1

Introduction

1.1 General

Shipboard power distribution systems have existed since the late nineteenth century. Only until recently, both commercial and naval ships have predominantly employed ungrounded power systems with nominal system voltages less than 1 kV. Ungrounded systems, equivalent to isolated systems (IEC), have a desirable feature in that the unintentional grounding of one conductor results in low ground fault currents and thus enables continued operation with a single ground fault. The ship's engineers can wait for a favorable time to find and clear the ground fault. For many years, ungrounded power systems served the maritime industry well.

However, over the past decades, the total electric load on many types of ships has risen, first due to the addition of heat loads that were previously served by steam prior to the adoption of diesel and gas turbine engines, and second due to the introduction of integrated electric propulsion in the form of an integrated power system (IPS) in the 1990s. In response to this growing load, ships started to employ increasingly higher power generation systems with nominal system voltages greater than 1 kV up to 13.8 kV. For these higher voltages, employing an ungrounded system is not recommended due to voltage stresses on system insulation and due to potential safety concerns. Instead, the use of a high-resistance grounded (HRG) system has become prevalent for distribution systems with nominal system voltages above 1 kV and more recently has been employed in some systems with a nominal system voltage as low as 440 V. The desire to be able to easily integrate commercial equipment designed for shore-based facilities has even resulted in some solidly grounded secondary distribution systems.

Additionally, power electronic conversion equipment, such as variable frequency drives (VFDs), has become prevalent in shipboard systems; VFDs enable

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motors and motor loads to operate at higher efficiencies, reduce inrush current, and increase displacement power factor. On the other hand, the integration of VFDs requires significant effort to ensure harmonic distortion and common mode (CM) currents and voltages are properly controlled. Controlling CM currents and voltages requires additional grounding considerations.

1.2 Grounding and Earthing Definitions

In terrestrial systems, the term "ground" (USA) or "earth" (IEC) refers to the voltage potential of the soil at a particular location and is used as a reference potential for measuring the voltage of other conductors. In some terrestrial power systems, the soil itself (at ground voltage potential) may be used as one of the conductors in the power circuit.

In shipboard systems, the term "ground" or "earth" refers to the voltage potential of the ocean. Since most ships have metallic hulls and structure in direct contact with the ocean, the hull and structure are also said to be at "ground" or "earth" potential. However, because of safety and corrosion concerns, the ship's hull and structure are not normally used as one of the conductors in the power circuit.

Bonding is the act of deliberately connecting exposed metal parts that are not designed to carry electrical currents under normal operation to the hull of the ship via a low-impedance path. Bonding is primarily performed as a safety measure to prevent electrical shock to personnel caused by capacitively coupled voltages on the exposed metal parts, inductively coupled currents in exposed metal parts, or insulation failures. The impacts of electric currents on humans are discussed in Appendix C.

The connection of exposed metal parts to the chassis or frame of a piece of equipment is indicated on circuit diagrams by IEC Symbol 5020 (Figure 1.1f). A terminal, such as one connected to the chassis, that is intended to be connected to ground for the purpose of implementing bonding is called a protective earth (PE) terminal and is represented by IEC Symbol 5019 (Figure 1.1c). This book will additionally use the symbol depicted in Figure 1.1d to represent the connection of

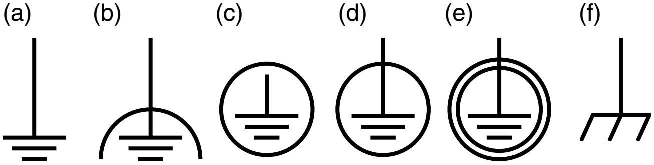

Figure 1.1 Ground symbols: (a) IEC Symbol 5017, (b) IEC Symbol 5018, (c) IEC Symbol 5019, (d) Protective earth, (e) CM ground, and (f) IEC Symbol 5020.

the terminal intended for bonding (IEC Symbol 5019) to the ship's hull. This symbol is used to represent a protective earth, and its incorporation into a design is called protective earthing.

The term "equipotential" means that two conductors have equal voltages with respect to a reference voltage. Two conductors that are electrically connected with a low impedance are equipotential. "Equipotential bonding" and "equipotential grounding" are equivalent to "bonding"; the conductors are at the same voltage as the hull of the ship.

