

IAEI | 12th Edition

# SOARES

## Book on Grounding & Bonding



International Association of Electrical Inspectors

# Soares Book on Grounding and Bonding

Twelfth edition



International Association of Electrical Inspectors  
Richardson, Texas



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# Preface

This book is dedicated to the memory of Eustace C. Soares, P.E., one of the most renowned experts in the history of the *National Electrical Code* in the area of grounding electrical systems. A wonderful teacher and man of great vision, Eustace foresaw the need for better definitions to clear up to the great mystery of grounding of electrical systems.

Eustace Soares' book, *Grounding Electrical Distribution Systems for Safety* was originally published in 1966 and was based upon the 1965 edition of the *National Electrical Code*. Over the years, this book has become a classic.

A great majority of the recommendations contained in the original edition of his book have been accepted as part of Article 250 of the *National Electrical Code*. The grounding philosophies represented in the original edition are just as relevant today as they were then. To say that Eustace contributed more than any other man to solving some of the mysteries of grounding of electrical systems would not be an overstatement of fact. Previous editions have been extensively revised both in format and in information. An effort has been made to bring this work into harmony with the 2014 edition of the *National Electrical Code* and to retain the integrity of the technical information for which this work has been well known, at the same time adding additional information which may be more recent on the subject of grounding and bonding.

IAEI acquired the copyright to Soares' book in 1981 and published the second edition under the title *Soares Grounding Electrical Distribution Systems for Safety*. IAEI acknowledges the contributions of Wilford I. Summers to editions two and three, and J. Philip Simmons as the principal contributor in the revision of the fourth through seventh editions. IAEI acknowledges Michael J. Johnston as the principal contributor in the revision of the eighth, ninth, and tenth editions. The principal contributors to the revision of the eleventh and twelfth editions were Charles F. Mello and L. Keith Lofland.

IAEI intends to revise this work to complement each new edition of the *National Electrical Code* so this will be an on-going project. Any suggestions for additional pertinent material or comments about how this work could be improved upon would be most welcome.





# General *Fundamentals*

## Objectives to understand...

- **Fundamentals and purpose of grounding of electrical systems**
- **Definitions relative to grounding equipment from grounded and ungrounded systems**
- **Effects of electric shock hazards**
- **Purpose of grounding and bonding**
  - **Short circuit vs. ground faults in electrical systems**
  - **Circuit impedance and other characteristics**
- **Basic electrical circuit operation**
  - **Ohm's Law**

From the beginning, the use of electricity has presented many challenges ranging from how to install a safe electrical system to how to develop minimum *Code* requirements for safe electrical installations. These installations depend on several minimum requirements, many of which are covered in NFPA 70, *National Electrical Code*, Chapter 2, Wiring and Protection. Understanding the protection fundamentals and performance requirements in Chapter 2 is essential for electrical installation, design, and inspection. To truly understand how and why things work as they do, one must always start with the basics. It is important that basic electrical circuits be understood, because grounding and bonding constitute an essential part to a safe electrical circuit. The process of grounding and bonding creates safety circuits that work together and are associated with the electrical circuits and systems.

The material in this book analyzes the how and why of these two functions of grounding and bonding and expresses their purpose in clear and concise language. It also examines grounding and bonding in virtually every article of the *Code* in addition to the major requirements of Article 250. Further, it provides information on grounding and bonding enhanced installations that exceed the minimum *NEC* requirements, such as for data



processing facilities and sensitive electronic equipment installations. Chapter seventeen expands the information about those types of installations that are designed to exceed the *Code* requirements. It covers establishing an enhanced grounding electrode system or earthing system and installing feeders and branch circuits in a fashion that helps reduce the levels of electrical or electromagnetic interference (EMI) noise on the grounding circuits. This is accomplished through insulation and isolation of the grounding circuit as it is routed to the original grounding point at source of supply (service or source of separately derived system).

Some definitions of electrical terms that should be understood as they relate to the performance of grounding and bonding circuits are also included in this first chapter. This book emphasizes the proper and consistent use of the defined terms in both the electrical field and the *NEC* in order to develop a common language of communication.

