Introduction to Electromagnetic Compatibility

Second Edition

CLAYTON R. PAUL

Department of Electrical and Computer Engineering, School of Engineering, Mercer University, Macon, Georgia and Emeritus Professor of Electrical Engineering, University of Kentucky, Lexington, Kentucky



Introduction to Electromagnetic Compatibility

Second Edition

Introduction to Electromagnetic Compatibility

Second Edition

CLAYTON R. PAUL

Department of Electrical and Computer Engineering, School of Engineering, Mercer University, Macon, Georgia and Emeritus Professor of Electrical Engineering, University of Kentucky, Lexington, Kentucky



This book is printed on acid-free paper. ⊚

Copyright © 2006 by John Wiley & Sons, Inc. All rights reserved.

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

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400, fax 978-646-8600, or on the web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services please contact our Customer Care Department within the U.S. at 877-762-2974, outside the U.S. at 317-572-3993 or fax 317-572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print, however, may not be available in electronic format.

Library of Congress Cataloging-in-Publication Data:

Paul, Clayton R.
Introduction to electromagnetic compatibility / Clayton R. Paul.--2nd ed. p. cm.
"Wiley-Interscience."
Includes bibliographical references and index.
ISBN-13: 978-0-471-75500-5 (alk. paper)
ISBN-10: 0-471-75500-1 (alk. paper)
1. Electromagnetic compatibility. 2. Electronic circuits--Noise. 3. Digital electronics. 4.
Shielding (Electricity) I. Title.

TK7867.2.P38 2006 621.382'24--dc22

2005049400

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

This textbook is dedicated to The humane and compassionate treatment of animals

"For every difficult problem there is always a simple answer and most of them are wrong."

"When you can measure what you are speaking about and express it in numbers you know something about it; but when you cannot measure it, when you cannot express it in numbers your knowledge is of meagre and unsatisfactory kind; it may be the beginning of knowledge but you have scarcely progressed in your thoughts to the stage of science whatever the matter may be."

Lord Kelvin

Contents

Pr	Preface >					
1	Introduction to Electromagnetic Compatibility (EMC)					
	1.1	Aspec	ts of EMC	3		
	1.2	Histor	y of EMC	10		
	1.3 Examples					
	1.4	ical Dimensions and Waves	14			
	1.5	Decib	els and Common EMC Units	23		
		1.5.1	Power Loss in Cables	32		
		1.5.2	Signal Source Specification	37		
	Prob	olems		43		
	Refe	erences		48		
2	EMC Requirements for Electronic Systems					
	2.1	Gover	nmental Requirements	50		
		2.1.1	Requirements for Commercial Products Marketed			
			in the United States	50		
		2.1.2	Requirements for Commercial Products Marketed			
			outside the United States	55		
		2.1.3	Requirements for Military Products Marketed in the			
			United States	60		
		2.1.4	Measurement of Emissions for Verification of Compliance	62		
			2.1.4.1 Radiated Emissions	64		
			2.1.4.2 Conducted Emissions	67		
		2.1.5	Typical Product Emissions	72		
		2.1.6	A Simple Example to Illustrate the Difficulty in Meeting			
			the Regulatory Limits	78		
				vii		