Power distribution system grounding (or earthing (IEC)) is the act of deliberately inserting a solid connection or an impedance between a conductor or neutral of a power system and the hull of the ship. Grounding is usually done to limit conductor voltages with respect to the ship's hull, to provide a path for fault current in the case of a ground fault, and to provide a path for CM currents under normal operations. A ground fault is an unintentional electrical connection between a power system conductor and the ship's hull. A ground fault can be a "solid" ground fault with little resistance, or a fault, such as an arc fault, with a higher resistance.

One may also encounter IEC Symbol 5018 (Noiseless earth), depicted as Figure 1.1b; it is intended to represent a special grounding system for a particular application to minimize CM disturbance or noise on a grounding conductor. These special grounding systems are not covered by this book.

This book distinguishes between power distribution system grounding, protective earthing, and CM grounding. For this book, power distribution system grounding addresses ground currents at frequencies less than three times the fundamental frequency, while CM grounding addresses frequencies at or above three times the fundamental frequency. The two types of grounding do interact; this interaction must be accounted for in the design of each. IEC Symbol 5017 (Figure 1.1a) is used to indicate power system grounding. This book additionally uses the symbol depicted in Figure 1.1e to denote an intentional CM ground. Parasitic connections to ground participate in protective earthing (bonding), power system grounding circuits, and CM circuits; by convention, parasitic component connections to ground are displayed as IEC Symbol 5017. In summary, of the six ground symbols depicted in Figure 1.1, this book will use only the three depicted in Figure 1.2.

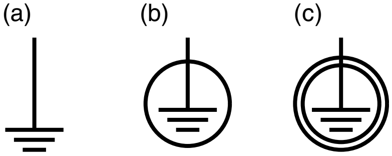

Figure 1.2 Ground symbols used in this book: (a) system ground, (b) protective earth, and (c) common mode ground.

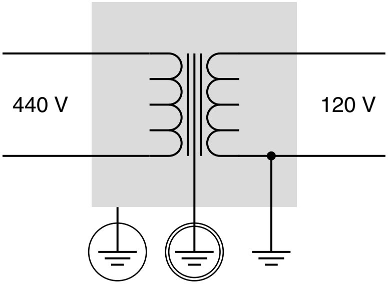

Figure 1.3 Use of ground symbols.

Figure 1.3 depicts the use of the three different ground symbols in the case of a single-phase transformer. The protective earth grounding (left) connects the exposed metallic structure and components of the transformer enclosure (not intended to carry current under normal operation) to ground through bonding. The CM ground (middle) is used to connect the transformer shield between the primary and secondary windings to ground; this shield is used to prevent capacitive coupling of CM currents between the primary and secondary windings. Finally, one of the conductors of the secondary winding is grounded (right) to form a system ground for a solidly grounded distribution system.

Electric current from the power system that, under normal conditions, flows through conductors that are not intended to carry power system current, such as conductors associated with protective earthing, is called objectionable current. Objectionable currents may arise when inappropriate connections are made between the power system and protective earthing conductors.

As defined by IEEE Std 45.1-2023 (2023), the nominal system voltage is "the designated voltage for a power system used as a reference value for establishing other power quality measures. For direct current, single-phase AC, and three-phase AC systems, the nominal system voltage is measured line-to-line." For AC systems, the nominal system voltage is expressed as a root-mean-square (rms) of the fundamental frequency component of the voltage waveform.

1.3 Common Mode Terminology

The neutral voltage of a set of conductors with respect to a reference voltage potential (typically ground) at any instant in time is the average value of the instantaneous conductor voltages with respect to the reference voltage. The neutral voltage is also called a CM voltage. Strictly speaking, the neutral voltage is a calculated quantity from the voltage measurements of multiple conductors and may not correspond to the voltage of any one conductor.

For a three-phase system, the neutral voltage with respect to ground can be expressed as

$$v_{ng} = \frac{1}{3}\left(v_{ag} + v_{bg} + v_{cg}\right) \tag{1.1}$$

$$\begin{aligned} v_{ag} &= v_{an} + v_{ng} \\ v_{bg} &= v_{bn} + v_{ng} \\ v_{cg} &= v_{cn} + v_{ng} \end{aligned} \tag{1.2}$$

where

v_{ng}, neutral-to-ground voltage
v_{ag}, v_{bg}, v_{cg}, phase-to-ground voltage
v_{an}, v_{bn}, v_{cn}, phase-to-neutral voltage

Through substitution

$$v_{ng} = \frac{1}{3}\left(v_{an} + v_{ng} + v_{bn} + v_{ng} + v_{cn} + v_{ng}\right)$$

$$v_{an} + v_{bn} + v_{cn} = 0$$

The sum of the phase voltages with respect to the neutral is identically zero.

