IGNITION OR SHOCK,
IS GROUNDING THE CULPRIT?

Frontiers in Power Conference – 2010
Oklahoma State University, Stillwater, OK

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Abstract – Ground is the reference for electrical system measurements and performance. Bonds and the neutral are connected to the ground system in a very precise way, but bonding and neutral is not a ground. Codes and standards for grounding are identified. A proper system is described. Stray current and transient management depends on proper ground connections. The three energization issues with grounding are illustrated. The fault process is described in detail. The difference in effect of electrical exposure to inanimate as well as biological organisms is discussed.

INTRODUCTION

What is the purpose of grounding? Can grounding or bonding issues cause ignition or shock? Where is a ground or return path used? What is the difference between ground, bond, and neutral?

An electrical ground is a connection to earth. *Ground* in electrical parlance is the common basis or reference for all electrical measurements, circuits, and safety.

Grounding is a very complex topic that is critical to electrical safety for biological specimens and property. The *National Electrical Code* (NEC) has over 28 pages devoted to the requirements plus numerous other Articles that reference the topic. [1] The *National Electrical Safety Code* (NESC) has specific requirements for grounding. [2] The Institute of Electrical and Electronics Engineers (IEEE) has multiple standards that are specific to grounding installations. [3] The National Fire Protection Association (NFPA) has myriad standards and guides that depend on grounding. [4,5,6]

The authors have published over 25 technical papers and have received numerous awards and recognition for their research on grounding and lightning. [7-16]

PERSPECTIVE

The significance of grounding is not readily understood by most engineers and investigators, but it is a major element of every electrical system.

It is well recognized that the "hot" wire in an electrical system is dangerous and can cause shock or a fire. Those incidents can only happen if there is a return path for the current from the "hot" wire. An electrical system involves a complete circuit or "circle" from the source through the wires to the load or fault and then returning back to the source.

The neutral or ground provides that return half of every conventional single-phase and direct-current electrical circuit.

Any electrical activity on a neutral or ground conductor is a clear indication of faulting involving the ground system. Improper grounding is a common problem. Ignition from electricity is often related to a grounding issue. Grounding issues are a code and therefore, a legal problem.

In looking at thousands of incidents, we have found that the ground system is seldom properly investigated. A complete and thorough examination of a failure incident has not been conducted until the grounding system is eliminated or the ground measurements have been made.

A SYSTEM

The three components of a grounding system are *grounding electrode*, *grounding electrode conductor*, and *bonding*.

Grounding electrode is the contact point with earth. The electrode may be existing metal in contact with earth, metal in concrete, or made electrodes. The grounding electrode may consist of a grid, loop, or rings. A ground rod is the poorest, but most common, form of a grounding electrode.

According to *NEC* requirements, if a made electrode has a contact resistance to earth of greater than 25 Ohms, an additional made electrode must be installed. The *NESC* is more specific. The ground must be less than 25 Ohms.

The *IEEE Green Boo*k - *Grounding* (IEEE Std 142) is even more direct. "This should not be interpreted to mean that 25 Ohm is a satisfactory resistance value for a grounding system." [3] The *Green Book* states "Resistances in the 1 Ohm to 5 Ohm range are generally found suitable for industrial plant substations and buildings and large commercial installations.” [3]

An acceptable ground resistance has been shown to be less than five (5) Ohms for normal 120 Volt, single-phase systems. A standard 20 Amp circuit breaker will not trip if a fault is directly to a ground system with circuit resistance (Z) greater than 6 Ohms. [7-16]

$$Z = \frac{V}{I} = \frac{120\ V}{20\ A} = 6\Omega$$

Unfortunately, very few installers, inspectors, or investigators measure ground contact resistance, due to lack of equipment, lack of knowledge, or both. As a result, inadequate grounding persists and is pervasive.

Grounding electrode conductor is the second component of a grounding system. The conductor is the wire that connects the grounding electrode to the rest of the system. The wire must be large enough to handle fault current that may arise when a failure occurs. The *NEC* specifies the minimum size of the conductor.

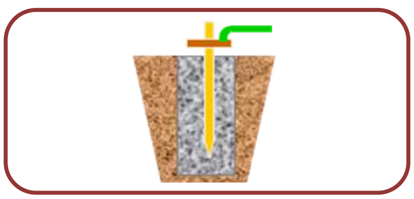

Figure 1: Grounding electrode & conductor

Bonding is the third component of a grounding system. Bonding connects metal surfaces that may become energized to the grounding system. Bonding is required between all grounding electrodes.