	2.2	Additi	onal Product Requirements	79
		2.2.1	Radiated Susceptibility (Immunity)	81
		2.2.2	Conducted Susceptibility (Immunity)	81
		2.2.3	Electrostatic Discharge (ESD)	81
		2.2.4	Requirements for Commercial Aircraft	82
		2.2.5	Requirements for Commercial Vehicles	82
	2.3	Design	n Constraints for Products	82
	2.4	Advan	tages of EMC Design	84
	Prob	lems		86
	Refe	erences		89
3	Sign	al Spec	tra—the Relationship between the Time Domain and	
	the	Freque	ncy Domain	91
	3.1	Period	lic Signals	91
		3.1.1	The Fourier Series Representation of Periodic Signals	94
		3.1.2	Response of Linear Systems to Periodic Input Signals	104
		3.1.3	Important Computational Techniques	111
	3.2	Spectr	a of Digital Waveforms	118
		3.2.1	The Spectrum of Trapezoidal (Clock) Waveforms	118
		3.2.2	Spectral Bounds for Trapezoidal Waveforms	122
			3.2.2.1 Effect of Rise/Falltime on Spectral Content	123
			3.2.2.2 Bandwidth of Digital Waveforms	132
			3.2.2.3 Effect of Repetition Rate and Duty Cycle	130
		2 2 2	5.2.2.4 Effect of Kinging (Undershool/Overshool)	157
		3.2.3	Output Spectrum of a Linear System	140
	3.3	Spectr	um Analyzers	142
		3.3.1	Basic Principles	142
		3.3.2	Peak versus Quasi-Peak versus Average	146
	3.4	Repres	sentation of Nonperiodic Waveforms	148
		3.4.1	The Fourier Transform	148
		3.4.2	Response of Linear Systems to Nonperiodic Inputs	151
	3.5	Repres	sentation of Random (Data) Signals	151
	3.6	Use of	f SPICE (PSPICE) In Fourier Analysis	155
	Prob	lems		167
	Refe	erences		175
4	Tran	smissio	on Lines and Signal Integrity	177
	4.1	The T	ransmission-Line Equations	181
	4.2	The Pe	er-Unit-Length Parameters	184
		4.2.1	Wire-Type Structures	186

