GROUNDS FOR GROUNDING
A Circuit-to-System Handbook

Elya B. Joffe
Kai-Sang Lock

IEEE Electromagnetic Compatibility Society, *Sponsor*

IEEE
IEEE Press

WILEY
A JOHN WILEY & SONS, INC., PUBLICATION

GROUNDS FOR GROUNDING

IEEE Press
445 Hoes Lane
Piscataway, NJ 08855

IEEE Electromagnetic Compatibility Society, *Sponsor*

Technical Reviewers
Keith Sueker, Curtiss Wright EM Corp
Venkata Dinavahi, University of Alberta
George Baier, Buchanan Ingersoll, PC

GROUNDS FOR GROUNDING
A Circuit-to-System Handbook

Elya B. Joffe
Kai-Sang Lock

IEEE Electromagnetic Compatibility Society, *Sponsor*

IEEE

IEEE Press

WILEY

A JOHN WILEY & SONS, INC., PUBLICATION

Published by John Wiley & Sons, Inc., Hoboken, New Jersey
Published simultaneously in Canada.

Library of Congress Cataloging-in-Publication Data is available.

ISBN 978-0471-66008-8

Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1

To my beloved wife, Anat,
and the apple of my eye, my daughter Tami-Lee,
who are the center of my universe
—Elya B. Joffe

To my wife, Eyan,
and Angela, Andrew, and Anthony
for their love, support, and understanding
—Kai-Sang Lock

To the Beloved Memory of my Mother,
Faiga Mary Joffe (Nee Bloom)

Faiga Mary Joffe (Nee Bloom)
1934–1984

This book is dedicated to the beloved memory of the first lady in my life—my mother, Faiga Mary Joffe (Nee Bloom), who was taken to the stay with the Lord in 1984, when she was only 50 years old. Her everlasting encouragement and attitude were the source of inspiration and motivation that gave me the strength to start (and complete) the writing of this book. Among her notes, we found after her passing, the following poem:

But once I pass this way.
And then . . . and then the Silent Door swings on its hinges;
Opens . . . Closes . . .
and no more I pass this way.
So, while I may, with all my might
I will essay sweet comfort and delight
to all I meet upon the pilgrim way.
For no man travels twice the Great Highway,
that winds through darkness up to light,
through night, to day.

—William Arthur Dunkerley (John Oxenham) 1852–1941

This was the story of her life. Thank you, Mom, for being there when I needed you so badly. I am so saddened that you do not see the results of your teachings.

Your Loving Son,
Elya B. Joffe

CONTENTS

FOREWORD

Israel procured several groups of F-16 Aircraft from my company, General Dynamics (now Lockheed Martin). Electromagnetic compatibility (EMC) engineering for these programs was accomplished by my group of thirty EMC engineers in Fort Worth, Texas. As the models of Israeli F-16 aircraft became more complex, direct interaction with Israeli engineers became appropriate. The first such meeting occurred in 1983 in Tel Aviv, and my attendance triggered the Israeli Air Force to find a suitable engineer to represent them.

They found Israeli Air Force Lieutenant Elya B. Joffe, who had a BSEE Degree from Ben Gurion University, and majored in wave propagation and electromagnetic theory. They told him he was now an EMC engineer, and sent him to my meeting! (Engineers usually wind up in EMC by accident, and Elya was no exception!)

Practical applications in engineering do not always follow the theory. In Israel, engineers were very knowledgeable of electromagnetic theory, but in Israel in 1983, the practice of the technology was limited. This limitation did not stop Elya. He readily grasped the differences between his technical background and the practical aspects of EMC, and progressed well. After 1983, he and I had many technical meetings both in Israel and in Fort Worth, and became good friends. One time, he and his wife, Anat, stayed at my home in Fort Worth while my wife and I were in San Francisco!

