustrated in this example. Using lower shunt resistor values, for example 500 Ω , will result in higher measurement errors. As illustrated in the table even under ideal conditions a 500- Ω shunt resistor will yield a measurement error of 9%, and that error increases to over 30% in typical conditions. The investigator should carefully consider the measurement conditions when selecting a shunt resistor.

Figure 11 provides an example of how low value shunt resistors can impact the measurement process when high contact impedances are present. In this example a sidewalk is energized due to failed insulation on a service conductor located beneath the sidewalk and the investigator is using a pointed test probe to make measurements. The pointed test probe is a high resistance connection to the sidewalk. When a 500- Ω shunt resistor is placed in parallel with the multi-meter the resultant measured voltage is 0.95 V. This is below the mitigation threshold set by a number of utilities and regulatory authorities and the investigator would likely take no action to mitigate the existing fault. When a higher resistance shunt is used, the measured voltage rises above the mitigation threshold and the potential hazard would likely be identified and addressed. Using a high impedance voltmeter in this example, either without the use of a shunt resistor or with the use of a higher value shunt resistor can help the investigator recognize the presence of the fault so that appropriate action can be taken.

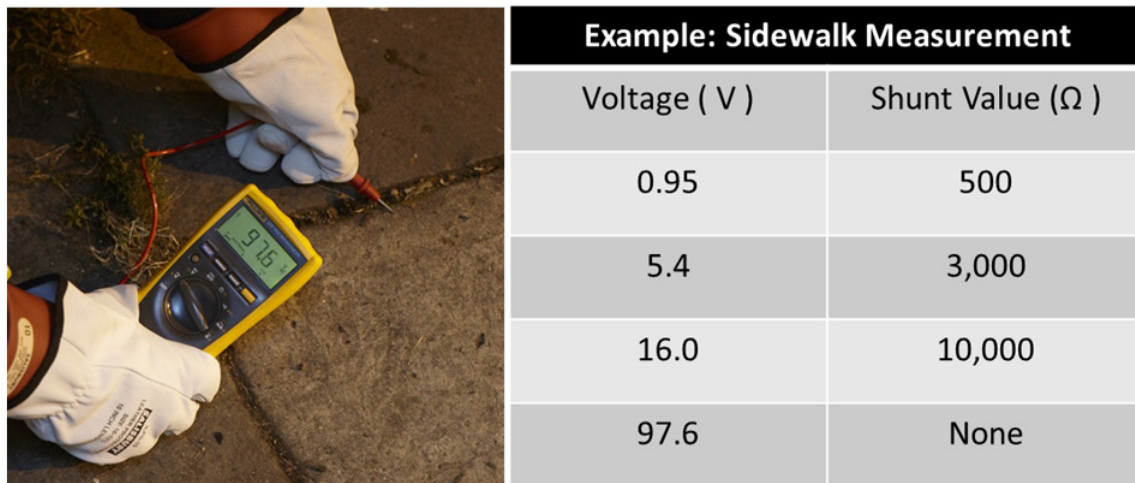


Figure 11—Sidewalk energized by underground fault

5.5.1.5 Handheld electric-field detectors

During a contact voltage investigation a handheld electric field detector as shown in Figure 12 and Figure 13 helps an investigator to determine that candidate references are not energized, thereby completing the first step for ensuring a qualified reference. They often have displays that give a relative indication of field strength. Any voltage on a surface gives rise to an electric field. If the electric field is at or near zero, the voltage is also

at or near zero. The detector should be capable of indicating electric field strengths that are indicative of an energized object. Handheld voltmeters are capable of indicating the presence of voltage to some reference location, but they are not suitable for validating a qualified reference.



Figure 12—Using a handheld electric field detector to check for the presence of electricity on a candidate reference

Handheld electric field meters are also valuable for detecting contact voltage on a nearby surface or structure. They can be more sensitive than pen type testers but their application as a primary detection tool in an asset list based testing program is subject to limitations imposed by the use of the asset list itself.

5.5.2 Investigation protocol

Once a voltage is detected, it can be verified and measured. The measurement scenario is unconventional compared with typical forms of electrical measurement. Voltages may be variable and far below line voltage. Suitable qualified reference points may not be close by. Significant contact and ground impedances may be present. Active faults should also be assumed, which could place nearby objects or the earth itself at an elevated voltage as shown below.

[Figure 14](#) illustrates a measurement scenario where the neutral conductor of the supply circuit is open or highly resistive. Most of the return current for the street light flows through the earth via the driven ground and the street light standard mounting bolts. In doing so it creates a voltage gradient in the sidewalk. See [Annex A](#) and [Annex B](#) for a complete description of how to make a contact voltage measurement and how to perform a contact voltage investigation.