 4.3 The Time-Domain Solution 4.3.1 Graphical Solutions 4.3.2 The SPICE Model 4.4 High-Speed Digital Interconnects and Signal Integrity 4.4.1 Effect of Terminations on the Line Waveforms 4.4.1.1 Effect of Capacitive Terminations 4.4.1.2 Effect of Inductive Terminations 4.4.2 Matching Schemes for Signal Integrity 4.4.3 When Does the Line Not Matter, i.e., When is Matching Not Required? 4.4.4 Effects of Line Discontinuities 4.5 Sinusoidal Excitation of the Line and the Phasor Solution 4.5.1 Voltage and Current as Functions of Position 4.5.2 Power Flow 4.5.3 Inclusion of Losses 4.5.4 Effect of Losses on Signal Integrity 4.6 Lumped-Circuit Approximate Models Problems References 5 Nonideal Behavior of Components 5.1.1 Resistance and Internal Inductance of Wires 5.1.2 External Inductance and Capacitance of Parallel Wires 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.1 Wires 5.1 External Inductance and Capacitance of Parallel Wires 5.1 External Inductance and Capacitance of Parallel Wires 5.1 Capacitors 5.6 Inductors 5.7 Capacitors 5.6 Inductors 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Arcing at Switch Contacts 			4.2.2	Printed Circuit Board (PCB) Structures	199		
 4.3.1 Graphical Solutions 4.3.2 The SPICE Model 4.4 High-Speed Digital Interconnects and Signal Integrity 4.4.1 Effect of Terminations on the Line Waveforms 4.4.1.1 Effect of Capacitive Terminations 4.4.1.2 Effect of Inductive Terminations 4.4.2 Matching Schemes for Signal Integrity 4.4.3 When Does the Line Not Matter, i.e., When is Matching Not Required? 4.4.4 Effects of Line Discontinuities 4.5 Sinusoidal Excitation of the Line and the Phasor Solution 4.5.1 Voltage and Current as Functions of Position 4.5.2 Power Flow 4.5.3 Inclusion of Losses 4.5.4 Effect of Losses on Signal Integrity 4.6 Lumped-Circuit Approximate Models Problems References 5 Nonideal Behavior of Components 5.1.1 Resistance and Internal Inductance of Wires 5.1.2 External Inductance and Capacitance of Parallel Wires 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.2 Printed Circuit Board (PCB) Lands 5.3 Effect of Component Leads 5.4 Resistors 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts 		4.3	The Ti	me-Domain Solution	204		
 4.3.2 The SPICE Model 4.4 High-Speed Digital Interconnects and Signal Integrity 4.4.1 Effect of Terminations on the Line Waveforms 4.4.1.1 Effect of Capacitive Terminations 4.4.1.1 Effect of Inductive Terminations 4.4.2 Matching Schemes for Signal Integrity 4.4.3 When Does the Line Not Matter, i.e., When is Matching Not Required? 4.4.4 Effects of Line Discontinuities 4.5 Sinusoidal Excitation of the Line and the Phasor Solution 4.5.1 Voltage and Current as Functions of Position 4.5.2 Power Flow 4.5.3 Inclusion of Losses 4.5.4 Effect of Losses on Signal Integrity 4.6 Lumped-Circuit Approximate Models Problems References 5 Nonideal Behavior of Components 5.1.1 Resistance and Internal Inductance of Wires 5.1.2 External Inductance and Capacitance of Parallel Wires 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.1.4 Effect of COmponent Leads 5.4 Resistors 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts 			4.3.1	Graphical Solutions	204		
 4.4 High-Speed Digital Interconnects and Signal Integrity 4.4.1 Effect of Terminations on the Line Waveforms 4.4.1.1 Effect of Capacitive Terminations 4.4.2 Matching Schemes for Signal Integrity 4.4.3 When Does the Line Not Matter, i.e., When is Matching Not Required? 4.4.4 Effects of Line Discontinuities 4.5 Sinusoidal Excitation of the Line and the Phasor Solution 4.5.1 Voltage and Current as Functions of Position 4.5.2 Power Flow 4.5.3 Inclusion of Losses 4.5.4 Effect of Losses on Signal Integrity 4.6 Lumped-Circuit Approximate Models Problems References 5 Nonideal Behavior of Components 5.1.1 Resistance and Internal Inductance of Wires 5.1.2 External Inductance and Capacitance of Parallel Wires 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.2 Printed Circuit Board (PCB) Lands 5.3 Effect of Component Leads 5.4 Resistors 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts 			4.3.2	The SPICE Model	218		
 4.1 Effect of Terminations on the Line Waveforms 4.4.1.1 Effect of Capacitive Terminations 4.4.1.2 Effect of Inductive Terminations 4.4.2 Matching Schemes for Signal Integrity 4.3 When Does the Line Not Matter, i.e., When is Matching Not Required? 4.4.4 Effects of Line Discontinuities 4.5 Sinusoidal Excitation of the Line and the Phasor Solution 4.5.1 Voltage and Current as Functions of Position 4.5.2 Power Flow 4.5.3 Inclusion of Losses 4.5.4 Effect of Losses on Signal Integrity 4.6 Lumped-Circuit Approximate Models Problems References 5 Nonideal Behavior of Components 5.1.1 Resistance and Internal Inductance of Wires 5.1.2 External Inductance and Capacitance of Parallel Wires 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.2 Printed Circuit Board (PCB) Lands 5.3 Effect of Component Leads 5.4 Resistors 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts 		4.4	High-S	Speed Digital Interconnects and Signal Integrity	225		
 4.4.1.1 Effect of Capacitive Terminations 4.4.1.2 Effect of Inductive Terminations 4.4.2 Matching Schemes for Signal Integrity 4.4.3 When Does the Line Not Matter, i.e., When is Matching Not Required? 4.4.4 Effects of Line Discontinuities 4.5 Sinusoidal Excitation of the Line and the Phasor Solution 4.5.1 Voltage and Current as Functions of Position 4.5.2 Power Flow 4.5.3 Inclusion of Losses 4.5.4 Effect of Losses on Signal Integrity 4.6 Lumped-Circuit Approximate Models Problems References 5 Nonideal Behavior of Components 5.1 Vires 5.1.1 Resistance and Internal Inductance of Wires 5.1.2 External Inductance and Capacitance of Parallel Wires 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.2 Printed Circuit Board (PCB) Lands 5.3 Effect of Component Leads 5.4 Resistors 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Areing at Switch Contacts 			4.4.1	Effect of Terminations on the Line Waveforms	230		
 4.4.1.2 Effect of Inductive Terminations 4.4.2 Matching Schemes for Signal Integrity 4.4.3 When Does the Line Not Matter, i.e., When is Matching Not Required? 4.4.4 Effects of Line Discontinuities 4.5 Sinusoidal Excitation of the Line and the Phasor Solution 4.5.1 Voltage and Current as Functions of Position 4.5.2 Power Flow 4.5.3 Inclusion of Losses 4.5.4 Effect of Losses on Signal Integrity 4.6 Lumped-Circuit Approximate Models Problems References 5 Nonideal Behavior of Components 5.1 Wires 5.1.1 Resistance and Internal Inductance of Wires 5.1.2 External Inductance and Capacitance of Parallel Wires 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.2 Printed Circuit Board (PCB) Lands 5.3 Effect of Component Leads 5.4 Resistors 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Areing at Switch Contacts 				4.4.1.1 Effect of Capacitive Terminations	233		
 4.4.2 Matching Schemes for Signal Integrity 4.4.3 When Does the Line Not Matter, i.e., When is Matching Not Required? 4.4.4 Effects of Line Discontinuities 4.5 Sinusoidal Excitation of the Line and the Phasor Solution 4.5.1 Voltage and Current as Functions of Position 4.5.2 Power Flow 4.5.3 Inclusion of Losses 4.5.4 Effect of Losses on Signal Integrity 4.6 Lumped-Circuit Approximate Models Problems References 5 Nonideal Behavior of Components 5.1 Wires 5.1.1 Resistance and Internal Inductance of Wires 5.1.2 External Inductance and Capacitance of Parallel Wires 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.2 Printed Circuit Board (PCB) Lands 5.3 Effect of Component Leads 5.4 Resistors 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.14 Areing at Switch Contacts 				4.4.1.2 Effect of Inductive Terminations	236		
 4.4.3 When Does the Line Not Matter, i.e., When is Matching Not Required? 4.4.4 Effects of Line Discontinuities 4.5 Sinusoidal Excitation of the Line and the Phasor Solution 4.5.1 Voltage and Current as Functions of Position 4.5.2 Power Flow 4.5.3 Inclusion of Losses 4.5.4 Effect of Losses on Signal Integrity 4.6 Lumped-Circuit Approximate Models Problems References 5 Nonideal Behavior of Components 5.1.1 Resistance and Internal Inductance of Wires 5.1.2 External Inductance and Capacitance of Parallel Wires 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.1.3 Limped Equivalent Circuits of Parallel Wires 5.4 Resistors 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10.1 DC Motors 5.10.3 AC Motors 5.10.3 AC Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Incurs at Switch Contacts 			4.4.2	Matching Schemes for Signal Integrity	238		