### **Taking the Mystery Out of Grounding**

For many years the subjects of grounding and bonding have been considered the most controversial and misunderstood concepts in the *National Electrical Code*. Yet there is no real reason why these subjects should be treated as mysteries and given so many different interpretations. Probably the single most effective method for clearing up the confusion is for one to review and clearly understand the definitions of the various elements of the grounding system. In addition, these terms should be used correctly during all discussions and instruction on the subject so that everyone will have a common understanding. For example, using the term *ground wire* to mean an *equipment grounding conductor* does no more to help a person understand what specific conductor is being referenced than does the use of the term *vehicle* when one specifically means a *truck*.

It is recommended that the reader carefully review the terms defined at the beginning of each chapter in order to develop or reinforce a clear understanding of how those terms are used in regard to that particular aspect of the subject. Also, many of the terms associated with the overall grounding

system are illustrated to give the reader a graphic or pictorial understanding of their meaning. It should be noted that the graphics in this text are designed to illustrate a specific point and that not all conductors or details required for a fully compliant installation are necessarily shown.

This book is intended to assist the reader in establishing a strong understanding of the fundamentals of and reasons for the requirements of grounding and bonding to attain the highest level of electrical safety for persons and property. Appendix A provides information on the origin of concrete-encased electrodes. Appendix B provides a short history of the National Electrical Grounding Research Project. IAEI is committed to providing the highest quality information on grounding and bonding to the electrical industry and hopes that the reader benefits immensely from this volume.

### **Definitions of Electrical Terms**

The following terms are not in alphabetical order; instead, they are sequenced on how the concepts are taught in logic starting with what pushes current, what current is, and then what impedes that current flow from dc then ac circuits.

**Voltage (Electromotive Force).** A volt is the unit of measure of electromotive force (EMF). It is the unit of measure of the force required to establish and maintain electric currents that can be measured. By international agreement 1 volt is the amount of EMF that will establish a current of 1 amp through a resistance of 1 ohm.

**Current (Amperes).** Current, measured in amperes, consists of the movement or flow of electricity. In most cases, the current of a circuit consists of the motion of electrons, negatively charged particles of electricity.

**Impedance.** The term *resistance* is often used to define the opposition to current in both ac and dc systems. The correct term for opposition to current in ac systems is *impedance*. Resistance, inductive reactance, and capacitive reactance all offer opposition to current in alternating-current circuits. The three elements are added together vectorially (phasorially), not directly. This results in the total impedance or opposition to current of an AC circuit.

Impedance is measured in ohms

**Resistance.** Resistance is the name given to the opposition to current offered by the internal structure of the particular conductive material to the movement of electricity through it, i.e., to the maintenance of current in them. This opposition results in the conversion of electrical energy into heat.

**Capacitance.** A capacitor basically consists of two conductors that are separated by an insulator. A capacitor stores electrical stress. Capacitive reactance is the opposition to current due to capacitance of the circuit. The Institute of Electrical and Electronics Engineers (IEEE) defines *capacitance* as, “The property of systems of conductors and dielectrics which permits the storage of electricity when potential difference exists between the conductors.”

**Inductance.** Inductance is the ability to store magnetic energy. Inductance is caused by the magnetic field of an alternating-current circuit as a result of the alternating current changing directions. This causes the magnetic lines of force that surround the conductor to rise and fall. Induction is measured as inductive reactance. As the magnetic lines of force rise and fall, they work to oppose the conductor and induce a voltage directly opposite the applied voltage. This induced voltage is called *counter-electromotive force* or counter EMF. Induction is the current effect of an ac circuit. Where there is an alternating magnetic field there will be induction. This induction will result in inductive reactance, which opposes the current.

