



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

IEEE Power and Energy Society

Developed by the
Transmission and Distribution

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STANDARDS

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

Developed by the

**Transmission and Distribution
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 1695-2024, IEEE Guide for 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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IEEE Guide for Understanding, Diagnosing, and Mitigating Stray and Contact Voltage

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

The purpose of this guide is to provide information essential to an understanding of stray and contact voltage and its effects, and to discuss widely used investigative and mitigative strategies. The guide will also help dispel misinformation surrounding this topic and enhance public safety.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{6,7}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

⁶The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁷The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

There are no normative references in this guide.

3. Definitions, abbreviations, and acronyms

3.1 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.⁸

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 frequencies (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 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: An area where wires, wire mesh, reinforcing bars, or other conductive elements are embedded in concrete and bonded together, thereby presenting a negligible impedance to current flow within the plane. The plane is bonded to the electrical grounding system along with any metallic structures or equipment that may become energized. This arrangement prevents a difference in voltage from developing within the plane and minimizes voltage differences between planes, grounded equipment, and the earth, for both stray voltage and contact voltage situations.

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.

⁸*IEEE Standards Dictionary Online* is available at: <https://ieeexplore.ieee.org/xpls/dictionary.jsp>.

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**).

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 public or animals. Stray voltage is not related to electrical faults.

3.2 Abbreviations and acronyms

CVD	contact voltage detection
DFT	discrete Fourier transform
DMM	digital multimeter
ESR	electric-shock report
GFCI	ground-fault circuit interrupter
NEV	neutral-to-earth voltage
PPE	personal protective equipment
THD	total harmonic distortion

4. General discussion

4.1 The nature of publicly and privately accessible voltages

Every time electricity is used, an 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 most electrical energy is delivered using alternating current (ac), expanding and collapsing electric and magnetic fields surround nearly all 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 the earth for reasons of safety, some amount of electrical current is also present in the following:

- 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 domesticated animals can be exposed to manmade voltages. These exposures can occur when contact is made between conductive surfaces that have a difference of electric potential between them. People are generally not always aware of these ubiquitous sources of potential voltage exposures. The exposure levels are generally imperceptible and far below the levels known to be hazardous or capable of causing harm.

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

Investigation into the presence of voltage on objects that are not part of the electrical system requires a consistent approach to accurately identify the source(s). The personnel that are charged with these investigations varies widely throughout the industry. This guide provides an understanding of the sources of stray and contact voltage, human and animal electrical sensitivity, and case studies to inform the user about the steps that can be used in an investigation. Equipment and measurement techniques are described to assist users in obtaining information that can be used in determining the source(s) of stray and contact voltages. Repair criteria for contact voltages and mitigation for stray voltage are also discussed.

4.2 Detection of elevated voltages

The voltage on a surface or structure not intentionally energized can be detected or reported 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 an elevated voltage can 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 because 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.

4.3 Differences between stray voltage and contact voltage

The term “stray voltage” has historically been used by the public and the press 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 the following:

- 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 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 utility’s and customer’s electrical systems are operating as intended. As defined in this guide, this type of accessible voltage is termed “stray voltage.”

Publicly 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 6](#).

Users of this guide should be aware that other references including the USDA Handbook no. 696 [B52] and the Merck Veterinary Manual [B38] use the terms “stray voltage” and “contact voltage” differently than they are used in this guide and may use the terms interchangeably. When a publicly accessible elevated voltage (an “exposure 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.

4.4 The difficulty of stating a level of hazard in terms of voltage

One of the difficulties of stray and contact voltage exposure assessment becomes apparent when trying to answer the question, “what level of voltage can be hazardous?” 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. People can 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 can also have increasingly negative consequences.

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. A specific voltage threshold or measurement alone cannot be used to distinguish stray voltage from contact voltage.

Because contact voltage is fault-related and can change from an imperceptible level to a potentially hazardous level in a short period of time, a determination of the voltage source should be made. This process requires a variety of measurements and tests and is described in [Clause 8](#) of this guide. 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 stray and contact voltage is well established. What we now know about human and animal exposure to conducted current, including levels of perception and sensitivity, is discussed in detail in [Clause 5](#) 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 8](#) and [Clause 9](#).

4.5 Energy loss

Energy losses can result from faults such as damaged underground secondary conductors and may persist for long periods of time. The impedance of the fault and the return pathway may result in current levels many times lower than the rating of the circuit breaker or fuse. Faults that do not result in a public report or concern may remain until detected through direct or incidental detection (see [4.2](#)).

In one example, Chen and Larson, 2018 [[B5](#)] estimated the annual losses due to electrical faults within the UK to be 0.59 TWh, roughly 0.17% of the total power supplied to the country. Utilities typically include these losses in their technical losses, defined as the difference between the energy input into a feeder and the energy billed to consumers. This category of losses includes transformer and cable losses that vary based on power delivery and can be reduced by addressing the efficiency ratings of transformers and increasing cable sizes. Unlike these traditional losses, contact voltage losses are not the result of power flowing through the system and only vary based on the operating voltage and fault impedance of the conductor. The authors estimated contact voltage losses to be 2.5% of the unmetered portion of the technical losses in the distribution networks within the UK.

4.6 Safety procedures and methods

The contents 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. Possible contact voltages present can be considered and planned for so that the correct PPE is available on-site.

5. 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 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 [[B45](#)]). 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 the objective is to identify and then mitigate the electrical fault that is the source of the contact voltage.

5.1 Impedance of the human body

Research shows that the shock severity is proportional to the 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 [B30] gives recommended values for body impedance, which are based on research conducted by Dalziel, 1946 [B7], Dalziel, 1972 [B9], Dalziel and Lee, 1969 [B10], Geddes and Baker [B19], Geiges [B20], Kiselev [B35], and Osypka [B43]. 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 [B12] 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 [B30] uses 1000 Ω for 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's 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 [B30] 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.

5.2 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 [B12] 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 [B11]). Perception thresholds are determined from experiments with 167 adult men (Dalziel, 1972 [B9]) and Thompson's experiments on 40 adult men and women (Thompson [B50]). 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. It was assumed that the thresholds for children are half of the thresholds for an adult male.

Dalziel and Lee [B10] derived the so-called "electrocution equation" from accidental electrocution data documented by Lee [B36]. The incidents occurred in England and Wales during the years 1962–1963. Of the incidents, 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 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 (1) 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 [B30] 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 (2) that is applicable to children.

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

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



Figure 1—Effects of 50/60 Hz electric current on body (3s contact)

Relying on the research of Dalziel and others, Whitaker [B53] of Underwriters' Laboratories (UL) established a maximum uninterrupted 60 Hz ac current of 5 mA as the threshold of 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 [B25]). UL 943 [B51], establishing a trip threshold of 6 mA for Class A ground fault circuit interrupters (GFCI) intended for the protection of personnel.