The instantaneous sum of the conductor currents in a set of conductors is called the CM current. In a balanced system, the CM current of a set of conductors is equal to zero; the sum of the currents in one direction is equal to the sum of the currents in the opposite direction. CM currents often, but not always, have a return path to a CM source via ground connections.

CM current is unintended; the intended differential mode (DM) currents of a set of conductors add to zero when measured in the same direction.

Power electronics, such as VFDs, and circuit asymmetry can be significant CM voltage sources in shipboard power systems. CM circuits include line impedances, parasitic capacitances to ground, and CM grounding systems. In some cases, inductive coupling with bonded conductors can also lead to CM voltages and currents.

A neutral conductor is intended to have a voltage potential equal to the neutral voltage of a set of conductors. However, due to voltage distortion of the phase voltages, the voltage potential of the neutral conductor may vary somewhat from the neutral voltage of an associated set of conductors.

1.4 Types of Power Distribution Systems

IEEE 45.1-2023 identifies the following types of buses to categorize shipboard power systems:

- Primary bus: distribution systems with a nominal system voltage greater than 1 kV.
- Distribution bus: distribution systems with a nominal system voltage between 400 V and 1 kV.

- Secondary bus: distribution systems with a nominal system voltage no greater than 400 V.
- Special bus: circuits for unique purposes such as medical use, control system power, or special control.

This book adapts the IEEE 45.1-2023 terminology to refer to power distribution systems:

- Primary distribution system: a power distribution system with an IEEE Std 45.1-2023 primary bus.
- Low-voltage distribution system: a power distribution system with an IEEE 45.1-2023 distribution bus.
- Low-voltage secondary distribution system: a power distribution system with an IEEE 45.1-2023 secondary bus.
- Low-voltage special circuits: a power system circuit with an IEEE 45.1-2023 special bus.

With the exception of high-voltage shore connections, the terms high voltage and medium voltage are not generally used in this book. For shipboard power systems, the terms high voltage and medium voltage usually refer to nominal system voltages above 1 kV; but they are not consistently defined by the various regulatory bodies, classification societies, and standards organizations. Instead, to avoid confusion, this book refers to primary distribution systems or refers to specific voltage levels.

Figure 1.4 depicts the relationships among the four types of power distribution systems. Not all ships will have all of the distribution systems; smaller mechanical

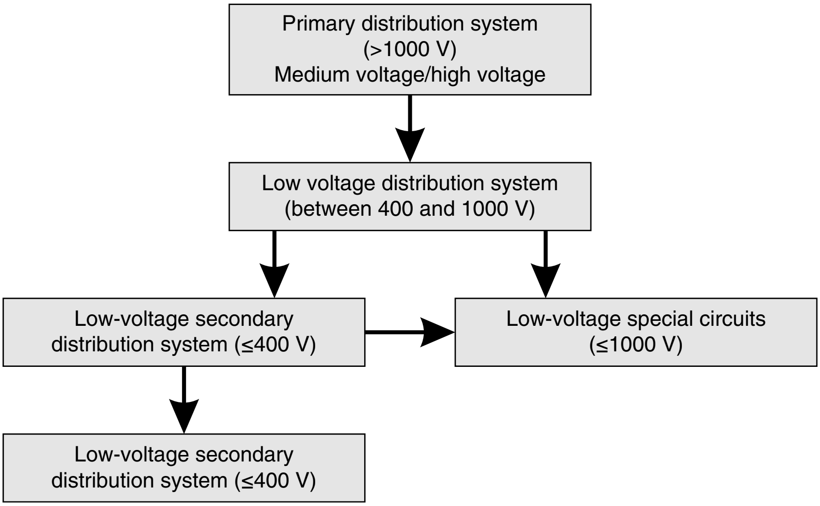

Figure 1.4 Relationships among shipboard power distribution systems.

drive ships typically do not have a primary distribution system. Although low-voltage special circuits may have a nominal system voltage up to 1 kV, most will have a nominal system voltage no more than 400 V. Some low-voltage secondary distribution systems may be derived from other low-voltage secondary distribution systems, typically with a higher nominal system voltage. Low-voltage special circuits may be derived from either low-voltage distribution systems or low-voltage secondary distribution systems.