## The Foundation of Grounding

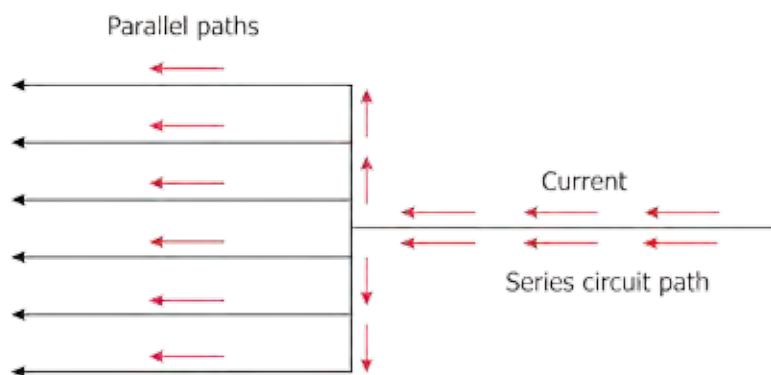
The first and most vital element of a sound, safe structure is a solid footing or foundation on which to build the building. This foundation, usually consisting of concrete and reinforcing bars, must be adequate to support the weight of the building

and provide a solid structural connection to the earth on which it sits. If the building or structure does not sit on a solid foundation, there can be continuous structural problems that might lead to unsafe conditions. Likewise, the electrical grounding system serves as the foundation for an electrical service or distribution system supplying electrical energy to the structure. Often the grounding of a system or metal objects is referred to as *earthing*, being connected to the earth. When solidly grounded, the electrical system must be connected to a dependable grounding electrode or grounding electrode system without adding any intentional impedance. The grounding electrode(s) supports the entire grounding system and makes the earth connection. It must be effective and all grounding paths must be connected to it. This serves as the foundation of the electrical system. Chapter six covers the grounding electrodes, their functions, and their installations.

## Electrical Circuitry Basics

Anyone who has been involved in the electrical field for any length of time has heard the phrase, “Electricity takes the path of least resistance.” From

## Series and Parallel Paths for Current



Current will always try to return to the source

Current will return in as many paths that are available to it

Amount of current on a particular path depends on the impedance of that path

**FIGURE 1.1** Series and parallel paths for current

## Watt's Wheel – Ohm's Law

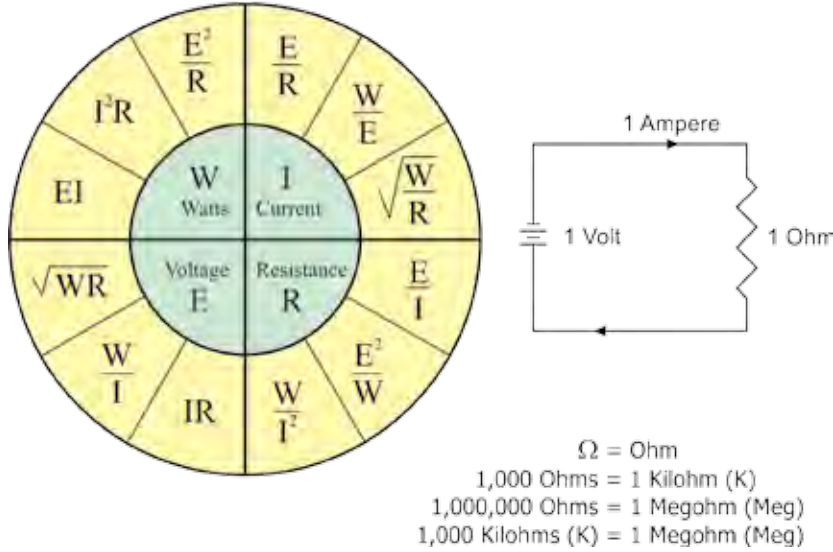


FIGURE 1.2 Watt's wheel—current in a circuit

grade school science class to the first-year apprentice to the seasoned veteran of the industry, the phrase is used to describe the path electrical current will take. The phrase is stated with pride, "Electricity takes the path of least resistance" or "Current takes the path of least resistance," and usually not much thought is given as to what is really going on. In reality, current will take all paths or circuits that are available. Where more than one path exists, current will divide among the paths (see figure 1.1). As we will review later, current will divide in opposite proportion to the impedance. The lower impedance path or circuit will carry more current than the higher impedance path(s). The study of grounding and bonding is vital to applying basic rules relative to this important safety element of the electrical circuit. It is important to review some basic principles and the fundamental elements of electricity and how current relates to electrical safety.