5.3 Animal electrical sensitivity

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

5.3.1 Dairy cows

Table 2 documents the electrical sensitivities of dairy cows (ASABE EP473.2 2001 [B4]).

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 are 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 is 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 the use of a 500 Ω resistor to conservatively represent both the cow's contact resistance and the resistance of the path from hoofs to mouth at poorly drained, wet locations surrounding watering devices, and 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 (Reinmann [B45]).

5.3.2 Swine

Table 3 documents the electrical sensitivities of swine (Godcharles, Matte, and Martineau [B21], Gustafson, 1986 [B23], Kennedy [B32], Reinmann [B45], Robert, Matte, and Martineau, 1996 [B47], Robert, Matte, and Bertin-Mahieux, 1992 [B48]). Research suggests that swine adapt to voltage exposure in a similar way as cattle (Matte et al. [B35] and Reinmann [B45]).

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.

The voltage threshold levels are based on the use of a 500 Ω resistor to conservatively represent the sow's contact resistance and the resistance of the path from hoofs to mouth.

5.3.3 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 [B14] and Duvaux-Ponter, et al., 2006 [B15]). Hoof-to-mouth impedances ranged between 2465 Ω and 9100 Ω in testing, with 50% of the test subjects measuring 4796 Ω (Roussel, Ennifar, Boissy, Louyout, and Duvaux-Ponter 2011 [B49]).

5.3.4 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 high electrical resistance of poultry (between 350 k Ω and 544 k Ω) (Reinemann [B45]).

6. Voltage sources

Although small voltages from a variety of sources can often be measured at publicly and privately accessible locations (e.g., dc voltage from naturally occurring galvanic cells and radio frequency voltage from nearby radio transmitters), this document discusses only voltage from power frequency sources related to the delivery and use of electricity.

As defined in 4.3, stray voltage is some amount of measurable voltage present between conductive surfaces that are near operating electrical systems, while contact voltage is publicly accessible voltages that are the result of an existing fault condition. As a result, the sources of these voltages are different.

6.1 Causes of contact voltage

Contact voltages can arise from two distinct types of faults in 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 most cases, the voltage measured at the time of investigation is more than 5 V, but many cases are reported below 5 V (New York State Public Service Commission [B41]). Multiple voltage measurements recorded at different times of day, or on different days often yield different results due to 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.

A fault can occur when 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, 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 a 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 the following:

- a) *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.

- b) *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.
- c) *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 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.
- d) *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.
- e) *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 interfere with 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.

6.2 Sources of contact voltage

Sources of contact voltage can be categorized into two sources, phase conductor and neutral conductor. 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. Total harmonic distortion (THD) is a measure of the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency. Equation 3) below shows the calculation for THD.

$$V_{THD}(\%) = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 \dots + V_n^2}}{V_1} * 100 \quad (3)$$

where

- V_1 is the voltage at the fundamental frequency, typically 60 HZ in North America
- V_2 is the voltage at second harmonic frequency
- V_3 is the voltage at third harmonic frequency
- V_4 is the voltage at fourth harmonic frequency
- V_n is the voltage at n^{th} harmonic frequency

The power quality standard IEEE Std 519-2022 [B31] requires that for voltage delivery of ≤ 1 kV utilities limit THD to 8%.

6.2.1 Contact voltage from phase conductor sources

The harmonic content of the source and the harmonic content of an inadvertently energized object will have the same THD percentages but may not have 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. As shown in Equation (4), the voltage at this location results from current passing through a series of resistances, behaving like linear loads and not contributing to a further increase in THD from its source.

$$V_{object} = i_{fault}(Z_{fault} + Z_{earth} + Z_{ground} + Z_{neut} + \dots) \quad (4)$$

where

V_{object} is the voltage measure on the energized surface
 i_{fault} is the fault current
 Z_{fault} is the impedance between the source conductor and the energized object
 Z_{earth} is the impedance of the earth return path
 Z_{ground} is the impedance of the grounding path
 Z_{neut} is the impedance of the neutral

Another way to look at this is shown in Equation (5). Figure 2 shows a simplified version of the measurement schematic.

$$V_{object} = \frac{V_{source}(Z_{earth})}{(Z_{fault} + Z_{earth})} \quad (5)$$

where

V_{object} is the voltage measure on the energized surface
 V_{source} is the source voltage (typically 120 V in North America)
 Z_{fault} is the impedance between the source conductor and the energized object
 Z_{earth} is the impedance of the earth return path

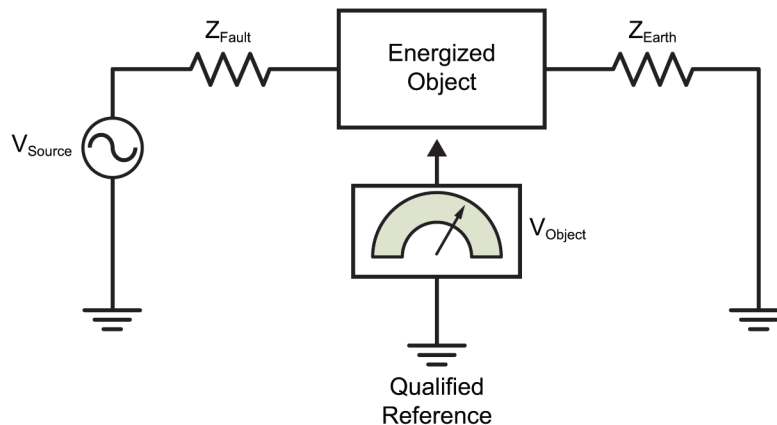


Figure 2—Phase conductor contact voltage source

The previous equation suggests that the voltage level on a conductive surface may change as the 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 3 depicts a typical contact voltage waveform resulting from damaged insulation on a phase conductor, with Figure 4 providing a histogram of the DFT of this waveform. A DFT provides amplitudes of the individual harmonics that make up the waveform.