 4.4.4 Effects of Line Discontinuities 4.5 Sinusoidal Excitation of the Line and the Phasor Solution 4.5.1 Voltage and Current as Functions of Position 4.5.2 Power Flow 4.5.3 Inclusion of Losses 4.5.4 Effect of Losses on Signal Integrity 4.6 Lumped-Circuit Approximate Models Problems References 5 Nonideal Behavior of Components 5.1.1 Resistance and Internal Inductance of Wires 5.1.2 External Inductance and Capacitance of Parallel Wires 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.1.4 Resistors 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Arcing at Switch Contacts 			4.4.3	When Does the Line Not Matter, i.e., When is Matching	244		
 4.4.4 Effects of Ene Discontinuities 4.5 Sinusoidal Excitation of the Line and the Phasor Solution 4.5.1 Voltage and Current as Functions of Position 4.5.2 Power Flow 4.5.3 Inclusion of Losses 4.5.4 Effect of Losses on Signal Integrity 4.6 Lumped-Circuit Approximate Models Problems References 5 Nonideal Behavior of Components 5.1 Wires 5.1.1 Resistance and Internal Inductance of Wires 5.1.2 External Inductance and Capacitance of Parallel Wires 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.2 Printed Circuit Board (PCB) Lands 5.3 Effect of Component Leads 5.4 Resistors 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.14 Arcing at Switch Contacts 			111	Not Required?	244		
 4.5 Sindoidal Excitation of the Line and the Phasor Solution 4.5.1 Voltage and Current as Functions of Position 4.5.2 Power Flow 4.5.3 Inclusion of Losses 4.5.4 Effect of Losses on Signal Integrity 4.6 Lumped-Circuit Approximate Models Problems References 5 Nonideal Behavior of Components 5.1.1 Resistance and Internal Inductance of Wires 5.1.2 External Inductance and Capacitance of Parallel Wires 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.2 Printed Circuit Board (PCB) Lands 5.3 Effect of Component Leads 5.4 Resistors 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.11 Digital Switch Contacts 		15	4.4.4 Sinuso	idel Excitation of the Line and the Discontinuities	247		
 4.5.1 Voltage and Current as Functions of Position 4.5.2 Power Flow 4.5.3 Inclusion of Losses 4.5.4 Effect of Losses on Signal Integrity 4.6 Lumped-Circuit Approximate Models Problems References 5 Nonideal Behavior of Components 5.1 Wires 5.1.1 Resistance and Internal Inductance of Wires 5.1.2 External Inductance and Capacitance of Parallel Wires 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.1 Printed Circuit Board (PCB) Lands 5.3 Effect of Component Leads 5.4 Resistors 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts		4.3		Velters and Current of Functions of Desition	200		
 4.5.2 Fower flow 4.5.3 Inclusion of Losses 4.5.4 Effect of Losses on Signal Integrity 4.6 Lumped-Circuit Approximate Models Problems References 5 Nonideal Behavior of Components 5.1 Wires 5.1.1 Resistance and Internal Inductance of Wires 5.1.2 External Inductance and Capacitance of Parallel Wires 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.2 Printed Circuit Board (PCB) Lands 5.3 Effect of Component Leads 5.4 Resistors 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts 			4.5.1	Power Flow	201		
 4.5.4 Effect of Losses on Signal Integrity 4.6 Lumped-Circuit Approximate Models Problems References 5 Nonideal Behavior of Components 5.1 Wires 5.1.1 Resistance and Internal Inductance of Wires 5.1.2 External Inductance and Capacitance of Parallel Wires 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.2 Printed Circuit Board (PCB) Lands 5.3 Effect of Component Leads 5.4 Resistors 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts 			453	Inclusion of Losses	209		
 4.6 Lumped-Circuit Approximate Models Problems References 5 Nonideal Behavior of Components 5.1 Wires 5.1.1 Resistance and Internal Inductance of Wires 5.1.2 External Inductance and Capacitance of Parallel Wires 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.2 Printed Circuit Board (PCB) Lands 5.3 Effect of Component Leads 5.4 Resistors 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts 			4.5.4	Effect of Losses on Signal Integrity	273		
 Problems References 5 Nonideal Behavior of Components 5.1 Wires 5.1.1 Resistance and Internal Inductance of Wires 5.1.2 External Inductance and Capacitance of Parallel Wires 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.2 Printed Circuit Board (PCB) Lands 5.3 Effect of Component Leads 5.4 Resistors 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts		4.6	Lumpe	ed-Circuit Approximate Models	283		
References 5 Nonideal Behavior of Components 5.1 Wires 5.1.1 Resistance and Internal Inductance of Wires 5.1.2 External Inductance and Capacitance of Parallel Wires 5.1 Lumped Equivalent Circuits of Parallel Wires 5.2 Printed Circuit Board (PCB) Lands 5.3 Effect of Component Leads 5.4 Resistors 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts		Prot	olems		287		
 5 Nonideal Behavior of Components 5.1 Wires 5.1.1 Resistance and Internal Inductance of Wires 5.1.2 External Inductance and Capacitance of Parallel Wires 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.2 Printed Circuit Board (PCB) Lands 5.3 Effect of Component Leads 5.4 Resistors 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts		References					
 5.1 Wires 5.1.1 Resistance and Internal Inductance of Wires 5.1.2 External Inductance and Capacitance of Parallel Wires 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.2 Printed Circuit Board (PCB) Lands 5.3 Effect of Component Leads 5.4 Resistors 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts	5	Non	Nonideal Behavior of Components				
 5.1.1 Resistance and Internal Inductance of Wires 5.1.2 External Inductance and Capacitance of Parallel Wires 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.2 Printed Circuit Board (PCB) Lands 5.3 Effect of Component Leads 5.4 Resistors 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts		5.1	Wires				
 5.1.1 Treastance and mitching inductance of which signals in the standard of the signal signals in the standard signa		0.1	511	Resistance and Internal Inductance of Wires	304		
 5.1.3 Lumped Equivalent Circuits of Parallel Wires 5.2 Printed Circuit Board (PCB) Lands 5.3 Effect of Component Leads 5.4 Resistors 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts 			5.1.2	External Inductance and Capacitance of Parallel Wires	308		
 5.2 Printed Circuit Board (PCB) Lands 5.3 Effect of Component Leads 5.4 Resistors 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts 			5.1.3	Lumped Equivalent Circuits of Parallel Wires	309		
 5.3 Effect of Component Leads 5.4 Resistors 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts 		5.2	Printed	l Circuit Board (PCB) Lands	312		
 5.4 Resistors 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts 		5.3	5.3 Effect of Component Leads				
 5.5 Capacitors 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts 		5.4	4 Resistors				
 5.6 Inductors 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts 		5.5	Capaci	tors	325		
 5.7 Ferromagnetic Materials—Saturation and Frequency Response 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts 		5.6	5.6 Inductors				
 5.8 Ferrite Beads 5.9 Common-Mode Chokes 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts 		5./	Ferron	hagnetic Materials—Saturation and Frequency Response	340		
 5.10 Electromechanical Devices 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts 		5.0 5.0	Comm	on-Mode Chokes	345		
 5.10.1 DC Motors 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts 		5.10	Electro	omechanical Devices	352		
 5.10.2 Stepper Motors 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts 		0.110	5 10 1	DC Motors	352		
 5.10.3 AC Motors 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts 			5.10.2	Stepper Motors	355		
 5.10.4 Solenoids 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts 			5.10.3	AC Motors	355		
 5.11 Digital Circuit Devices 5.12 Effect of Component Variability 5.13 Mechanical Switches 5.13.1 Arcing at Switch Contacts 			5.10.4	Solenoids	356		
5.12 Effect of Component Variability5.13 Mechanical Switches5.13.1 Arcing at Switch Contacts		5.11	Digital	Circuit Devices	357		
5.13 Mechanical Switches5.13.1 Arcing at Switch Contacts		5.12	Effect	of Component Variability	358		
5.13.1 Arcing at Switch Contacts		5.13	Mecha	nical Switches	359		
			5.13.1	Arcing at Switch Contacts	360		