1.5 Types of Power System Grounding Systems

A power system grounding (or earthing) system is composed of the equipment used to insert a solid connection or an impedance between a conductor or neutral of a power system and the hull of the ship. The impedance, if employed, is typically designed to manage steady-state ground fault currents at the fundamental frequency. The impedance will also impact the transient response during fault initiation and fault clearing.

A solidly grounded system incorporates a very low impedance (approaching 0 Ω) between a conductor or neutral of a power system and the hull of a ship. A ground fault typically results in large fault currents that activate protective devices to isolate the fault. An advantage of a solidly grounded system is that the insulation systems in cables and equipment need only be designed to accommodate the line-to-ground voltage.

An ungrounded system does not have a grounding system. The power system is only electrically connected to the ship's hull via parasitic resistances, capacitances, and inductances. Parasitic capacitances typically dominate for AC systems and parasitic resistances typically dominate for dc systems. A ground fault will result in relatively low amounts of fault current that flows through the ground fault and the parasitic impedances. Continued operation without clearing the first ground fault is usually possible. Generally, the crew should localize and isolate the ground fault as soon as operational conditions permit; a second ground fault on a different phase will result in large fault currents and protective devices tripping. The insulation systems in cables and equipment must be designed to accommodate the full line-to-line voltage between each line and ground, in addition to a transient voltage that occurs due to a resonance between the line inductance and parasitic capacitances to ground.

An HRG system incorporates a grounding (earthing) resistor between the power system (typically a neutral conductor) and the ship's hull. The grounding resistor has a resistance high enough to preclude fault protection circuits from activating on overcurrent due to a ground fault. Like an ungrounded system, an HRG system allows continued operation with one line-to-ground fault. By inserting a resistance

Table 1.1 Recommended grounding methods.

Application	**Ungrounded**	**High-resistance grounded**	**Solidly grounded**
AC primary distribution system	No	Yes	No
AC low-voltage distribution system	Yes	Yes	No
AC low-voltage secondary distribution system	No	No	Yes
AC low-voltage special circuits	See Chapter 9	See Chapter 9	See Chapter 9
DC primary distribution system	No	Yes	No
DC low-voltage distribution system	Yes	Yes	No
DC low-voltage secondary distribution system	Yes	No	Yes
DC low-voltage special circuits	See Chapter 9	See Chapter 9	See Chapter 9

into the ground fault circuit, when a ground fault clears, the charge trapped in the parasitic line-to-ground capacitance has a way to dissipate. The line-to-ground voltage of the conductors quickly returns back to normal; the voltage stress on insulation systems is thereby reduced. HRG systems also facilitate automated detection of a ground fault; the voltage across the grounding resistor is a simple indicator of a ground fault.

Recommendations for the application of each grounding type to the different power distribution system types are shown in Table 1.1 and discussed in detail in Chapter 9.

Equipment may incorporate filter networks that include connections to ground for the purpose of managing electromagnetic interference (EMI) and CM voltages and currents. These filter networks include EMI filters and are typically focused on controlling CM currents and voltages at frequencies substantially higher than the fundamental frequency. EMI filters are one type of a broader set of CM grounding systems.

Finally, equipment enclosures and other accessible conducting components of equipment (not directly connected to the power system) are bonded together and then connected to earth via a protective earth (protective ground) connection. The ground pin on a 120 V appliance plug is an example of protective earthing.

1.6 Modeling and Simulation

This book provides physics-based models of shipboard power cables and other equipment. These models, however, are by necessity simplified; they do not account for certain types of nonlinearities and environmental factors. The cable models, for example, do not account for frequency dependencies of the inductances, to include the impact of the skin effect at high frequencies. Wherever possible, direct measurement of model parameters should be made on physical equipment and components. In general, design margins should be employed to account for the uncertainty associated with model simplifications and parameter estimation. System modeling should include parameter sweeping to ensure the final design is robust to model errors.

