

OVERVIEW

The term “ground” too often seems to be associated with a sort of cure-all concept, like snake oil, money or motherhood. Remember that, while you can always trust your mother, you should never trust your “ground.” Examine and think about it. [1]

Grounding is probably the most important aspect of electrical or electronic system design, yet it is probably the least understood by most engineers. Often blended with misconceptions, in the final implementation it is typically necessary to strike a balance between electromagnetic interference (EMI) control, safety, and good engineering practices. Grounding theory is not intuitive. Achieving a functional grounding philosophy often results from battles of wits, perseverance, and the resolution of conflicts between instinct, intuition and engineering experience and judgment.

Electromagnetic interference and noise are generally pervasive in all electrical and electronic systems. Because this is true, it would be fair to say that every electrical and electronics design engineer will ultimately encounter grounding problems during the span of his career.

Ask two engineers for “their” solution to EMI or electrical noise problems and, if you are lucky, you will end up with only two different recommended approaches. It is for this reason that many design engineers are wont to say, “For every grounding problem there are many solutions, most of which are wrong. . . .”

When such casually provided approaches are attempted, it will often be revealed that what worked in one situation may not necessarily work well in another. Experi-

ence *does* play a prime role in the details of the grounding design of a specific system. Unfortunately, that experience is generally not transferable to another system, even if they both utilize the same technology. Grounding design is so system-specific, that rarely is there a “generic” solution that is fit for all cases.

Many proposed solutions appear conflict with fundamental physical principle requirements imposed on the system. They may be based on myths and misconceptions regarding the very concept of grounding. Indeed, design of any grounding system, contrary to common belief, is founded on solid science. The watchful engineer may be generally aware of the correct principles but be guilty of their misapplication, either through inexperience, negligence, or even an intentional effort to avoid Maxwell’s equations and their consequences.

Electrical and electronic design is usually taken to be “well founded.” By that is meant it can be modeled, analyzed, and simulated using commonly known circuit analysis tools such as Spice, for instance. Electrical and electronic circuit design seems repeatable, the solution appears to be straightforward, and the parameters are typically simply outlined and implemented in a well-understood model.

For a successful analysis to be carried out, the engineer must be able to clearly state the issues of concern or the problem to be addressed down to the component level, including any related variables. This data is provided via measurement or simulation or both. However, when grounding problems are encountered, it is not so simple to identify the components involved, or even the path or paths of interest. This can be a challenging problem at DC or low frequencies. At higher frequencies in radio frequency (RF) circuitry as well as in the now commonly used high-speed digital switching circuits, components stubbornly obey the laws of physics, with capacitors acting like inductors, inductors exhibiting capacitive responses, and printed circuit boards introducing parasitic reactive circuit elements that cannot be found in the drawing.

As Don R. Bush, (1942–2001) said, “Anyone can construct a mathematical model and generate data. But if the predictions of your mathematical model do not match experimental data, either your model is worthless or your measurements are not done properly.”*

Analysis of grounding systems, particularly in large installations, but even in small-scale circuits, may be a very complex issue and typically defies straightforward definition. The challenge increases when considering the risk of safety code violation, caused by misinterpretation and wrong implementation of grounding requirements, which may result in significant negative consequences.

The novice may be surprised to observe that electrical and electronics experts find the issue of grounding so complex. “After all,” they may say, “what could ever be so difficult in connecting the ‘zeros’ all together?” The truth is that grounding problems, if not properly addressed in the early phases of design, are bound to surface at the end of the project, at which time a solution is likely to be both costly and complex. With budget and schedule virtually depleted in the panic of finding a solution, attempts may be made to modify the grounding system layout and design by disconnecting, reconnecting, removing, or adding grounding connections randomly in a trial-and-error ap-

*Paul, C., *IEEE EMC Society Newsletter*, Issue No. 192, Winter 2002.

proach. It is at this time that critical conflicts may be overlooked and safety-compromising situations may not be acknowledged.

When the attempts seem to yield good results, the solution is called “successful,” leading all to believe that grounding system design is indeed founded in “black magic.”