### Ohm's Law in Review

Before we can have current flowing, there needs to be a complete circuit (see the circuit diagram in figure 1.2). The amount of current in an electrical circuit depends on the characteristics of the circuit. Voltage or electromotive force (E) will cause

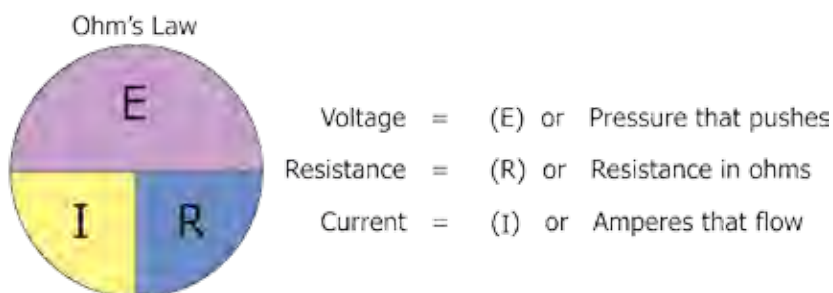
(push) current or intensity (I) through a resistance (R). These are the basic components of Ohm's law (see Ohm's law and its derivatives in Watt's wheel in figure 1.2). Electrical current can be compared with water flowing through a water pipe. With the pressure being the same, the bigger the pipe, the less the resistance is to the flow of water through the pipe. The smaller the pipe, the greater the resistance is to the flow of water through it. The same holds true for electrical current.

Larger electrical conductors (paths) offer lower resistance to current. Smaller electrical conductors (paths) offer greater resistance to current. There must be a complete circuit or path and a voltage (difference of potential) or there will be no current. This is true of both normal current and fault current.

### Resistance as Compared to Impedance

Understanding the differences between the pure resistance of an electric circuit and the impedance of a circuit is important in gaining a thorough understanding of the grounding or safety circuit. In Ohm's law, resistance is the total opposition to current in a dc circuit. In an alternating-current circuit, the total opposition to current is the total impedance comprised of three components. The impedance (Z) of an ac circuit is the inductive reactance, capacitive reactance, and the resistance added together vectorially (phasorially) [see formula in figure 1.3]. In a 60-cycle ac circuit, alternating current changes amplitude and direction 120 times per second and develops a magnetic field that results from the inductive reactance of the circuit. Therefore, minimizing the amount of the overall opposition (impedance) to current in the grounding and bonding circuits of electrical systems is very important. These circuits can be looked upon as si-

## Basic Electrical Theory Terms



Opposition to current in a dc circuit is *resistance*

Opposition to current in an ac circuit is made up of three components:

R Resistance

$X_L$  Inductive reactance

$X_C$  Capacitive reactance

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

Impedance formula

Impedance = Opposition (Z) or total opposition to current in an ac circuit

**FIGURE 1.3** Basic electrical theory terms and formulas, including basic formulas for ac circuit resistance and impedance

lent servants, just waiting to perform the important function of carrying enough current so overcurrent protective devices can operate to clear a fault.

### Current in a Circuit

In any complete circuit or path that is available, current—be it normal current or fault current—will always try to return to its source. The statement on taking the path of least resistance is partially correct. Electrical current will take any and all available paths to return to its source (see figures 1.1 and 1.5). If several paths are available, current will divide and the resistance or the impedance of each path will determine how much current is on that particular path. It can be concluded from the above that if there is no complete circuit, then there is no current. Care is given to the installation of ungrounded (phase or hot) conductors so that the circuit will be complete to provide a suitable path for current during normal operation. The same principles and fundamentals apply to the installation of grounding and bonding conductors that make up the safety circuits. The equipment grounding (safety) circuit must be complete and must meet three important criteria:

(1) the path for ground-fault current must be electrically continuous; (2) it must have adequate capacity to conduct safely any ground-fault current likely to be imposed on it; and (3) it must be of low impedance (see figure 1-26 and chapter eleven for more specific information relative to clearing ground faults and short circuits).

Article 250 mentions the term *low-impedance path* several times. As a quick overview, the opposition to current in a dc circuit is resistance. The total opposition to current in an ac circuit is impedance. When the phrase “low-impedance path” is used

in the *Code*, it is referring to a path that offers little opposition to current whether it is normal current or fault current. The key element is ensuring there is low opposition or impedance to the flow of the current.