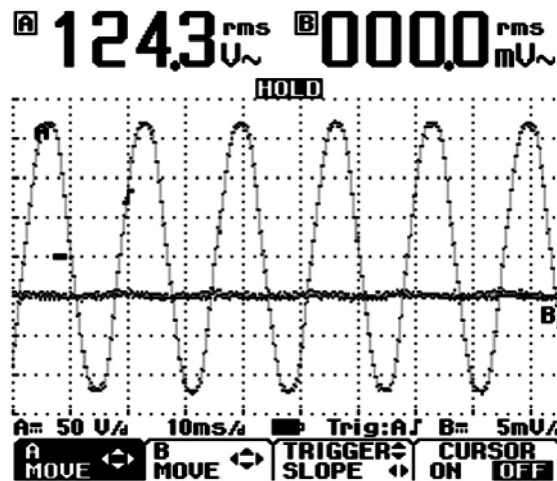


Figure 3—Contact voltage waveform resulting from damaged insulation on a phase conductor

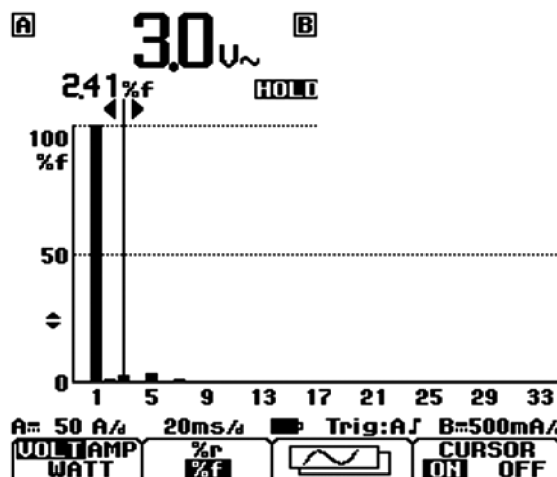


Figure 4—Contact voltage histogram resulting from damaged insulation on a phase conductor

Contact voltage from phase conductor sources will consistently show the fundamental frequency (i.e., 50/60 Hz) sinusoidal waveform with a low harmonic 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. As previously discussed, these contact voltages can 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 hazards to the public and maintain system reliability. It should be noted that some contact voltages associated with neutral conductor faults may also exhibit a THD of less than 10% THD and can occur when the load is predominately a linear load, or where the utility circuit is single phase and the fundamental neutral current is not canceled.

In summary, when the THD is below 5%, it is more likely that the source of the contact voltage is from a phase conductor. When the THD is above 10%, it is more likely that the contact voltage source is from the neutral.

6.2.2 Contact voltages from neutral conductor sources

An uncompromised neutral conductor is a low impedance path for return current. Open and/or high-impedance neutrals are considered electrical faults because normal return current and fault current are forced to take higher impedance parallel return paths. This can negatively impact protection schemes and create publicly accessible contact voltages. Because they are fault-related these voltages may be capable of rising to a potentially hazardous level. In addition to electric-shock reports (ESRs) and contact voltage detections (CVDs) a defective neutral may result in customer voltage complaints and reports by cable TV and telecommunication crews of excessive current on their cable shields and messengers.

A higher level of harmonics in faults is typically associated with neutral conductors and is a result of the characteristic of the current on that 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, LED 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 to 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 (6).

$$V = Z\sqrt{(I_{h1}^2 + I_{h2}^2 + I_{h3}^2 + \dots I_{hn}^2)} \quad (6)$$

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 the return-path impedance is high (e.g., a high-impedance neutral connection), the voltage drop can be significant. And because the voltage drop is directly proportional to the total current (fundamental and the harmonics), it is expected that 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 typically caused by system return current on a neutral return path.

Many of the circuits feeding residential, commercial, or industrial facilities have neutral return currents with at least a 10% or greater harmonic current content. There are exceptions such as when a circuit has only motor or heater load and may exhibit less than 10% THD due to the linear current flowing in the neutral return path.

Figure 5 depicts an example of a contact voltage waveform from a neutral conductor source, with Figure 6 providing a histogram of the discrete Fourier transform (DFT) of this waveform.

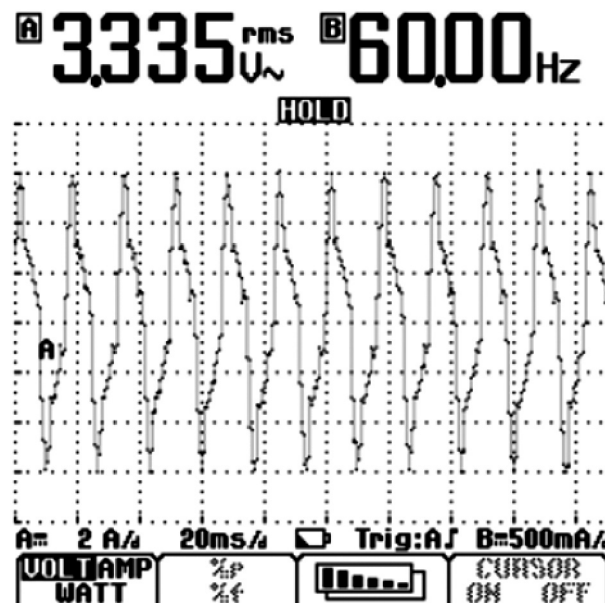


Figure 5—Contact voltage waveform from a neutral conductor source

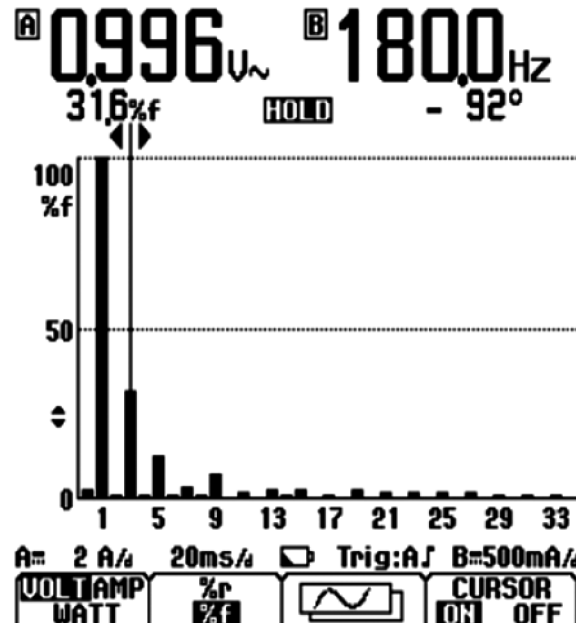


Figure 6—Contact voltage harmonics histogram from a neutral conductor source

In cases where the THD of the measured voltage is greater than 10%, it may not be clear whether the source of the voltage is a result of a normal return current, or a faulted neutral conductor (open or nearly open neutral). Harmonic level measurements alone cannot determine the voltage source, additional inspection and testing 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.

In cases without defective equipment identified after a thorough investigation with the voltage resulting from normally operating equipment, investigators may consider the voltage under investigation as a stray voltage.

6.3 Causes of stray voltage

Stray voltages are present as a normal result of operating an electrical delivery system. They are most prevalent on grounded electrical systems where they are caused by voltage drop as normal system return current (primary and secondary) passes through the impedance of the neutral/ground network. Under specific physical and electrical circuit conditions, stray voltage may also be caused by inductively coupled currents and capacitively coupled voltages.