The typical electrical or electronics engineer will often avoid highly mathematical electromagnetic field theory. After all, “Physics is for the physicists,” right? *Wrong!* All answers to electrical and electronic design questions, particularly those related to grounding questions, are well founded in electromagnetic field theory, more specifically, Maxwell’s equations.

In any discipline, lack of knowledge and comprehension of the science behind the rules may bring about the use of “rules of thumb,” resulting in either inadequate design, faulty or lacking (and possibly hazardous) results, or, worse still, overdesign and, thus, a costly solution.

“Rules of thumb,” by their very essence, divest the engineer of his common sense and true engineering judgment. Such rules, which may have been appropriate years or decades before, are likely not applicable to new technologies. More importantly, they may not be compatible with current safety codes, which may have evolved independently through the years. Applying those rules of thumb may be inappropriate for the intended application (e.g., EMI control) or may introduce serious violation of current safety requirements. Many of these rules of thumb are like urban myths, evolved from misconceptions regarding grounding, and their use should be discouraged.

Most misconceptions and rules of thumb related to grounding theory were established in previous generations and were directly applicable to the technology available at the time. For example, how often do design engineers still recommend single-point grounding topologies for their high-speed digital circuits? Or still think that cable shields should be grounded at one end only? Or still use the 0.1 μF capacitors for decoupling of high-speed digital devices having rise/fall times on the order of tens of picoseconds?

Consider, for instance, the evolution of computing speeds and slew rates, coupled with the increased density on printed circuit boards. Today’s digital circuits have gradually evolved into RF circuits, with their frequency content exceeding 10 GHz. The increase of switching speeds implies an increase in high-frequency spectral content, virtually from DC to daylight, leading to greater significance of parasitic reactive effects and heightened emissions and interference. Rules of thumb developed decades ago will not suffice for today’s technology.

Traditional analog or digital design rules of thumb will not provide functional grounding system design or help control EMI either, and many, in fact that employ transmission line theory, for instance, are necessary today for explaining high-frequency effects encountered in modern circuits. Use of such techniques will yield appropriate grounding schemes, providing both performance and EMI control, while not compromising safety.

Grounding design for modern systems must cover many disciplines, including digital and analog design, power engineering, lightning protection, and many others, not to

mention system safety concerns. Rather than an intuitive approach, the design of the grounding system must be founded on electromagnetic field theory, in particular Maxwell's equations.* A practical approach must be maintained, in consideration of safety and other codes and regulations, and conflicting situations, which may arise due to contradicting requirements in practical systems.

A key objective of this book is to dispel the mystery associated with grounding. This shall be accomplished by providing a methodical approach for the design of grounding systems, from circuits through systems and up to platforms and facilities.

The book attempts to meet the above challenge by putting grounding into the proper perspective. It outlines a physical foundation for explaining the concept of grounding, founded on electromagnetic field theory, while providing insight into practical aspects of grounding system implementation, particularly as related to its interdisciplinary nature, extending from circuits to facilities. It will be clearly demonstrated that grounding systems in facilities, systems, or circuits do, in fact, follow a consistent scheme.

From the topological perspective, there is no fundamental difference between a circuit, a rack, a platform, or a facility. The laws of electromagnetics revealed in Maxwell's equations remain unchanged regardless of the system dimensions. Only the manner and complexity of their application differs from one to the next.

In practice, though, circuit and equipment designers are electronic engineers, whereas the facility and platform designers are electrical engineers. The crossroad between the two, electronics and electrical engineering, also constitutes the borderline between power levels (milivolts and kilovolts, microamps and kiloamps) and, of greater significance, between frequency contents, particularly power frequency to signal frequencies ranging from DC to daylight.

Integrating equipment and systems in a large facility does require not only a new way of thinking and different comprehension of terms, but also a distinctive appreciation of numbers; the difference in units of measurement affect their actions because "they work on the opposite side of the decimal point" [1]. Can an electronic circuit designer truly internalize a 200 kA lightning return stroke current? And what concern are miliamps to the electrical power engineer?

This book is thus also targeted at developing a universal approach to the understanding of grounding at whichever tier is considered, delineating the distinctiveness of each while emphasizing the resemblance between them, hoping to remove the present fuzziness.