The NEC fine print note (FPN) advises to bond all metal even that not specifically noted in other sections of the Code. *FPN: Bonding all piping and metal air ducts within the premises will provide additional safety.*

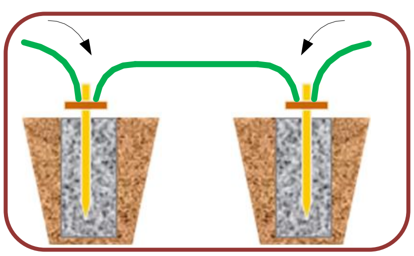

Figure 2: Multiple grounds bonded together

Consider two ground rods driven in the earth. There will be a potential difference (V_D) between them, because of the difference in ground resistance. Differences in resistance are caused by the electrolyte, moisture, and metals. When there is a voltage difference, current (I) will flow. A bond is necessary between the two grounds and all other metal surfaces to prevent a stray current path. [17]

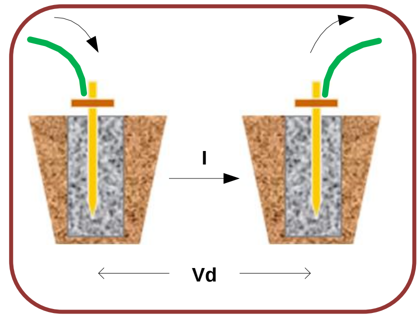

Figure 3: Unbonded results in stray current

GROUND CURRENTS

Ground currents may be *intentional*, *stray*, or *short duration*. The neutral carries intentional current. Stray current follows unintended paths. Transients are short duration. Each will be discussed in detail in the following paragraphs.

THE NEUTRAL

Neutral is a current carrying conductor. The neutral is sometimes called the common. The neutral is the return path for conventional single-phase circuits. The neutral carries the unbalance current.

The neutral is identified by white or gray insulation or markings. It is connected to the ground at one point and one point only. If connected at multiple points, the ground (earth) carries part of the neutral current and the ground is energized.

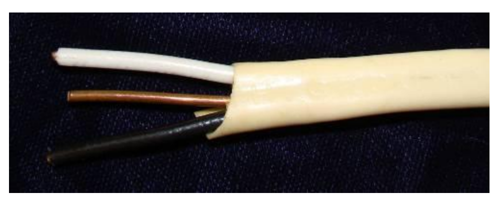

Figure 4: Neutral is white

A proper neutral is grounded at one point only, has good low-impedance connections, and carries only the current of the associated circuit.

STRAY CURRENT

Stray current is caused by three conditions. The most common is a neutral that is grounded at *multiple points*. Second, stray current can result from a *fault* of a hot wire to ground. Third, stray current is caused by a *difference* in potential of ground connections.

Stray currents are the result of improper grounding and bonding. Stray currents result from uncontrolled flow of electrical energy. The current takes an alternate path through the earth. The current can reenter a metal path at some point on its journey back to the source.

Research has been conducted to evaluate the amount of current that flows in the earth for a power system that has multiple ground points on the neutral. Multi-point grounds are typical of most utility overhead power lines. [14] The research found that 60% of the neutral return current actually travelled through the earth as stray current. [18]

In effect any system that has a neutral with two or more ground points, the return (neutral) current flows partially through the wires and partially through the earth. If one of the grounds is improper, the neutral current will take an alternate route through other conductive paths such as facility metal.

Risks: Stray current will energize unintended metal and will cause a potential difference between the soil and metal. The result is shock to living creatures and risk of fire to property.

MULTI-POINT NEUTRAL

Figure 5 illustrates a typical supply from the utility to the electrical service entrance meter at the facility, then to a receptacle or other load. The neutral is connected to earth at two locations. A portion of the energized neutral current traverses through the earth.

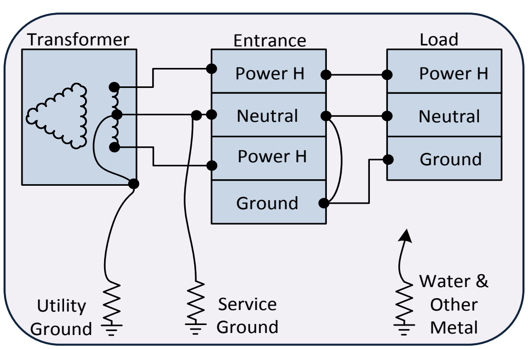

Figure 5: Multi-point ground has stray current

Disturbances in grounding, bonding, and transients will cause stray current to flow through alternate routes. The result is risk of property damage and personnel safety. It has been shown that high impedance, low energy connections can create ignition. [19] Similarly, it is known that very low current in the milliamp range (1/1000 Amp) can cause injury or death. [9-13,20-21].