		5.13.2 5.13.3	The Showering Arc Arc Suppression	363 364		
	Prob Refe	olems erences		369 375		
6	Con	ducted	Emissions and Susceptibility	377		
	6.1	Measu	rement of Conducted Emissions	378		
		6.1.1	The Line Impedance Stabilization Network (LISN)	379		
		6.1.2	Common- and Differential-Mode Currents Again	381		
	6.2	Power	Supply Filters	385		
		6.2.1	Basic Properties of Filters	385		
		6.2.2 6.2.3	A Generic Power Supply Filter Topology Effect of Filter Elements on Common- and	388		
			Differential-Mode Currents	390		
		6.2.4	Separation of Conducted Emissions into Common-			
			and Differential-Mode Components for	201		
		-	Diagnostic Purposes	396		
	6.3	Power	Supplies	401		
		6.3.1	Linear Power Supplies	405		
		6.3.2	Switched-Mode Power Supplies (SMPS)	406		
		0.5.5	Emissions	409		
	64	Power	Supply and Filter Placement	414		
	6.5	Condu	cted Susceptibility	416		
	Proh	Problems				
	References					
7	Ante	ennas		421		
	7.1	Elemen	ntal Dipole Antennas	421		
		7.1.1	The Electric (Hertzian) Dipole	422		
		7.1.2	The Magnetic Dipole (Loop)	426		
	7.2	The Ha	alf-Wave Dipole and Quarter-Wave Monopole Antennas	429		
	7.3	Antenn	na Arrays	440		
	7.4	Charac	cterization of Antennas	448		
		7.4.1	Directivity and Gain	448		
		7.4.2	Effective Aperture	454		
		7.4.5	Antenna Factor Effects of Balancing and Baluns	430		
		7.4.4	Impedance Matching and the Use of Pads	460		
	75	The Fr	is Transmission Equation	466		
	7.6	Effects	s of Reflections	470		
		7.6.1	The Method of Images	470		
			\mathbf{c}			

