

KEITH BILLINGS  
TAYLOR MOREY



# SWITCHMODE POWER SUPPLY

## HANDBOOK

THIRD EDITION

---

# **SWITCHMODE POWER SUPPLY HANDBOOK**

---

**Keith Billings  
Taylor Morey**

**Third Edition**



**New York Chicago San Francisco Lisbon London Madrid  
Mexico City Milan New Delhi San Juan Seoul  
Singapore Sydney Toronto**

Copyright © 2011 by The McGraw-Hill Companies. All rights reserved. Except as permitted under the United States Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in a database or retrieval system, without the prior written permission of the publisher.

ISBN: 978-0-07-163972-9

MHID: 0-07-163972-1

The material in this eBook also appears in the print version of this title: ISBN: 978-0-07-163971-2, MHID: 0-07-163971-3.

All trademarks are trademarks of their respective owners. Rather than put a trademark symbol after every occurrence of a trademarked name, we use names in an editorial fashion only, and to the benefit of the trademark owner, with no intention of infringement of the trademark. Where such designations appear in this book, they have been printed with initial caps.

McGraw-Hill eBooks are available at special quantity discounts to use as premiums and sales promotions, or for use in corporate training programs. To contact a representative please e-mail us at [bulksales@mcgraw-hill.com](mailto:bulksales@mcgraw-hill.com).

Information has been obtained by McGraw-Hill from sources believed to be reliable. However, because of the possibility of human or mechanical error by our sources, McGraw-Hill, or others, McGraw-Hill does not guarantee the accuracy, adequacy, or completeness of any information and is not responsible for any errors or omissions or the results obtained from the use of such information.

#### TERMS OF USE

This is a copyrighted work and The McGraw-Hill Companies, Inc. ("McGrawHill") and its licensors reserve all rights in and to the work. Use of this work is subject to these terms. Except as permitted under the Copyright Act of 1976 and the right to store and retrieve one copy of the work, you may not decompile, disassemble, reverse engineer, reproduce, modify, create derivative works based upon, transmit, distribute, disseminate, sell, publish or sublicense the work or any part of it without McGraw-Hill's prior consent. You may use the work for your own noncommercial and personal use; any other use of the work is strictly prohibited. Your right to use the work may be terminated if you fail to comply with these terms.

THE WORK IS PROVIDED "AS IS." McGRAW-HILL AND ITS LICENSORS MAKE NO GUARANTEES OR WARRANTIES AS TO THE ACCURACY, ADEQUACY OR COMPLETENESS OF OR RESULTS TO BE OBTAINED FROM USING THE WORK, INCLUDING ANY INFORMATION THAT CAN BE ACCESSED THROUGH THE WORK VIA HYPERLINK OR OTHERWISE, AND EXPRESSLY DISCLAIM ANY WARRANTY, EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO IMPLIED WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE. McGraw-Hill and its licensors do not warrant or guarantee that the functions contained in the work will meet your requirements or that its operation will be uninterrupted or error free. Neither McGraw-Hill nor its licensors shall be liable to you or anyone else for any inaccuracy, error or omission, regardless of cause, in the work or for any damages resulting therefrom. McGraw-Hill has no responsibility for the content of any information accessed through the work. Under no circumstances shall McGraw-Hill and/or its licensors be liable for any indirect, incidental, special, punitive, consequential or similar damages that result from the use of or inability to use the work, even if any of them has been advised of the possibility of such damages. This limitation of liability shall apply to any claim or cause whatsoever whether such claim or cause arises in contract, tort or otherwise.

---

## **ABOUT THE AUTHORS**

---

KEITH BILLINGS, President of DKB Power Inc. and engineering design consultant, has over 46 years of experience in switch-mode power supply design. He is a Chartered Electronics Engineer and a full member of the former Great Britain's Institution of Electrical Engineers (now the Institution of Engineering and Technology).

TAYLOR MOREY is a Professor of Electronics Engineering Technology at Conestoga College Institute of Technology and Advanced Learning in Kitchener, Ontario, and design consultant with over 30 years experience in power supplies.