TRANSIENTS

Transients, such as switching and lightning, should be shunted to ground. Transients are short duration disturbances on a power system as shown in Figure 6. Transients are commonly called surges, although that is only one type transient.

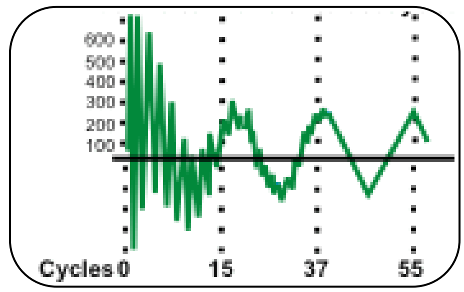

Figure 6: Transient

Transients are associated with *utility power* system operations. Transients also result from *lightning* discharge in the area. Finally, transients occur in every *on/off* activity of an electrical system. The difference between the three is the energy levels and the equipment that is exposed to the transient.

Most incidents associated with switching transients happen when the line is reenergized. Consider a traditional, incandescent light bulb. When does the bulb most frequently fail? Most failures occur when the switch is turned on and the bulb is energized resulting in thermal shock. That failure is due to an electrical transient.

With utilities, the transients may be associated with recloser operation, power transfers, capacitors, or outages.

Another common transient is lightning. Lightning is considered an act of God by some. Think about other weather conditions such as rain and temperature. These are equally an act of God. However, we have learned to control them with buildings and other structures.

Similarly, lightning can be controlled and directed by following electrical industry practices and standards. [3,4] The origin of lightning, like other weather, is an act of God. However, electrical damage due to lightning in most cases is an act of negligence or omission as illustrated in our previously published papers. [8]

Consider the example of a utility transient. If the ground path is adequate, the transient is shunted to earth, often by a lightning arrestor. [14] If the ground for the utility is inadequate, the transient seeks alternate paths to earth.

The path is any structure or ground that is nearby. Since the current will take multiple paths, only a portion may enter a structure which has a higher resistance than the utility. Nevertheless, as we have demonstrated previously, a high resistance path may very well be a source of ignition. [19]

ENERGIZATION ISSUES

There are three fundamental energization issues with grounding conductors – *energized ground*, *floating neutral*, and *energized neutral*.

An *energized ground* has current from another circuit flowing in the conductor. The cause is poor connections and poor ground resistance. The "tell" is melted insulation on the ground wire, or on the jacket of multi-conductor cable, even though the energized conductor may not be melted.

Figure 7: Energized ground

Floating neutral has a poor connection to the source. The result is heat and current taking an alternate path. Shock and fire will result.

Figure 8: Floating neutral

Energized neutral has current from another circuit on the conductor. The cause is poor connections and poor ground path. The "tell" is melted insulation on the neutral or ground wire but the normally energized conductor may not be melted. Energized neutral is particularly observed on devices and fixtures connected to another ground path, such as a water line. The effects are commonly seen on clothes washers, dishwashers, and refrigerators with ice makers. Shock and fire will result.

FAULT FORMS

Electric malfunction can follow three forms - *loss of insulation*, *high impedance connection*, and *breaking* faults.

Loss of insulation causes a voltage breakdown malfunction. The relatively low impedance, or *direct*, fault creates arcs across an insulating material (or air). These type faults generate intense localized heat, high temperature ejecta, and loss of material (divots) in conductors. These type faults are those most easily recognized, particularly by those less experienced in electrical failure.

Faults can be created by making or *breaking* an electrical connection, such as switching or pulling apart energized cable. These *transient* type faults have a very high frequency component and a resulting sudden increase in voltage. They can damage insulation, particularly in areas where electrical inductance is high, such as at a bend in wire. These are sometime referred to as "parting arcs", though this is an unnecessarily limiting term.

A relatively *high impedance connection* fault is common when electrical contacts misalign, when connectors do not make good contact, or when insulation on cables is partially damaged but not completely removed. This current type fault results in localized heat that can easily exceed ignition temperature of common combustibles.

The most dangerous characteristic of these high impedance type faults is that they draw current more consistent with a load than a short. Protection systems, such as fuses and circuit breakers, would not operate to prevent overheating from this type fault.