6.3.1 Normal return current

Stray voltage can occur in the vicinity of any operating electrical system, whether referenced to earth or not. This is more likely to occur on a grounded electrical system, especially a multi-grounded system consisting of a neutral conductor with multiple intentional and un-intentional connections to earth (Figure 7). As the return current passes through the impedance of the neutral return path to the source a voltage is developed (Figure 8) between the neutral conductor (and all conductive objects connected to the neutral conductor) and the earth. This voltage is referred to as neutral-to-earth voltage (NEV).

Elevated NEV can be caused by the flow of normal neutral return current through the electrical circuit's return-path impedance, or it can be the result of fault current flow through the return-path impedance. When the NEV is caused by normal neutral return current, that portion of the NEV that can be measured between surfaces that can be simultaneously contacted by people or their animals is stray voltage. Generally, as the amount of normal neutral return current increases or the return-path impedance increases, the level of stray voltage also increases.

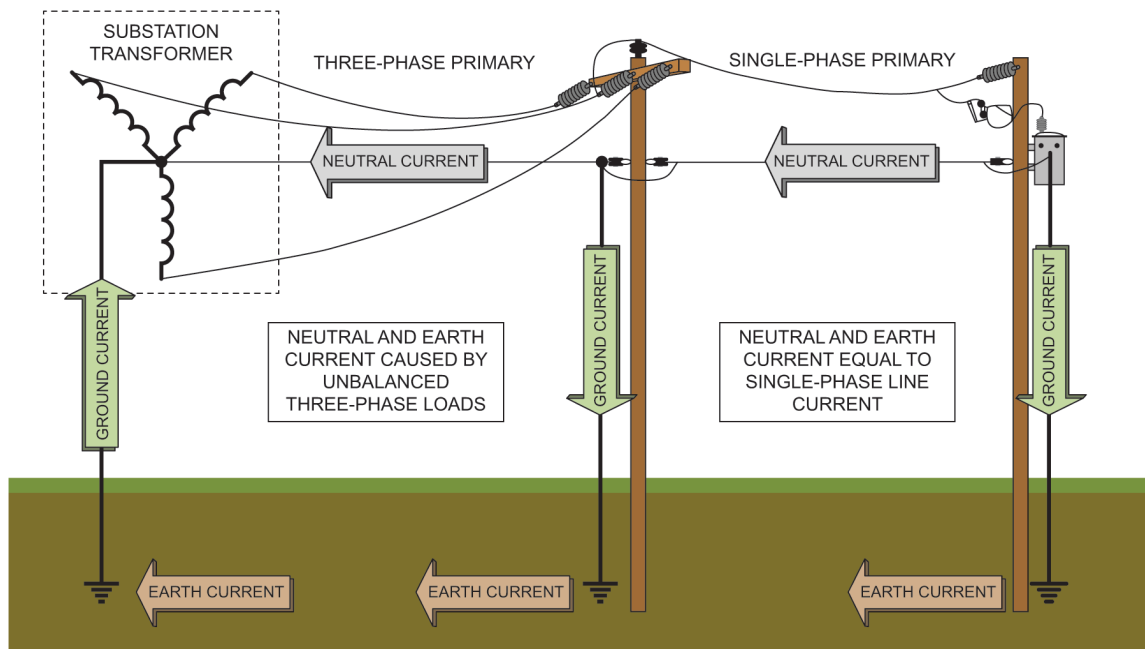


Figure 7—Normal neutral, ground, and earth current paths in a multi-grounded Wye distribution system

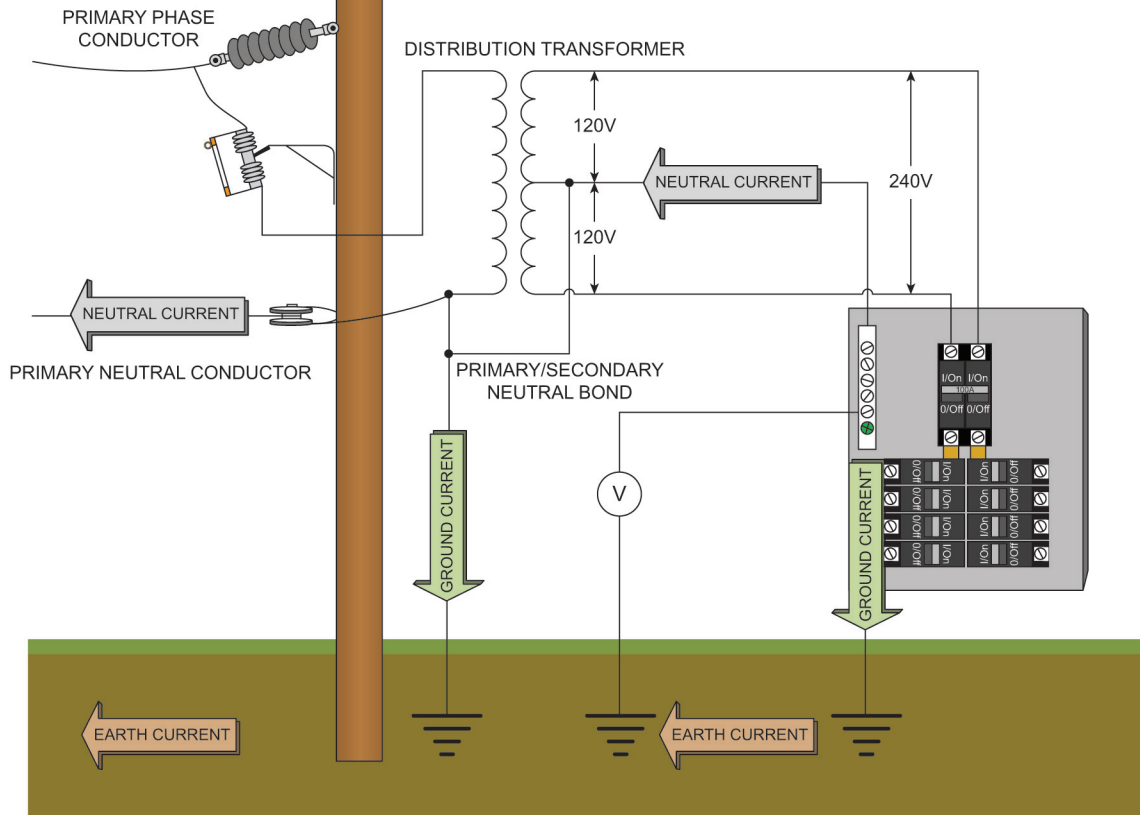


Figure 8—Typical residence with secondary neutral bonded to primary neutral and earth

A discussion of the harmonic content of voltage sourced from the neutral conductor can be found in 6.2.2. NEV measurements typically contain 10% or greater harmonic content with magnitudes that vary depending on loading. A recorded NEV profile can sometimes reveal the source as either primary or secondary depending on the different loads in the area. Monitoring NEV is also an important step in determining whether the neutral return path impedance needs to be lowered.