After completing his military service as a Major, he joined Israeli Aircraft Industries as an EMC engineer. He became very active in the Israeli Chapter of the IEEE EMC Society and was elected its chairman. Elya was nominated and elected to the EMC Society Board of Directors. In 2007, he was elected President-Elect of the IEEE EMC Society and served as president in the years 2008–2009; the first and only non-American ever to hold this office to-date!

Years ago, Elya recognized the need for a treatise on electrical grounding, the foundation for achieving system electromagnetic compatibility. He has spent many years researching the subject and preparing his manuscript. Now, he has provided the world with this valuable and long-needed reference.

Thank you, Elya!

Jack L. Moe

Fort Worth, Texas

FOREWORD

The topic of Grounding in EMC is one of the most controversial in this engineering discipline. A solution implemented in one system may not work in another, and "rules of thumb" and "good engineering practices" serve well mostly in presentations.

Elya B. Joffe and Dr. Kai Sang Lock have undertaken a monumental task and complied into this book, *Grounds for Grounding*, most of the data and information required by the designer. The treatment covers the electromagnetic basics, explanation of the reasoning behind the grounding solutions and up to their practical implementation. The book is perhaps the most comprehensive publication to date on the subject of grounding. It deals with every aspect of grounding, from component to system to facility. Because of its vast coverage and detailed discourse, it may take some time and effort to read through. However, each chapter can be approached for specific grounding solutions.

I applaud Elya B. Joffe, President of the IEEE EMC Society plus a full-time EMC Engineer, and Dr. Kai Sang Lock, the President of PQR Technologies Pte Ltd. in Singapore, for addressing the topic and spending the time and effort, despite their duties, to get this well written, important book, completed.

This book will not replace experience and experiment, but it will shorten the path to a successful design.

OREN HARTAL

Qiryat Tivon, Israel

PREFACE

The understanding of grounding as described in this book could not have been made possible without the achievements of Michael Faraday and the great philosopher who followed him, James Clerk Maxwell. The following excerpt was written by Maxwell after Faraday's death in 1867. It is from the introduction by T. F. Torrance to Maxwell's *A Dynamical Theory of the Electromagnetic Field* (Wipf and Stock Publishers, Eugene, OR, 1996).

> The high place which we assign to Faraday in electromagnetic science may appear to some inconsistent with the fact that electromagnetic science is an exact science, and that in some of its branches it had already assumed a mathematical form before the time of Faraday, whereas Faraday was not a professed mathematician, and in his writings we find none of these integrations of differential equations which are supposed to be the very essence of exact science. Open Poisson and Ampere, who went before him, and you will find their pages full of symbols, not one of which Faraday would have understood. It is admitted that Faraday made some great discoveries, but if we put these aside, how can we rank his scientific method so high without disparaging the mathematics of these eminent men?
>
> It is true that no man can essentially cultivate any exact science without understanding the mathematics of that science. But we are not to suppose that the calculations and equations which mathematicians find so useful constitute the whole of mathematics. The calculus is but a part of mathematics.
>
> The geometry of position is an example of mathematical science established without the aid of a single calculation. Now Faraday's lines of force occupy the same position in electromagnetic science that pencils of lines do in the geometry of position. They furnish a method of building up an exact mental image of the thing we are reasoning about. The way in which Faraday made use of his idea of lines of force in coordinating the phenomena of the magnetoelectric induction shows him to have been in reality a mathematician of a very high order—one from whom the mathematicians of the future may derive valuable and fertile methods. . . .
>
> [W]e are probably ignorant even of the name of science which will be developed out of the materials we are now collecting, when the great philosopher after Faraday makes his appearance.

ACKNOWLEDGMENTS

This book would have never come to be a reality had it not been for two special persons in my professional career. Without their guidance and mentorship, I would have never been able to attain the knowledge and experience in my profession. Both are not only good friends of mine but also of each other.

First, John (Jack) Moe, who initially introduced me to this magical discipline of EMC and with limitless patience, through "on-job training," revealed to me the very basics of EMC. The very first book I owned on EMC was presented to me by Jack. I have retained and value his hand-written sketches and notes explaining cable shield grounding.