---

# CONTENTS

---

Preface	xv
Acknowledgments	xvii
Units, Symbols, Dimensions, and Abbreviations Used in This Book	xviii
List of Figures and Tables	xxvi

## PART 1 FUNCTIONS AND REQUIREMENTS COMMON TO MOST DIRECT-OFF-LINE SWITCHMODE POWER SUPPLIES

<b>1. COMMON REQUIREMENTS: AN OVERVIEW</b>	<b>1.3</b>
1.1 Introduction 1.2 Input Transient Voltage Protection 1.3 Electromagnetic Compatibility 1.4 Differential-Mode Noise 1.5 Common-Mode Noise 1.6 Faraday Screens 1.7 Input Fuse Selection 1.8 Line Rectification and Capacitor Input Filters 1.9 Inrush Limiting 1.10 Start-Up Methods 1.11 Soft Start 1.12 Start-Up Overvoltage Prevention 1.13 Output Overvoltage Protection 1.14 Output Undervoltage Protection 1.15 Overload Protection (Input Power Limiting) 1.16 Output Current Limiting 1.17 Base Drive Requirements for High-Voltage Bipolar Transistors 1.18 Proportional Drive Circuits 1.19 Antisaturation Techniques 1.20 Snubber Networks 1.21 Cross Conduction 1.22 Output Filtering, Common-Mode Noise, and Input-to-Output Isolation 1.23 Power Failure Signals 1.24 Power Good Signals 1.25 Dual Input Voltage Operation 1.26 Power Supply Holdup Time 1.27 Synchronization 1.28 External Inhibit 1.29 Forced Current Sharing 1.30 Remote Sensing 1.31 P-Terminal Link 1.32 Low-Voltage Cutout 1.33 Voltage and Current Limit Adjustments 1.34 Input Safety Requirements	
<b>2. AC POWERLINE SURGE PROTECTION</b>	<b>1.17</b>
2.1 Introduction 2.2 Location Categories 2.3 Likely Rate of Surge Occurrences 2.4 Surge Voltage Waveforms 2.5 Transient Suppression Devices 2.6 Metal Oxide Varistors (Movs, Voltage-Dependent Resistors) 2.7 Transient Protection Diodes 2.8 Gas-Filled Surge Arresters 2.9 Line Filter, Transient Suppressor Combinations 2.10 Category A Transient Suppression Filters 2.11 Category B Transient Suppression Filters 2.12 A Case for Full Transient Protection 2.13 The Cause of “Ground Return Voltage Bump” Stress 2.14 Problems	
<b>3. ELECTROMAGNETIC INTERFERENCE (EMI) IN SWITCHMODE POWER SUPPLIES</b>	<b>1.31</b>
3.1 Introduction 3.2 EMI/RFI Propagation Modes 3.3 Powerline Conducted-Mode Interference 3.4 Safety Regulations (Ground Return Currents) 3.5 Powerline Filters 3.6 Suppressing EMI at Source 3.7 Example 3.8 Line Impedance Stabilization Network (LISN) 3.9 Line Filter Design 3.10 Common-Mode Line Filter Inductors 3.11 Design Example, Common-Mode Line Filter Inductors 3.12 Series-Mode Inductors 3.13 Problems	

<b>4. FARADAY SCREENS</b>	<b>1.43</b>
4.1 Introduction 4.2 Faraday Screens as Applied to Switching Devices 4.3 Transformer Faraday Screens and Safety Screens 4.4 Faraday Screens on Output Components 4.5 Reducing Radiated EMI in Gapped Transformer Cores 4.6 Problems	
<b>5. FUSE SELECTION</b>	<b>1.49</b>
5.1 Introduction 5.2 Fuse Parameters 5.3 Types of Fuses 5.4 Selecting Fuses 5.5 SCR Crowbar Fuses 5.6 Transformer Input Fuses 5.7 Problems	
<b>6. LINE RECTIFICATION AND CAPACITOR INPUT FILTERS FOR “DIRECT-OFF-LINE” SWITCHMODE POWER SUPPLIES</b>	<b>1.55</b>
6.1 Introduction 6.2 Typical Dual-Voltage Capacitor Input Filter Circuit 6.3 Effective Series Resistance $R_s$ 6.4 Constant-Power Load 6.5 Constant- Current Load 6.6 Rectifier and Capacitor Waveforms 6.7 Input Current, Capacitor Ripple, and Peak Currents 6.8 Effective Input Current $I_e$ , and Power Factor 6.9 Selecting Inrush-Limiting Resistance 6.10 Resistance Factor $R_{sf}$ 6.11 Design Example 6.12 DC Output Voltage and Regulation for Rectifier Capacitor Input Filters 6.13 Example of Rectifier Capacitor Input Filter DC Output Voltage Calculation 6.14 Selecting Reservoir and/or Filter Capacitor Size 6.15 Selecting Input Fuse Ratings 6.16 Power Factor and Efficiency Measurements 6.17 Problems	
<b>7. INRUSH CONTROL</b>	<b>1.73</b>
7.1 Introduction 7.2 Series Resistors 7.3 Thermistor Inrush Limiting 7.4 Active Limiting Circuits (Triac Start Circuit) 7.5 Problems	
<b>8. START-UP METHODS</b>	<b>1.77</b>
8.1 Introduction 8.2 Dissipative (Passive) Start Circuit 8.3 Transistor (Active) Start Circuit 8.4 Impulse Start Circuits	
<b>9. SOFT START AND LOW-VOLTAGE INHIBIT</b>	<b>1.81</b>
9.1 Introduction 9.2 Soft-Start Circuit 9.3 Low-Voltage Inhibit 9.4 Problems	
<b>10. TURN-ON VOLTAGE OVERSHOOT PREVENTION</b>	<b>1.85</b>
10.1 Introduction 10.2 Typical Causes of Turn-On Voltage Overshoot in Switchmode Supplies 10.3 Overshoot Prevention 10.4 Problems	
<b>11. OVERVOLTAGE PROTECTION</b>	<b>1.89</b>
11.1 Introduction 11.2 Types of Overvoltage Protection 11.3 Type 1, SCR “Crowbar” Overvoltage Protection 11.4 “Crowbar” Performance 11.5 Limitations of “Simple” Crowbar Circuits 11.6 Type 2, Overvoltage Clamping Techniques 11.7 Overvoltage Clamping with SCR “Crowbar” Backup 11.8 Selecting Fuses for SCR “Crowbar” Overvoltage Protection Circuits 11.9 Type 3, Overvoltage Protection by Voltage Limiting Techniques 11.10 Problems	