### Overcurrent Device Operation

Overcurrent devices operate because of more current (amps) flowing than the device is rated to carry. Generally speaking, the more current through overcurrent devices above their rating the faster they open or operate; this is because they are designed to operate in inverse time. Relative to the discussion about impedance, the higher the impedance of the path, the lower the current through the overcurrent device and therefore longer time to open. The lower the impedance of the path, the greater is the current through the overcurrent device and faster opening time. Understanding these basic elements of electrical circuits helps one apply some important rules in Article 250. The following examples clearly demonstrate that amps operate overcurrent devices (see figures 1.6 and 1.7.



## Amperes Operate Overcurrent Devices

E = Voltage	R = Ohms	I = Amperes
Voltage	= *Resistance	x **Current
120	= 60	x 2
120	= 40	x 3
120	= 20	x 6
120	= 10	x 12
120	= 5	x 24

\* As the resistance or opposition to current increases, the current in the circuit decreases

\*\* As the resistance or opposition to current decreases, the current in the circuit increases

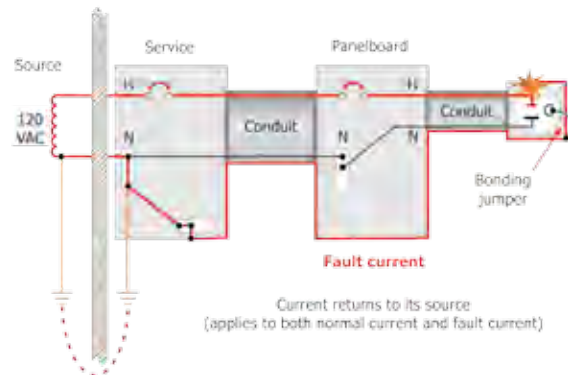
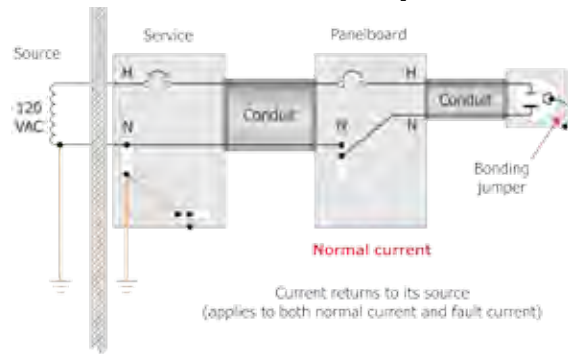
**FIGURE 1.4** Proper grounding and bonding facilitates the operation of overcurrent devices.

As with the electrical circuit installed for normal current, the equipment grounding (safety) circuit must also be installed for abnormal current to ensure overcurrent device operation in ground-fault conditions. The equipment grounding or safety circuit must be complete and constructed with as little impedance as practicable for quick, sure overcurrent device operation. Care must be taken when installing electrical systems and circuits, including the equipment grounding and bonding circuits of the system. Where the human body gets involved in the circuit it can, or often, results in an electrical shock or even electrocution in some cases. The human body introduces a relatively high level of impedance that impacts the overcurrent device operation. Ground-fault circuit interrupters provide a degree of protection from electrical shock, but standard overcurrent devices do not. Later in this chapter is a discussion about shock hazards and effects on the human body, and chapter fourteen provides more information about ground-fault circuit interrupters.

### Proper Language of Communication

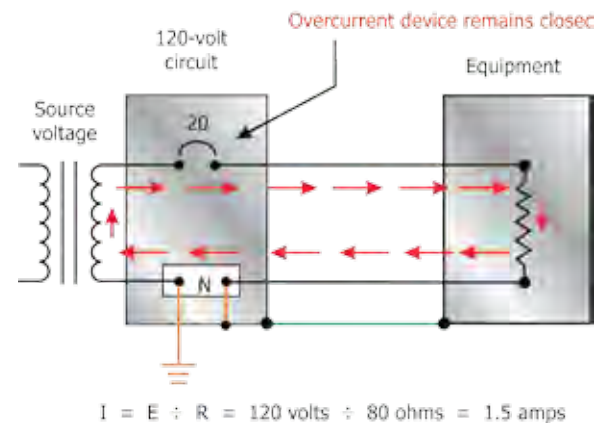
A common language of communication has been established to enable one to understand the requirements of the *NEC*, in general, and of grounding and bonding, in particular. A common

## Overcurrent Device Operation



**FIGURE 1.5** Current will try to return to its source (normal and fault current work the same way)

## Normal Current in the Circuit



**FIGURE 1.6** Normal electrical circuit (normal current in circuit)

set of terms, defining and explaining the function of the terms as used in the *Code*, is included in Article 100 and in sections xxx.2 of other articles. Two conductors of grounding grounded system should be mentioned and a brief story told about each: the grounded conductor and the equipment grounding conductor.