From our research, a fault with an impedance as low as ½ **Ω** can cause temperatures to exceed 700°F. Faults generating heat as low as 11 – 23 watts create enough thermal energy to initiate combustion. [19]

Example: On a twelve volt circuit, such as on a vehicle or wall-wart power supply, a 23 watt fault would draw approximately two (2) amps. This is a much lower current draw than can be typically detected by simple fusing.

Risks: High impedance faults do not create an easily identifiable "arc", and thus are not easy to identify visually. These are insidious and are often missed in grounding and bonding investigations.

A further problem with analysis is many electrical ignition sources are obliterated or destroyed by the heat of ignition and localized burning. As a consequence, there may be no visible electrical artifact of ignition. [6] The scientific method must be employed considering all factors to identify the ignition source.

FAULT ROUTES

There are three routes for electrical effects – *direct contact*, *stray current*, and *electromagnetic fields*. The first, *direct contact* to an energized electrical conductor is the most obvious cause of electrical effects. The second, indirect or *stray current* is a more common, but less recognized source of electrical energization. The third, *electromagnetic fields*, radiates from every live electric circuit.

Interestingly, every route and phenomenon that causes physical effects on inanimate objects in the form of fire or corrosion on property can also cause biological effects on living organisms. [17]

Direct contact and electromagnetic radiation are used to intentionally create heat in the forms of heating elements and microwaves respectively. All three routes – direct, stray, and electromagnetic – can inadvertently cause fires resulting in damage or destruction of property.

What are the differences in electrical effects on biological and physical systems? The difference is the type system. The physics are the same.

WHY NOW?

Why does a failure occur after a problem exists for an extended period of time, even years? A malfunction, mistake, or improper installation will not necessarily bring immediate consequences.

Seldom do systems have serious problems when only one component is improper. Failures and catastrophes are the result of multiple conditions.

Unfortunately over time many systems develop problems due to maintenance, operation, or abuse. Nevertheless, these problems may not develop into a recognizable failure. But for a second event the catastrophe would not occur.

CODES & STANDARDS

The purpose of Codes and Standards is "*the practical safeguarding of persons and property from hazards arising from the use of electricity*" as stated in the *NEC*. The *NEC* is the standard for electrical installations in structures and related locations.

The *National Electrical Safety Code* is specific to utility type installations. The *NESC* states "*These rules contain the basic provisions that are considered necessary for the safety of employees and the public under the specified conditions.*"

NFPA publishes 70E, *Standard for Electrical Safety in the Workplace*. "*The purpose of this standard is to provide a practical safe working area for employees relative to the hazards arising from the use of electricity.*"

In many jurisdictions, both the *NEC* and *NESC* have been adopted by the state as the minimum standard for electrical installations. Furthermore, *NFPA 70E* is the foundation of workplace safety regulations including OSHA. Not following the *Codes* is a violation of state or other jurisdiction law and may be negligence *per se* in the legal system. [22]

Appropriate action is required for codes to be effective. Codes are the minimum requirements for safety and protection from danger, both to property and people.

Codes and Standards are developed by knowledgeable professionals using known science to preclude problems.

As noted earlier, the significance of grounding and other requirements is not readily understood by most engineers and investigators. Not understanding the aspects of the codes will result in erroneous engineering and investigation analysis and decisions. Not following Codes and Standards will result in hazards to persons and property.

GROUNDING PURPOSE

The purpose of adequate grounding and bonding connections is three-fold.

1. To ensure that the all systems (facility and service) are operating at the same potential reference. This is critical to control voltages seen in the facility.
2. To prevent circulating currents from developing in the ground systems. Circulating currents cause overheating of ground and neutral conductors and equipment.
3. To allow building and service protection systems to operate effectively and as designed.

The fact that a ground and bonding system is not adequate and proper allows voltages in the facility to "float" and exceed equipment ratings, allows circulating currents to overheat the existing conductors and equipment, and prevents both the facility and utility protection systems from operating.

SUM IT UP

Multiple observations can be made concerning inadequate grounding and bonding.

1. Improper grounding and bonding is a frequent problem.

2. Electrical ignition and shock that is undetermined is often related to a grounding issue.

3. Codes and standards are the minimum requirements for installation. Not following codes and standards results in hazards to persons and property.

4. Grounding issues are a code, and therefore legal, problem.

REFERENCES

[1] *National Electrical Code*, NFPA 70, 2008, National Fire Protection Association, Quincy, MA.

[2] *National Electrical Safety Code, IEEE C2*, Institute of Electrical and Electronics Engineers, New York.