6.3.2 Factors that increase return current

On a radial single-phase electrical system return current increases when the amount of load served increases. As the system becomes more complicated (e.g., polyphase, with power factor correction, with multiple bridging points), the return current may increase for other reasons.

On three-phase electrical systems with phase-to-neutral connected transformers load unbalance results in return current. The greater the unbalance, the larger the return current. Non-linear loads such as EV chargers, variable frequency drives, and switch mode power supplies used in mobile phone chargers and computer power supplies generate a multitude of harmonics in the power system, some of which are the 3rd harmonic. On three-phase systems, triplen harmonics (especially the 3rd harmonic) are of particular concern because they add arithmetically in the neutral conductor and can significantly increase the amount of neutral return current (Dorr, Martino, and Hanebuth [B13]).

Figure 9 shows a typical switch mode regulated power supply and input current waveform. Notice current is only drawn as the capacitor charges, creating a very non-linear load current. Figure 10 shows the harmonic spectrum of the current waveform and a large number of harmonics, with a few harmonics having magnitudes nearly as large as the fundamental. Figure 11 shows a balanced three-phase system with only fundamental (60 Hz) current and demonstrates how balanced load currents cancel. Figure 12 shows a perfectly balanced three-phase system with fundamental and 3rd harmonic currents and demonstrates that these currents do not cancel. These non-linear loads create a neutral current because of triplen harmonics.

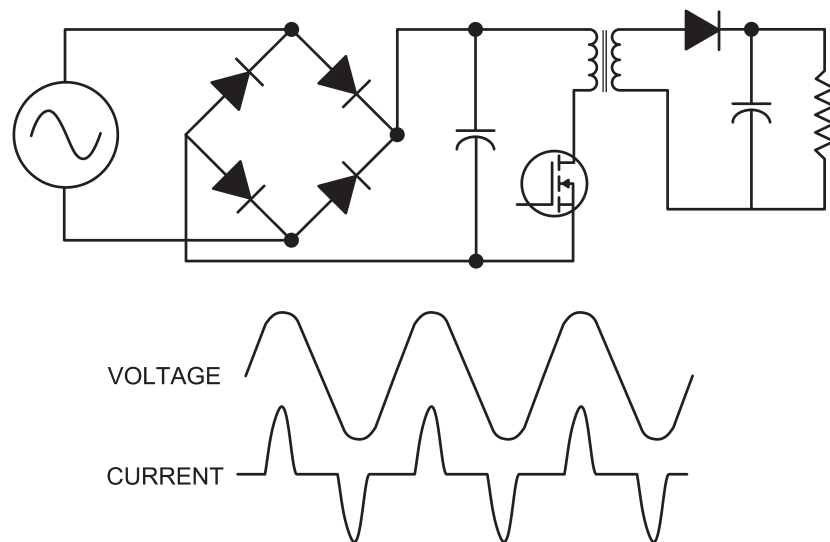


Figure 9—Switch mode power supply diagram and input current waveform

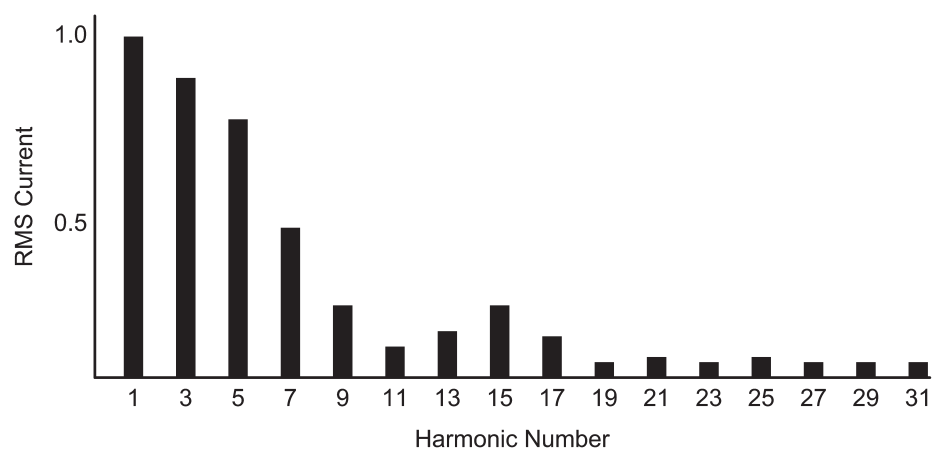
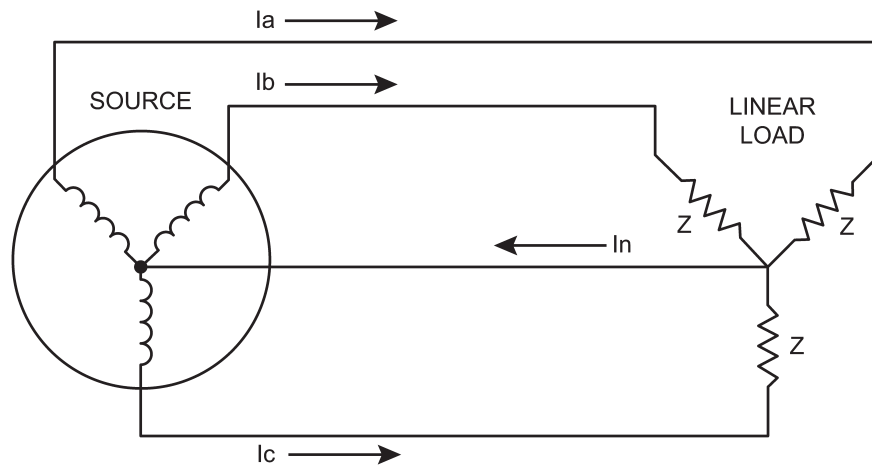