# Bonding and Grounding Terminology

IAEI's *Soares Book on Grounding and Bonding* places a huge emphasis on definitions of words and terms used for proper application of Code rules relating to the subject of grounding and bonding. Using a common language of communication is imperative to understanding this subject, and applying the *Code* to installations and systems in the field as clearly indicated in chapter one of this book. It is important that words and terms related to this subject mean what they imply by definition for all code users.

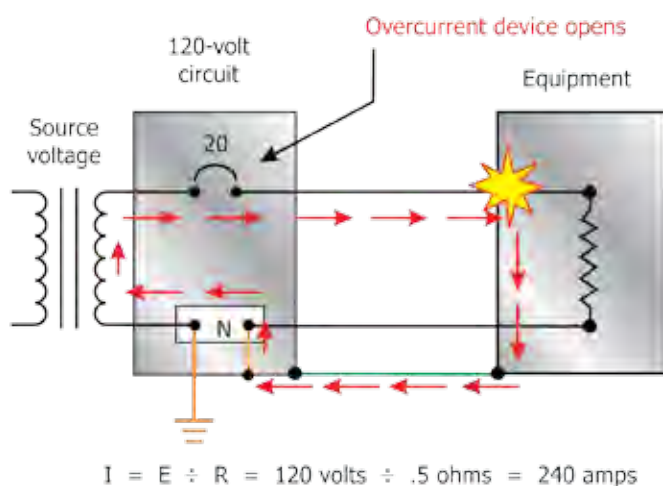
## NEC Grounding and Bonding Revisions

In recent editions of the *Code*, there have been numerous revisions to many of the grounding and bonding terms used in the *NEC*. These revisions were the result of significant efforts of a special task group assigned by the NEC Technical Correlating Committee. The primary objective of this task group was to ensure accuracy of defined terms related to *grounding* and *bonding*, differentiate between the two concepts, and verify

the use of these terms is uniform and consistent throughout the *NEC*. The work of this task group resulted in simply changing the meaning of defined grounding and bonding terms to improve clarity and usability within the *NEC* requirements where they are used. *Code* rules that use defined grounding and bonding terms were revised as needed to clarify the meaning of the rule and to ensure that these terms are used consistently with how they are defined in Article 100 and at 250.2. In many instances, rules were revised to become more prescriptive for code users to provide clear direction on what is intended to be accomplished from a performance standpoint. As an example, many rules throughout the *Code* used the phrase "shall be grounded," which was replaced with the phrase "shall be connected to an equipment grounding conductor." This simple revision will relay to the code user that a certain object not only needs to be grounded, but more importantly, "how" the object is to be grounded.

SIDEBAR 01.1 Bonding and Grounding Terminology

## Ground-Fault Current in the Circuit



Note: Unless ungrounded conductors are totally severed (broken), a certain amount of load current in the normal circuit will be present (under ground-fault conditions)