No doubt, the concepts presented herein may put several designers at unease. These concepts will conflict with the widespread notion that there is no scientific foundation for grounding, which is well known to amount to "black magic." The theories and practices discussed herein will diverge from the body of "common knowledge" related to the way grounding should really be accomplished. Without a doubt, many may choose to carry on utilizing former practices, finding that easier than attempting to understand these concepts.

*A detailed discussion of Maxwell's equations as they apply to grounding theory and practices is presented in Chapter 2.

We are confident that, eventually, this book will help to do away with old, outdated, and erroneous practices, which may have been acceptable where low frequencies were concerned, but constitute poor design practices for the high-frequency circuits and systems so widespread today.

Application of theory, observing physics principles working in practice, and proving Maxwell's equations' validity for grounding and EMC design practices have provided particular satisfaction and made this book, in the authors' opinion, of even greater consequence.

With this in mind, the book begins by introducing the reader to the fundamental concepts pertaining to grounding, starting with a discussion of Maxwell's equations, particularly as they apply to the topic of grounding. Essential terms and concepts relating to real-world electrical circuit behavior are also laid out in Chapter 2.

Chapter 3 presents the basics of grounding, beginning with a discussion of the term "ground" and the different objectives of grounding.

Chapter 4 provides an in-depth review of the fundamentals of grounding design. It discusses in detail the fundamental topologies of grounding systems and provides a novel yet practical systematic approach for planning grounding systems. The concept of "ground loops" is developed in Chapter 4 and solutions are presented. The implementation of the fundamental grounding architectures in large-scale systems and installation are further examined. Chapter 4 is completed with grounding-related case studies.

Chapter 5 explains the principles of bonding. The approaches of achieving low-impedance connections between metallic surfaces and structures as a fundamental objective for meeting the desired grounding objectives are portrayed.

Chapter 6 describes in detail safety-related grounding concerns. Rationale for electrical safety grounding requirements is provided and safety grounding design principles in power distribution and lightning protection systems are presented.

Chapter 7 covers grounding in wiring and cable systems. One of the most controversial and misunderstood aspects of system grounding design stems from the question of cable shield termination ("grounding"). This Chapter will clearly make a distinction between signal grounding and shield termination, putting this question to rest.

Chapter 8 provides the foundation for understanding the essential necessity of adequate grounding of EMI terminal protection devices (e.g., EMI filters and transient-suppressing devices) performance. The effect of acceptable versus objectionable grounding of such protective devices is clearly demonstrated.

In Chapter 9, the application of grounding in printed circuit boards (PCBs) is discussed in depth, particularly as related to power conditioning and signal return paths. The question of grounding in mixed analog/digital circuits is also addressed.

Chapter 10 leads the reader to the facility and platform levels. The design of integrated grounding systems in facilities is described. The complexity of and approaches to the integration of multiple subsystems into a larger system as related to grounding system design are discussed. It also expands the concept of grounding architecture design to the unique cases of mobile platforms, for example, tactical C³I (command, control, communication, and intelligence) shelters, aircraft, space systems, and ships.

The several appendices in the book provide extensive supporting information and

supplemental data, which will be of great use for the reader. Appendix A provides a glossary of grounding-related terms and definitions, with references to their sources, particularly when derived from official international standards and codes. When several definitions exist for a term, they are all included, with reference to the context of their applicability. Appendix B lists commonly used acronyms employed throughout the book for easy reference by the reader. Appendix C presents commonly used symbols associated with variables referred to throughout the book. Appendix D presents a list of many grounding-related standards, specifications, and codes and their scope. Appendix E demonstrates the equivalence between Ohm's Law and Fermat's "Least Time" Principle, which is useful for understanding the reason why current selects a particular return path. Finally, Appendix F provides an overview of S-parameters and their application for the evaluation of grounding performance, particularly on printed circuit boards, extensively used in Chapter 9.

With the emergence of new technologies—nanotechnology, in particular—the importance of proper grounding design is greater than ever. We are certain that this book, founded on fundamental physical principles on the one hand and on real-world, practical experience on the other, provides an excellent resource for achieving successful, cost-effective, and timely state-of-the-art designs of electronic and electrical equipment, systems, and networks.

BIBLIOGRAPHY

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