The simulations in this book use LTspice; LTspice is a circuit simulation software program available for free (as of 2023) from Analog Devices (https://www.analog.com/en/design-center/design-tools-and-calculators/ltspice-simulator.html). LTspice is derived from the Simulation Program with Integrated Circuit Emphasis (SPICE), which was developed by Laurence Nagel at the Electronics Research Laboratory of the University of California, Berkeley, and released in 1973.

The models presented in this book can also be implemented in other simulation tools. The MATLAB/Simulink environment from MathWorks is another simulation environment often used in the analysis of shipboard power systems. The techniques presented in this book also apply to modeling within MATLAB/Simulink.

1.7 Book Overview

While there are other books that discuss shipboard power system design, the discussion on grounding systems is usually brief and incomplete. This book is unique in that it comprehensively covers the issues associated with shipboard power system grounding and hull currents.

IEEE Std. 3003.1-2019 (2019) provides recommended practices for system grounding of industrial and commercial power systems. This book covers many of the same topics, but focuses on the unique characteristics of shipboard power systems and their impact on grounding system design. This book also discusses a number of topics that are unique to ships.

In a similar vein, in the United States, the National Electrical Code (NFPA 702023 2023) provides grounding requirements for terrestrial applications and floating buildings where the ground means the earth. It specifically does not cover ships where the ground means the water the ship is floating in (and, by extension, the metal hull or ground plate).

This book does not extensively cover EMI/EMC issues such as the coupling between signal cables and power cables, or the coupling between signal cables. Other resources, such as NAVSEA S9407-AB-HBK-0102010 (2010), should be consulted for recommended shielding practices and cable separation recommendations.

Chapter 2, System Grounding: Shipboard Ungrounded AC Systems. Applicable to AC power systems with a nominal system voltage no greater than 1 kV, the chapter provides guidance for modeling cables and other components of an ungrounded system and shows the potential hazards due to intermittent ground faults. Other special cases, such as stuck breaker contacts and ground faults on rectifier outputs, are examined. The chapter also discusses ground fault detection and localization methods, including the impact of an ungrounded system on ground fault circuit interrupter (GFCI) operation.

Chapter 3, System Grounding: Shipboard HRG AC Low-Voltage Distribution Systems. Chapter 3 covers HRG for distribution systems with a nominal system voltage no greater than 1 kV. The damping effect of the HRG on voltage transients due to intermittent ground faults is demonstrated. The multiple ways of implementing an HRG are discussed: neutral grounding resistor (NGR), zigzag transformer, wye-delta transformer, and wye-broken delta transformer. The issue of grounding transformer saturation due to DC currents is covered, as well as ground fault detection and localization.

Chapter 4, System Grounding: Shipboard Solidly Grounded AC Systems. Chapter 4 covers solidly grounded AC secondary distribution systems. Examples are provided to demonstrate why a delta-wye transformer should be used instead of a wye-wye transformer for supplying power to a solidly grounded AC system. The chapter also discusses the need to limit EMI filter capacitance to avoid GFCI nuisance tripping.

Chapter 5, System Grounding: Shipboard HRG AC Primary Distribution Systems. Chapter 5 covers HRG for AC distribution systems with a nominal system's voltage greater than 1 kV. The advantages of using a wye-broken delta grounding transformer configuration over the other configurations are explained. For transient analysis, more detailed models of cables, to include conductor and cable shields, are presented. Methods to predict parasitic capacitances for many different types of power system apparatus are provided. In addition to fault detection and localization, cable terminations for primary distribution system cables are discussed. The characteristics of shielded insulated bus pipe (IBP) are described.

Chapter 6, System Grounding, Shipboard Ungrounded DC Systems. Chapter 6 covers ungrounded DC low-voltage distribution systems and low-voltage secondary distribution systems. Models for unshielded two-conductor and four-conductor dc cables are provided. CM current performance of 12-pulse rectifiers during a ground fault is presented. The chapter also includes a discussion of ground fault detection and localization.

Chapter 7, System Grounding: Shipboard HRG DC Systems. Chapter 7 covers HRG for DC primary distribution systems and DC low-voltage distribution systems. A basis for determining the HRG resistance is presented. The chapter also provides a model for shielded four-conductor DC cables, as well as methods for ground fault detection and localization.

Chapter 8, System Grounding: Shipboard Solidly Grounded DC Systems. Chapter 8 covers solidly grounded DC low-voltage and low-voltage secondary distribution systems. Ground fault detection and localization are discussed, as well as the performance of GFCI and similar devices in a low-voltage secondary distribution system.