		7.6.2	Normal	Incidence of Uniform Plane Waves on Plane,			
		7()	Material	Boundaries	470		
		7.0.3	Multipat	In Effects	4/9		
	7.7	Broad	band Mea	surment Antennas	486		
		7.7.1	The Bico	onical Antenna	487		
		1.1.2	The Log	-Periodic Antenna	490		
	Prob	lems			494		
	Refe	rences			501		
8	Radi	ated E	nissions a	and Susceptibility	503		
	8.1	Simple	e Emissio	n Models for Wires and PCB Lands	504		
		8.1.1	Differen	tial-Mode versus Common-Mode Currents	504		
		8.1.2	Differen	tial-Mode Current Emission Model	509		
		8.1.3	Common	n-Mode Current Emission Model	514		
		8.1.4	Current	Probes	518		
		8.1.5	Experim	ental Results	523		
	8.2	Simple	e Suscepti	bility Models for Wires and PCB Lands	533		
		8.2.1	Experim	ental Results	544		
		8.2.2	Shielded	Cables and Surface Transfer Impedance	546		
	Prob	Problems					
	Refe	rences			556		
9	Crosstalk						
	9.1	0.1 Three-Conductor Transmission Lines and Crosstalk					
	9.2	The T	on-Line Equations for Lossless Lines	564			
	9.3	The P	er-Unit-Le	ength Parameters	567		
		9.3.1	Homoge	neous versus Inhomogeneous Media	568		
		9.3.2	Wide-Se	paration Approximations for Wires	570		
		9.3.3	Numeric	al Methods for Other Structures	580		
			9.3.3.1	Wires with Dielectric Insulations			
				(Ribbon Cables)	586		
			9.3.3.2	Rectangular Cross-Section Conductors			
				(PCB Lands)	590		
	9.4	The Ir	ductive-	Capacitive Coupling Approximate Model	595		
		9.4.1	Frequen	cy-Domain Inductive-Capacitive Coupling			
			Model		599		
			9.4.1.1	Inclusion of Losses: Common-Impedance			
			o	Coupling	601		
		.	9.4.1.2	Experimental Results	604		
		9.4.2	Time-Do	Smain Inductive–Capacitive Coupling Model	612		
			9.4.2.1	Inclusion of Losses: Common-Impedance Coupling	616		
			9.4.2.2	Experimental Results	617		