Figure 10—Harmonic components of switch mode power supply input current



$$I_a = I \sin(\omega\tau)$$

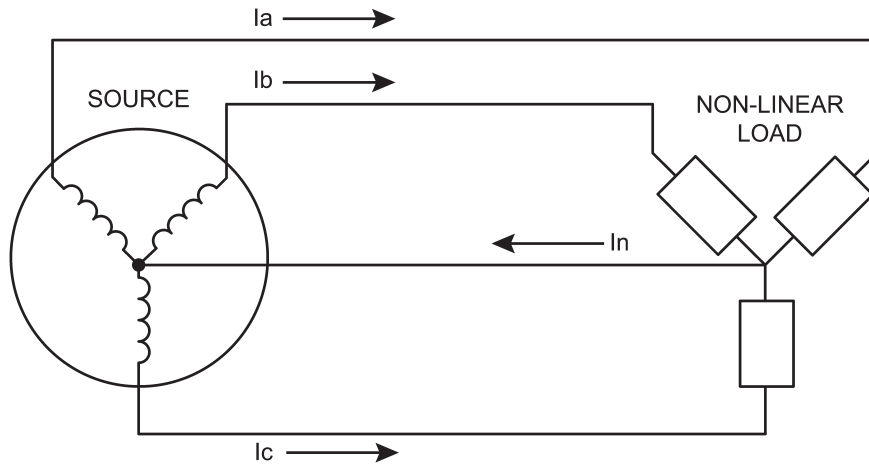
$$I_b = I \sin(\omega\tau + 240^\circ)$$

$$I_c = I \sin(\omega\tau + 120^\circ)$$

$$I_n = I_a + I_b + I_c$$

$$I_n = I \sin(\omega\tau) + I \sin(\omega\tau + 240^\circ) + I \sin(\omega\tau + 120^\circ) = 0$$

Figure 11—Balanced linear load results in zero-neutral current



$$I_a = I \sin(\omega\tau) + I \sin(3\omega\tau)$$

$$I_b = I \sin(\omega\tau + 240^\circ) + I \sin[3 \times (\omega\tau + 240^\circ)]$$

$$I_c = I \sin(\omega\tau + 120^\circ) + I \sin[3 \times (\omega\tau + 120^\circ)]$$

$$I_n = I_a + I_b + I_c$$

$$I_n = I \sin(\omega\tau) + I \sin(3\omega\tau) + I \sin(\omega\tau + 240^\circ)$$

$$+ I \sin[3 \times (\omega\tau + 240^\circ) + I \sin(\omega\tau + 120^\circ) + I \sin[3 \times (\omega\tau + 120^\circ)]]$$

$$= I \sin(3\omega\tau) + I \sin(3\omega\tau + 720^\circ) + I \sin(3\omega\tau + 360^\circ)$$

$$I_n = 3 \times I \sin(3\omega\tau)$$

Figure 12—Balanced non-linear load elements

6.3.3 Factors that increase return-path impedance

Factors that may cause an increase in return-path impedance include poor soil condition (e.g., highly resistive soil, such as dry sand), loose, or corroded grounded and grounding conductor connections, neutral conductor size and length, inadequate and/or ineffective bonding, and insufficient system grounding.

6.4 Electromagnetically coupled currents and voltages

The magnetic and electric fields from a line can result in inductive and capacitive coupling on nearby objects. These topics are discussed below, primarily focusing on distribution-related coupling. Transmission lines can also produce similar ac interference effects on adjacent facilities such as long parallel pipelines and railroads. IEEE Std 2746 [B32] focuses on these transmission-line related aspects in greater detail.

6.4.1 Inductive coupling (magnetic field)

Inductive coupling is the transfer of energy between a current-carrying conductor and nearby conductive loops due to a time-varying magnetic field that is created by a time-varying current in the energized conductor. A common example of inductive coupling capable of creating stray voltage can occur when a multi-grounded distribution circuit is underbuilt on a transmission structure. The magnetic fields associated with transmission system operation will induce a current in the conductive loops formed by the distribution system neutral, its connections to earth (e.g., ground rods), and the earth path between those connections. The amount of current that flows in each conductive loop and the amount of NEV created is dependent on numerous factors,

including the amount of current in the transmission-phase conductors, the distance between the transmission and distribution systems, the integrity of distribution neutral and ground lead connections, and soil resistivity. Increased levels of NEV due to inductive coupling can result in increased levels of stray voltage.

Within the range of the electromagnetic fields, non-canceling triplen harmonics created by respective harmonic voltages (Electric Field) and harmonic currents (Magnetic Field) may be observed on pipelines, railroad tracks and virtually any conductive apparatus. The waveform characteristics are similar to what is seen by a down ground or guy wire bonded to an unbalanced neutral wire, which connects the multigrounded neutral to earth.

Figure 13 and Figure 14 show typical waveforms and harmonic content of an induced voltage.