Chapter 9, Designing Shipboard Power System Grounding/Earthing Systems. Chapter 9 provides recommendations for the types of grounding systems that should be used with each of the distribution system types. It also provides insight on the impact of not isolating power systems with large voltage differences. The chapter presents a series of ship power system one-line diagrams highlighting the grounding system design to include all of the grounding systems described in Chapters 2 through 8. These one-line diagrams include:

- Shipboard power system for mechanical propulsion with low ship service load.
- Shipboard power system for mechanical propulsion with low ship service load and grounding bus.
- Shipboard power system for integrated power systems (IPS) with grounding transformers.
- Shipboard power system for IPS with generator neutral grounding resistors.
- Shipboard power system for IPS with grounding bus.
- Low-voltage AC zonal distribution system.
- Zonal AC primary distribution system with HRG in generator switchboards.
- Zonal AC primary distribution system with HRG in zonal switchboards.
- Commercial ship DC distribution system – integrated converters.
- Commercial ship DC distribution system – separate converters.
- Zonal DC primary distribution system.

Chapter 10, Power Conversion Equipment Grounding. Chapter 10 discusses the grounding implications of different power conversion options, to include: three-phase transformers, isolated power conversion equipment, and non-isolated power conversion equipment. Means for controlling CM voltages and currents in power conversion equipment are also presented. The chapter provides a number of examples of power conversion equipment configurations to explain how system grounding, bonding/protective earthing, and CM grounding apply to power conversion equipment.

Chapter 11, Shore Power (Cold Ironing) Connection Grounding. Chapter 11 covers shore power (cold ironing) connection grounding. A description of low-voltage shore power connections and high-voltage shore power connections is provided. The chapter includes details on equipotential grounding of the ship's hull with the shore-side ground, as well as a method for monitoring the equipotential bonding.

Chapter 12, Vehicle Connections Grounding. Chapter 12 covers grounding issues associated with embarked vehicles. It includes discharging of static electricity from hovering helicopters, power system grounding, and equipotential bonding of embarked vehicles.

Chapter 13, Common Mode Grounding: Impact of Common Mode Currents and Voltages on Grounding System. Chapter 13 covers the impact of CM currents and voltages on grounding systems. The chapter begins with a presentation of CM fundamentals. It continues with a discussion on the relationship of CM currents and voltages on EMI and philosophies and means for controlling CM currents and voltages. The chapter includes the theory of how CM chokes and CM shunts work.

Chapter 14, **Protective Earthing: Bonding**. Chapter 14 provides design considerations for implementing equipotential bonding of equipment to the ship's hull. A short discussion on testing of effective bonding is also included.

Chapter 15, Current Related Corrosion. Chapter 15 covers current-related corrosion, primarily on the ship's hull. The chapter provides an introduction to galvanic corrosion theory, including a discussion on how to use polarization curves to understand galvanic corrosion. The impact of galvanic corrosion on the ship's hull and other shipboard components and equipment is discussed. A short description is included of bearing corrosion due to CM currents flowing from a rotor, through the bearing, and into the equipment foundation. The chapter presents methods to counter current-related corrosion to include shaft brushes, sacrificial anodes, and impressed current cathodic protection.

Chapter 16, Lightning Protection Systems. Chapter 16 provides a description of lightning protection systems, along with design considerations to include: air terminals, down conductors, low impedance ground connection, and surge protection.

Chapter 17, Grounding Systems for Nonmetallic Hull Ships. Chapter 17 covers design considerations for power system grounding of nonmetallic hull ships.

Appendix A, Glossary. Appendix A provides a glossary of terms used in this book.

Appendix B, Acronyms and Abbreviations. Appendix B lists acronyms and abbreviations.

Appendix C, Impact of Electric Current on Humans. Appendix C provides information on the impacts of electric current on humans.

The aim of this book is to provide the reader with the background and insight necessary to analyze and design grounding systems for shipboard power systems.

1.8 Legal Notice

While this book provides many recommendations, class rules and regulations should always be consulted and followed. A thorough analysis should be conducted to ensure recommendations in this book are appropriate for any given application.

The examples, data, and other information provided in this document are believed by the authors to be correct. However, the examples, data, and other information should be independently verified and tested before being used in any design, particularly those where incorrect operation could result in equipment damage or injury to personnel.

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