[3] *IEEE Green Book – Grounding of Industrial and Commercial Power Systems*, IEEE Std 142, Institute of Electrical and Electronics Engineers, Piscataway, NJ.

[4] *Standard for the Installation of Lightning Protection Systems*, NFPA 780, National Fire Protection Association, Quincy, MA, 2008.

[5] *Standard for Electrical Safety in the Workplace*, NFPA 70E, National Fire Protection Association, Quincy, MA, 2008.

[6] *Guide for Fire and Explosion Investigations*, NFPA 921, National Fire Protection Association, Quincy, MA, 2008.

[7] "CSST Response to Lightning and Transients, A Technical Analysis", Marcus O. Durham and Robert A. Durham, *Fire and Arson Investigator*, IAAI, July 2009.

[8] "Lightning Damage: An Act of God or Act of Negligence" Marcus O. Durham, Robert A. Durham, Randel Overton, Curtis Ozment, Proceedings of 40th Annual Frontiers in Power Conference, OSU, Stillwater, OK, October 2007.

[9] "The Flat Earth Society Perception of Grounding" Marcus O. Durham, Robert A. Durham, Proceedings of 39th Annual Frontiers in Power Conference, OSU, Stillwater, OK, October 2006.

[10] "Data Quality and Grounding in Mixed Use Facilities", Marcus O. Durham and Robert A. Durham, *IEEE Industry Applications Magazine*, May-June 2006.

[11] "Ground System Design Considerations for Vessels," Marcus O. Durham and Robert A. Durham, *IEEE Industry Applications Magazine*, November-December 2001.

[12] "Grounding System Design for Isolated Locations and Plant Systems," Marcus O. Durham, and Robert A. Durham, *IEEE Transactions on Industry Applications*, Vol 33, Issue 2, March-April 1997, pp 374-382. March/April 1998.

[13] "Lightning, Grounding, and Protection for Control Systems," Marcus O. Durham and Robert Durham, *IEEE Transactions on Industry Applications*, Vol. 31, No. 1, January/February 1995, pp 45-54.

[14] "Covering All the Bases: Industrial Power System Design in a Utility Environment", Robert A. Durham and Marcus O. Durham, *IEEE Industry Applications Magazine*, November/December 2003.

[15] "Transient Voltage Surge Suppression Design and Correlation," Marcus O. Durham, Robert A. Durham, Karen D. Durham, *Institute of Electrical and Electronics Engineers PCIC*, Institute of Electrical and Electronics Engineers PCIC, September 2000.

[16] "Electric Submersible Pump Grounding, T. R. Brinner, J. D. Atkins, and M. O. Durham, *Institute of Electrical and Electronics Engineers PCIC*, September 2003.

[17] *Electrical Failure Analysis for Fire and Incident Investigations*, Marcus O. Durham, Robert A. Durham, Rosemary Durham, Jason Coffin, Dream Point Publishers w/ IAAI-OK, Tulsa, OK, 2009.

[18] "Death by Grounding", Donald W. Zipse, *Institute of Electrical and Electronics Engineers PCIC*, Sept. 22, 2008, IAS/PCIC 08-03.

[19] "Unraveling the Myths of Low Energy Electrical Ignition" Marcus O. Durham, Robert A. Durham, Curtis Ozment, Jason Coffin, Proceedings of 42nd Annual Frontiers in Power Conference, OSU, Stillwater, OK, October 2009.

[20] "Safe Work Practices: A Real World Implementation," Marcus O. Durham, *IEEE Transactions on Industry Applications*, Vol. 30, No. 1, January/February 1994, pp179-187.

[21] "A Universal Systems Model Incorporating Electrical, Magnetic, and Biological Relationships," Marcus O. Durham, *IEEE Transactions on Industry Applications*, Vol. 29, No. 2, March/April 1993, pp 436-446.

[22] *Leadership and Success in Economics, Law, and Technology*, Marcus O. Durham, Robert A. Durham, Rosemary Durham; Dream Point Publishers, Tulsa, OK, ISBN 978-0-9719324-7-6.

VITAE

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Licensed Professional Engineer - multiple states
Licensed Electrical Contractor
Licensed Commercial Radiotelephone & Amateur Extra
Certified Fire & Explosion Investigator, NAFI
Certified in Homeland Security, ABCHS
Registered Investigator, ABRI
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She has been active in traveling to over 15 countries on business and development. She has co-authored three books on leadership, two books on theology, and two eBooks on technology and incident investigation.

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