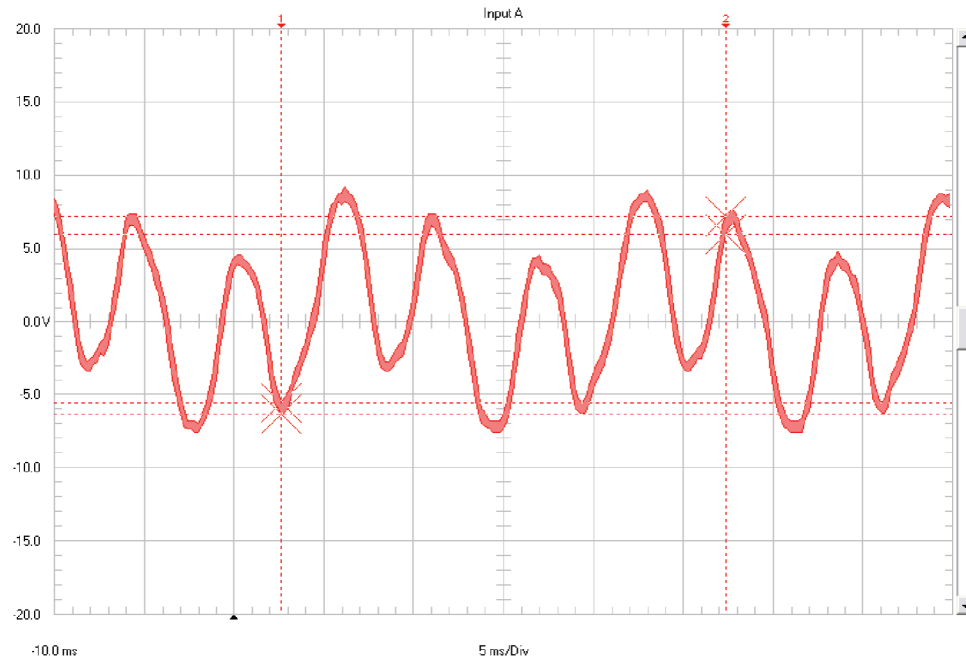


Figure 13—Typical stray voltage waveform as a result of an induced voltage

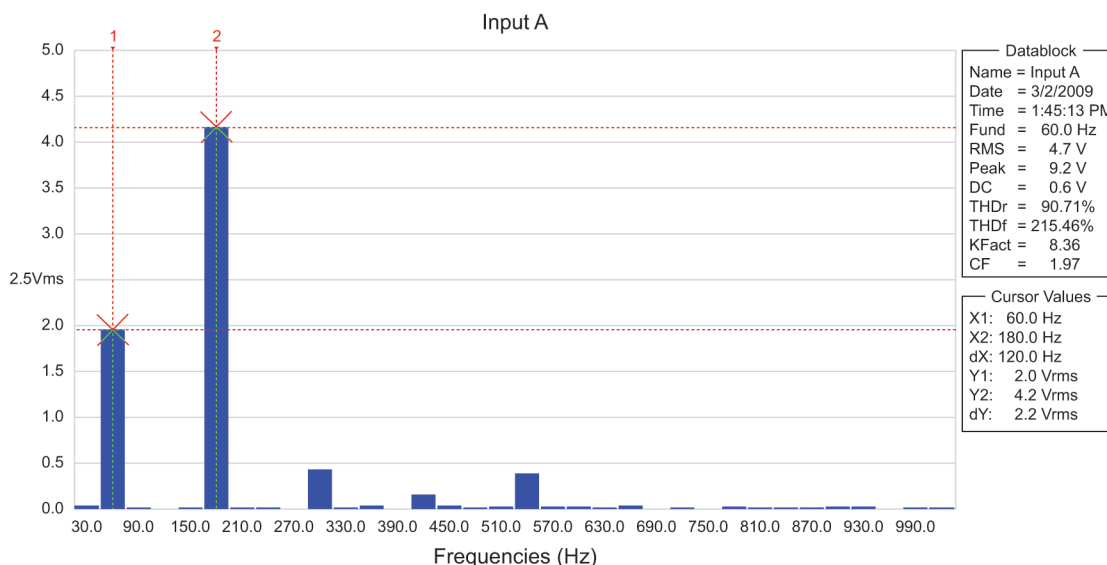


Figure 14—Typical stray voltage waveform as a result of an induced voltage

6.4.2 Capacitive coupling (electric field)

Capacitive coupling occurs when a time varying electric field exists between two adjacent conductors, typically less than a wavelength apart. An example of capacitive coupling that can result in a stray voltage exposure may occur when a long metallic poorly grounded animal feed bunk is constructed near or beneath a high voltage transmission line. The magnitude of the capacitively coupled voltage on the feed bunk depends on the distance to the energized conductor, the electric field strength (i.e., system voltage), the size and shape of the feed bunk, and how well it is connected to earth. If the feed bunk is effectively grounded, the voltage on it is reduced to near zero potential with respect to earth. When near zero potential a person or animal standing on the earth and making contact with the feed bunk will not be exposed to perceptible current. If the feed bunk is poorly grounded or not grounded at all, a voltage can exist between it and the earth and a perceptible exposure is more likely to occur.

7. Detection and measurement equipment

A variety of test equipment is needed to detect and measure voltages effectively. Traditional instruments are widely used for this purpose. Additionally, equipment and instrumentation designed specifically for use in stray and contact voltage detection and measurement is available.

7.1 Detection equipment

7.1.1 Equipment for detecting voltage

This clause 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 hand-held 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 help ensure that the selected devices perform as required for the objectives of the given test program and as expected in the given application.

7.1.1.1 Mobile electric field detection

Mobile electric field detection relies on a capacitive sensor that 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 15. 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 the 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 the low-voltage signals in their immediate proximity. Therefore, mobile detection is not generally suitable in areas directly under or near these high-voltage overhead conductors.



Figure 15—Example of a mobile detection system

7.1.1.2 Hand-held detection

There are three types of hand-held detectors currently in use for detecting inadvertently energized objects and surfaces. These include the following:

- a) Probe-based (test lead) voltmeters
- b) Physical contact-based hand-held capacitive or “pen” testers (as shown in Figure 16)
- c) Non-contact based electric field strength indicators

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



Figure 16—Voltage detection using a pen tester

7.1.2 Probe-based voltmeters

Probe-based voltmeters and their uses are additionally described elsewhere in [Clause 7](#). 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-off inefficiencies are the amount of time it takes to test individual assets and the need to identify a qualified reference (see [7.2.2](#)). Since voltage measurements are often made with a qualified reference located some distance from the energized object, it may be necessary to use an extended length of test probe wire to make a connection (see [7.2.6](#)).

[Figure 17](#) shows a streetlight and its base. It is important to note that physical contact is not electrical contact. Therefore, each part of the streetlight should be tested separately (e.g., access panel, post, attachment points, etc.)

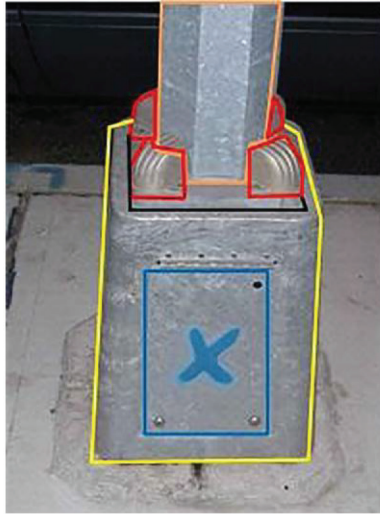


Figure 17—Streetlight components

7.1.3 Physical contact pen testers

Contact-based pen testers are capacitively coupled detectors that provide a visible or audio indication the object under test is energized at a voltage above the detector's specified voltage threshold. Pen testers operate assuming the user is capacitively coupled to the earth and at zero potential and, therefore, do not require a test lead connected to a qualified reference 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, streetlights, 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. Hand-held pen testers are far more practical for testing many 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 obtain the following repeatable measurements:

- 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 17](#)).
- 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 barehand 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 against a known reference often as battery performance may change due to environmental conditions (cold weather) and the batteries age.

7.1.4 Non-contact electric-field detectors

Hand-held 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 hand-held 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 7.2.2).

The sensitivity of hand-held electric-field detectors can vary greatly based on their intended application. For example, some hand-held electric-field detectors are designed for measuring human exposure 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 voltage, hand-held electric-field detectors are also subject to false readings that may be caused by a variety of electrical noise sources. Like mobile electric-field detectors, hand-held detectors may be affected by electric fields from nearby overhead distribution and transmission lines (Consolidated Edison Co. of NY, Inc. [B46]).

During an investigation a hand-held electric field detector, as shown in Figure 18 and Figure 19, helps an investigator to determine that candidate references are not energized, thereby completing the first step for establishing 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. Hand-held voltmeters can indicate the presence of voltage to some reference location, but they are not suitable for validating a qualified reference.