	9.5 L	umped-	Circuit Approximate Models	624
	9.6 A	n Exac	t SPICE (PSPICE) Model for Lossless, Coupled Lines	624
		9.6.1	Computed versus Experimental Results for Wires	633
		9.6.2	Computed versus Experimental Results for PCBs	640
	9.7	Shield	ed Wires	647
		9.7.1	Per-Unit-Length Parameters	648
		9.7.2	Inductive and Capacitive Coupling	651
		9.7.3	Effect of Shield Grounding	658
		9.7.4	Effect of Pigtails	667
		9.7.5	Effects of Multiple Shields	669
		9.7.6	MTL Model Predictions	675
	9.8	Twiste	ed Wires	677
		9.8.1	Per-Unit-Length Parameters	681
		9.8.2	Inductive and Capacitive Coupling	685
		9.8.3	Effects of Twist	689
		9.8.4	Effects of Balancing	698
	Prob	olems		701
	Refe	erences		710
10	Shiel	ding		713
	10.1	Shield	ing Effectiveness	718
	10.2	Shield	ing Effectiveness: Far-Field Sources	721
		10.2.1	Exact Solution	721
		10.2.2	Approximate Solution	725
			10.2.2.1 Reflection Loss	725
			10.2.2.2 Absorption Loss	728
			10.2.2.3 Multiple-Reflection Loss	729
			10.2.2.4 Total Loss	731
	10.3	Shield	ing Effectiveness: Near-Field Sources	735
		10.3.1	Near Field versus Far Field	736
		10.3.2	Electric Sources	740
		10.3.3	Magnetic Sources	740
	10.4	Low-F	Frequency, Magnetic Field Shielding	742
	10.5	Effect	of Apertures	745
	Probl	ems	-	750
	Refer	rences		751
11	Syste	m Desi	gn for EMC	753
	11.1 Changing the Way We Think about Electrical Phenomena			758
		11.1.1	Nonideal Behavior of Components and the	
			Hidden Schematic	758
		11.1.2	"Electrons Do Not Read Schematics"	763