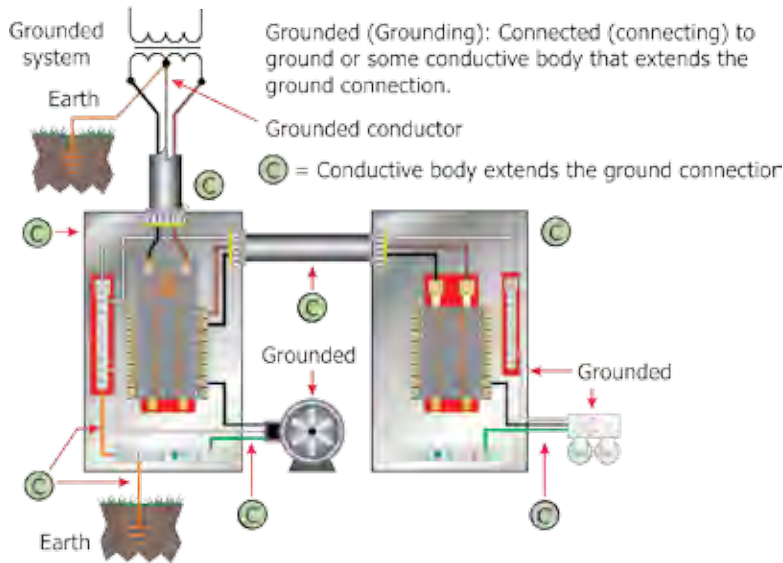
FIGURE 1.7 Electrical circuit with ground fault to enclosure

## Grounded and Grounded Conductor

The grounded conductor (usually a neutral) is generally a system conductor intended to carry current during normal operation of the circuit. The connection to ground (earth) of the system grounded (often a neutral) conductor is accomplished by a connection through a grounding electrode conductor either at the service or at a separately derived system. Generally, it should be understood that the grounded conductor should not be used for grounding of equipment on the load side of the system grounding



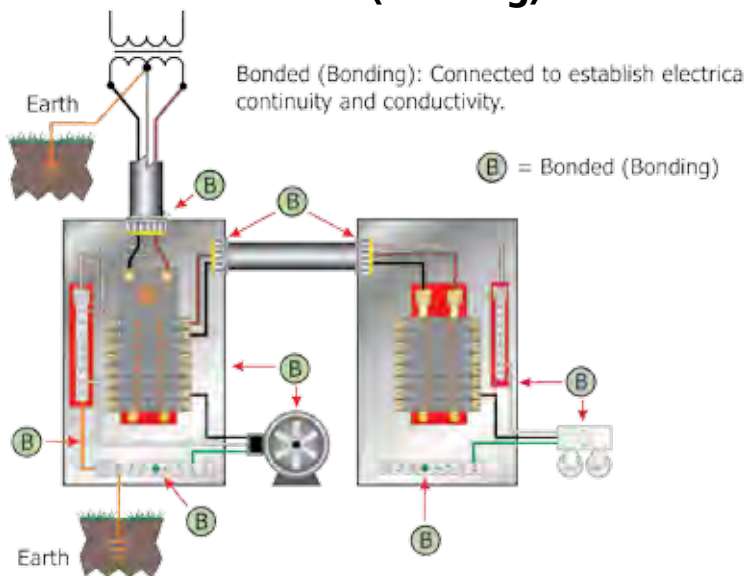
## Grounded (Grounding)



**FIGURE 1.8** Grounding connects equipment and systems to ground (the earth).

connection at the service or source of separately derived systems. This separation between grounded conductors and equipment grounding conductors keeps the normal return current on the neutral (grounded) conductor of the system, where it belongs, when returning to its source. These principles are reinforced by requirements in 110.7, 250.24(A)(5) and 250.30(A). Code rules and requirements for the grounded conductors are covered in depth in chapter three of this text.

## Bonded (Bonding)



**FIGURE 1.9** Bonding (bonded) establishes electrical continuity and conductivity.

## Grounding and Equipment Grounding Conductor

As used in Article 250 and other articles, grounding is a process that is ongoing. The conductor to look at is the equipment grounding conductor. The action is ongoing through every electrical enclosure it is connected to all the way to the last outlet on the branch circuit. The equipment grounding conductor provides a low-impedance path for fault-current if a ground fault should occur in the system and also connects all metal enclosures to the grounding point of the service or system.

So it is important that the equipment grounding conductor make a complete and reliable circuit back to the source. At the service is where the grounded (neutral) conductor and the equipment grounding conductor(s) are required to be connected together through a main bonding jumper. In a separately derived system, this connection is made with a system bonding jumper installed between the grounded conductor and the equipment grounding conductor(s). The main bonding jumper and the system bonding jumper complete the ground fault-current circuit back to the source. The rules and requirements for equipment grounding conductors are covered in depth in chapter nine.