Figure 18—Using a hand-held electric field detector to check for the presence of electricity on a candidate reference

Hand-held electric field meters are also valuable for detecting 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 using the asset list itself.



Figure 19—The use of a hand-held electric field detector to locate energized objects

7.2 Measurement equipment

Several parameters are routinely measured in stray and contact voltage investigations. Much of the test equipment employed should be familiar to personnel involved in this field of work. Instruments to measure voltage, current, and harmonics are needed. Typically, portable battery-powered instruments are used. Some additional items, such as shunt resistors and load banks, are also used.

When performing electrical testing, it is important to follow safety guidelines and maintain and use instruments per the manufacturer's directions.

7.2.1 True rms voltmeter

Usually, voltage is measured with a digital multimeter (DMM.) The DMM used should meet the following three basic requirements:

- a) It should be able to separate ac and dc voltages
- b) It should have a minimum voltage resolution of 0.01 V
- c) It should have an impedance of at least 1 M Ω

It is important to understand the properties of the voltmeter when used to evaluate potential cases of stray or contact voltage. Energized surfaces and objects can have ac, dc, or both voltages present.

An ac coupled voltmeter is useful to separate electrical system contributions to voltage on an energized object from dc that may be imposed by other sources such as a cathodic protection system.

When routing measurement leads greater than 7.5 m (25 ft) care should be taken to help avoid areas where there is significant RFI or other noise sources, such as radio transmission towers or large adjustable-speed drives.

It is not recommended to use an analog voltmeter as the typically low input impedance of these devices can introduce measurement error.

7.2.2 Qualified reference

Accurate measurements of voltage levels on energized objects and surfaces, including the neutral/ground network 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 has a low impedance connection to the earth. All voltage measurements other than exposure measurements should be made via the qualified reference.

A qualified reference is selected from available nearby candidates that include fire hydrants, fence and signposts, and other conductive metal objects in intimate contact with earth. In rural settings, a temporary ground rod may be used, but the investigator should verify that it is of adequate length to provide a low impedance pathway to the earth. This is especially important when low values of shunt resistance, such as 500 Ω are employed.

When using a temporary ground rod, it should be installed in moist soil 30 m (i.e., ~100 ft) or more from buildings and any conductive underground structures such as water pipes or well casings, building grounds, etc. Temporary ground rods are rarely used in urban environments due to concerns about driving a rod into existing underground infrastructure. Before placing rods into the earth, check local requirements for avoiding underground infrastructure such as electrical, water, gas, and telecommunications.

A candidate reference can be confirmed to have low impedance to earth. Measure voltage from the energized object, surface, or structure to the candidate reference both with and without a shunt resistor connected. The shunt resistor typically has a value of 500 Ω to 10 000 Ω , depending on the conditions being evaluated. See 7.2.11 for more information. A comparison of those two voltage readings will indicate if the reference has a low impedance to earth. If there is a significant change in measured voltage an attempt should be made to seek lower ground resistance by selecting another candidate reference. When the shunt and no shunt voltage readings are similar, the candidate reference has low impedance to earth.

Since a qualified reference is being used for repeatable measurements, any voltage on the reference will introduce measurement error. A hand-held electric field detector can be used to determine if a candidate reference is within the voltage gradient of a fault or is in contact with the electrical system. If a suitable hand-held electric field meter is not available, candidate references can be qualified by making voltage measurements from the surface under test to multiple candidate reference locations. The voltage reading should be the same among them if all reference locations are at or near zero potential. If they differ, one or more references could be at elevated potential. The larger voltage measured is usually the correct one, though it is appropriate to corroborate recorded values with more measurements rather than assuming a value based on only one measurement.

The above procedures will help ensure that an adequate qualified reference has been established.

General considerations for selecting a qualified reference include the following:

- a) Do carry long test leads (see 7.2.6), 15 m (50 ft) minimum, to easily reach a qualified reference in the immediate area. Test leads with strong spring clamps are advisable.
- b) Do verify the continuity of reference leads using a multimeter before beginning an investigation.
- c) Do spend extra time making a clean, bare metal contact for your measurement.
- d) Do verify that the candidate references are not energized.
- e) Do make a record (photographic if possible) of the qualified reference, as it can be used to verify future measurements.
- f) Do not drive ground rods without following applicable procedures to help avoid disturbing underground infrastructure.
- g) Do not use references (i.e., ground rods, anchor bolts, etc.) inside or directly adjacent to the object under test. If the object is energized the candidate reference may also be energized.
- h) Do not connect to an auxiliary part of a candidate reference, such as an operating handle or knob. The main body is more likely to have better electrical connectivity to earth.

7.2.3 True rms ammeter

There are many types of clamp-on ammeters available in the market. Some digital clamp-on ammeters or DMM accessory clamp-on probes have auto-ranging from 1 A to their maximum current range value and are easily and accurately read. They may also have a locking function to measure peak amperes from rapidly changing loads such as motor starting current. The accuracy of many clamp-on ammeters is degraded when measuring currents below 1 A and these are not considered reliable. Detection of currents less than 1 A in grounding conductors can be of significant value in locating sources of stray and contact voltage. Special ac clamp-on ammeters are available, which have ranges from 1 mA to 20 A full scale. These ammeters can be used for measurements of low currents. 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. Digital multimeters (DMMs) with a built-in clamp-on ammeter are available and provide the user with the same functionality as using a separate current clamp. Care should be taken to select the proper measurement range of the meter to provide accurate current measurement.

During investigations, it may be necessary to make several current measurements. These measurements commonly include primary and secondary neutral current, load current, net current, and fault or leakage currents. The current in motors, lights, or other equipment can be measured to determine whether the equipment is operating properly. The current in the equipment grounding conductor can be measured to check for fault or leakage currents. Neutral current measurements can be made to assess neutral voltage drops and to determine whether the electric loads are properly balanced. For many current measurements, clamp-on-type ammeters or recording ammeters are used.

7.2.4 Power quality analyzer

A power quality analyzer is often used to measure the harmonic content of a voltage waveform during stray and contact voltage investigations. Understanding the harmonic content is to gain an understanding of the possible sources of voltage appearing on a surface or object. Several manufacturers offer multi-purpose instruments capable of measuring voltage, current, and harmonic content.

An important function of a power quality analyzer is the ability to perform a DFT of the voltage or current waveforms to provide individual harmonics on a bar graph. An example output from a harmonic analyzer is shown in Figure 20. A power quality analyzer complying with the specifications of IEC 61000-4-7 [B52] and IEC 61000-4-30 [B53] can provide consistent results when performing these measurements.