Second, I would like to recognize Oren Hartal, under whose guidance (similar to most EMC engineers in Israel) I discovered the hidden mysteries of the science and art of EMC. The very first course on EMC I had taken was taught by Oren, and through his guidance I truly gained a deep understanding of this discipline. Many years of work with and encouragement by Oren in IEEE and URSI have, additionally, brought me to the international recognition I benefit from today.

I am especially grateful to my dear friend Mark M. Montrose, who encouraged me to undertake the tremendous challenge of writing this book. Through his support during the writing of the book, Mark redefined the term "friend." Mark's advice helped shape the outline of the book, and made significant contributions in many ways to the final manuscript. His technical review, professional scrutiny, and criticism of the material, made with a fine-tooth comb, helped ensure that concepts were clear, correct, and easy to follow, and that the language and style were appropriate. Without his guidance and support, the technical quality and clarity of this book would not have been as they are. I thank Mark wholeheartedly for his friendship, collegiality, and support.

A particular acknowledgment is given to Kai Sang Lock, the coauthor of this book. Kai Sang was the perfect choice for the task, with his expertise on high-power electrical systems. Without his contribution, a major aspect of grounding could not have been included in this book.

The authors are indebted and wish to gratefully acknowledge the contributions made by many individuals who helped to develop the material for this book, provided material, spent time, and exerted efforts in order to make this book of the high quality I believe it is. Acknowledgments of their contributions are included in the context of this book. Special gratitude is expressed to Bruce Archambeault (IBM), Douglas C. Smith, Keith Armstrong (Cherry Clough Consultants), Todd Hubing (Clemson University), Alexander Perez (Agilent), Edoardo Genovese, and David Johns (CST), as well as to Glenair, Inc. and MAJR Products, Inc., for their outstanding support and contribution of material used throughout this book.

Gratitude is extended to the editorial and technical reviewers of this book for their dedicated toil, and for spending long and frustrating hours of their personal time in tedious study and literal dissection the book. Their professionalism and experience have greatly enhanced the quality and value of this book.

My appreciation is also expressed to the many engineers and students whom I have educated and trained in EMC throughout the years, for their challenging and thought-provoking questions.

> I have learnt much from my teachers, but from my students I have learnt even more.
> —Shimon Ben Zoma, a second century Jewish Scholar, based on *Psalms,* 119:99

Above all, in a personal note, my most special gratitude is due to my wonderful, supporting, and understanding family: my mother, Faiga, who gave me the inspiration and taught me the power of words; my wife, Anat, who helped me appreciate the power of persistence and endured my endless frustrations and foibles without (or with little) protest while this book was being created. Most of all, my gratitude goes to my daughter, Tami Lee, whose beaming smile at the end of each day gave me the strength to go on with this effort.

Anat and Tami Lee must have often felt they had taken the back seat to this project and put up with the long hours during the years I spent at the computer keyboard. Combined with my extensive global traveling commitments, particularly as president of the EMC Society of the IEEE (2008–2009), this effort has no doubt taken its toll on their own lives. I shall forever treasure their sympathy to my passion and their faith in my ability to create this book.

ELYA B. JOFFE

Hod-Hasharon, Israel
October 2009

1

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-

Grounds for Grounding. By Elya B. Joffe and Kai-Sang Lock

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 C^3I (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

[1] Brokaw, P., "An I.C. Amplifier Users' Guide to Decoupling, Grounding, and Making Things Right for a Change," *Application Note, Analog Devices,* 1982.

[2] Perez, R. (Ed.), *Handbook of Electromagnetic Compatibility,* Academic Press, 1995.

[3] Morrison, R., Lewis, W. H., *Grounding and Shielding in Facilities,* Wiley, 1990.

[4] Hartal, O., *Electromagnetic Compatibility By Design,* R&B Enterprises, USA, 1994.