## Grounding as Compared to Bonding

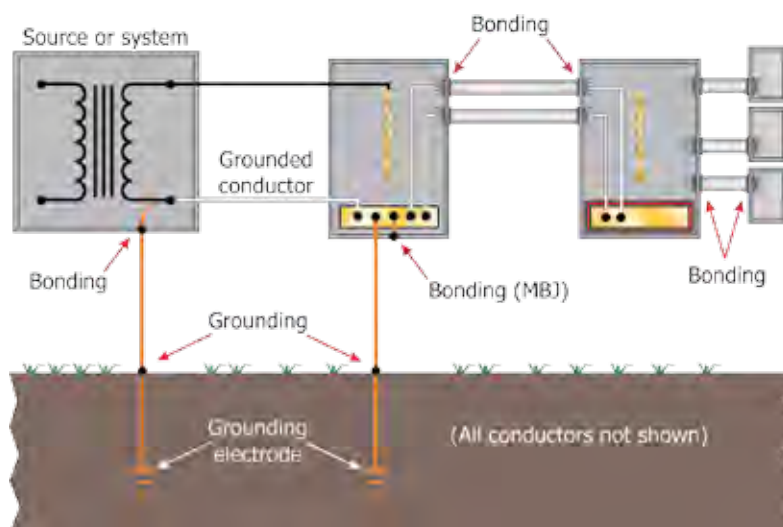
Defined in Article 100, both of these functions are essential for the complete safety anticipated by the rules in Article 250 (see figure 1.10).

**Ground.** “The earth.”

**Grounded (Grounding).** “Connected (connecting) to ground or to a conductive body that extends the ground connection” (see figure 1.8).

**Bonded (Bonding).** “Con-

## Grounding Compared to Bonding



**FIGURE 1.10** Grounding compared to bonding showing the connection to earth at the source (utility) and service and everything bonded to that point of grounding

connected to establish electrical continuity and conductivity” (see figure 1.9).

These are two separate functions with two different purposes. It is important to establish a clear understanding of the grounding (earthing) circuit and its purpose as compared to the equipment grounding conductors and bonding jumpers or connections.

Section 250.4 has been broken down into grounded systems and ungrounded systems. Requirements in this section include descriptive performance requirements and establish the purposes served by each of these actions. The title of Article 250 is “Grounding and Bonding.” The article contains an equally strong emphasis on bonding requirements. Chapter eight presents detailed information on these bonding requirements (see sidebar for important information about grounding and bonding terminology revisions started with the 2008 *NEC* and with additional revisions in the 2011 and 2014 *NEC*).

### The *National Electrical Code* Trend

The *NEC* in recent cycles has been revised to reduce the allowance of using the grounded conductor for grounding equipment downstream from the main bonding jumper in a service, or downstream from the system bonding jumper at a separately derived system. As stated earlier, the reasons are

elementary. Current, be it normal current or fault current, will take all the paths available to it to try to return to its source. If the grounded conductor (neutral) and equipment grounding conductors are connected at points downstream of the service or separately derived system, such as at sub-panels, multiple paths will be available on which the current will try to return to the source. This can lead to normal neutral current on water piping systems, conduit, wire-type equipment grounding conductors, and any other electrically conductive paths, and all these extra paths can compromise electrical safety

and even proper overcurrent device operation in ground-fault conditions.

In recent editions of the *NEC* (1996), electric range and dryer circuits were required to include an equipment grounding conductor in addition to an insulated grounded conductor. Existing range and dryer circuits are allowed to continue the use of the grounded conductor, or neutral, to ground the boxes at the outlet and the frames of the equipment. New installations, however, are required to maintain isolation (insulation) between the grounded conductor and the equipment grounding conductor.

The rules covering the use of the grounded conductor for equipment grounding purposes at a second building or structure are provided in Section 250.32. Section 250.32(B) requires an equipment grounding conductor to be installed with the feeder supplying the second building or structure; separation between the grounded (neutral) conductors is to be maintained. There is an allowance in 250.32(B) Exception, for existing installations only, to utilize the grounded conductor of the feeder for grounding equipment under three specific and very restrictive conditions. First, an equipment grounding conductor is not included with any feeders and/or branch circuits supplying the building or structure. Second, there are no continuous metal-

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