	11.1.3	What Do We Mean by the Term "Shielding"?	766		
11.2	What Do We Mean by the Term "Ground"?				
	11.2.1	Safety Ground	771		
	11.2.2	Signal Ground	774		
	11.2.3	Ground Bounce and Partial Inductance	775		
		11.2.3.1 Partial Inductance of Wires	781		
		11.2.3.2 Partial Inductance of PCB Lands	786		
	11.2.4	Currents Return to Their Source on the Paths of Lowest			
		Impedance	787		
	11.2.5	Utilizing Mutual Inductance and Image Planes to Force			
		Currents to Return on a Desired Path	793		
	11.2.6	Single-Point Grounding, Multipoint Grounding, and	-		
	1107	Hybrid Grounding	796		
	11.2.7	Ground Loops and Subsystem Decoupling	802		
11.3	Printed	Circuit Board (PCB) Design	805		
	11.3.1	Component Selection	805		
	11.3.2	Component Speed and Placement	806		
	11.3.3	Cable I/O Placement and Filtering	808		
	11.3.4	The Important Ground Grid	810		
	11.3.5	Power Distribution and Decoupling Capacitors	812		
	11.3.6	Reduction of Loop Areas	822		
	11.3.7	Mixed-Signal PCB Partitioning	823		
11.4	System	Configuration and Design	827		
	11.4.1	System Enclosures	827		
	11.4.2	Power Line Filter Placement	828		
	11.4.3	Interconnection and Number of Printed			
		Circuit Boards	829		
	11.4.4	Internal Cable Routing and Connector Placement	831		
	11.4.5	PCB and Subsystem Placement	832		
	11.4.6	PCB and Subsystem Decoupling	832		
	11.4.7	Motor Noise Suppression	832		
	11.4.8	Electrostatic Discharge (ESD)	834		
11.5	Diagno	stic Tools	847		
	11.5.1	The Concept of Dominant Effect in the Diagnosis of			
		EMC Problems	850		
Proble	em		856		
Refere	References				

Appendix A	The Phasor Solution Method			
	A.1	Solving Differential Equations for Their Sinusoidal,		
		Steady-State Solution	859	