<b>12. UNDERVOLTAGE PROTECTION</b>	<b>1.101</b>
12.1 <i>Introduction</i> 12.2 <i>Undervoltage Suppressor Performance Parameters</i> 12.3 <i>Basic Principles</i> 12.4 <i>Practical Circuit Description</i> 12.5 <i>Operating Principles (Practical Circuit)</i> 12.6 <i>Transient Behavior</i> 12.7 <i>Problems</i>	
<b>13. OVERLOAD PROTECTION</b>	<b>1.107</b>
13.1 <i>Introduction</i> 13.2 <i>Types of Overload Protection</i> 13.3 <i>Type 1, Overpower Limiting</i> 13.4 <i>Type 1, Form A, Primary Overpower Limiting</i> 13.5 <i>Type 1, Form B, Delayed Overpower Shutdown Protection</i> 13.6 <i>Type 1, Form C, Pulse-by-Pulse Overpower/Current Limiting</i> 13.7 <i>Type 1, Form D, Constant Power Limiting</i> 13.8 <i>Type 1, Form E, Foldback (Reentrant) Overpower Limiting</i> 13.9 <i>Type 2, Output Constant Current Limiting</i> 13.10 <i>Type 3, Overload Protection by Fuses, Current Limiting, or Trip Devices</i> 13.11 <i>Problems</i>	
<b>14. FOLDBACK (REENTRANT) OUTPUT CURRENT LIMITING</b>	<b>1.113</b>
14.1 <i>Introduction</i> 14.2 <i>Foldback Principle</i> 14.3 <i>Foldback Circuit Principles as Applied to a Linear Supply</i> 14.4 <i>“Lockout” in Foldback Current-Limited Supplies</i> 14.5 <i>Reentrant Lockout with Cross-Connected Loads</i> 14.6 <i>Foldback Current Limits in Switchmode Supplies</i> 14.7 <i>Problems</i>	
<b>15. BASE DRIVE REQUIREMENTS FOR HIGH-VOLTAGE BIPOLAR TRANSISTORS</b>	<b>1.121</b>
15.1 <i>Introduction</i> 15.2 <i>Secondary Breakdown</i> 15.3 <i>Incorrect Turn-Off Drive Waveforms</i> 15.4 <i>Correct Turn-Off Waveform</i> 15.5 <i>Correct Turn-On Waveform</i> 15.6 <i>Antisaturation Drive Techniques</i> 15.7 <i>Optimum Drive Circuit for High-Voltage Transistors</i> 15.8 <i>Problems</i>	
<b>16. PROPORTIONAL DRIVE CIRCUITS FOR BIPOLAR TRANSISTORS</b>	<b>1.127</b>
16.1 <i>Introduction</i> 16.2 <i>Example of a Proportional Drive Circuit</i> 16.3 <i>Turn-On Action</i> 16.4 <i>Turn-Off Action</i> 16.5 <i>Drive Transformer Restoration</i> 16.6 <i>Wide-Range Proportional Drive Circuits</i> 16.7 <i>Turn-Off Action</i> 16.8 <i>Turn-On Action</i> 16.9 <i>Proportional Drive with High-Voltage Transistors</i> 16.10 <i>Problems</i>	
<b>17. ANTISATURATION TECHNIQUES FOR HIGH-VOLTAGE TRANSISTORS</b>	<b>1.133</b>
17.1 <i>Introduction</i> 17.2 <i>Baker Clamp</i> 17.3 <i>Problems</i>	
<b>18. SNUBBER NETWORKS</b>	<b>1.135</b>
18.1 <i>Introduction</i> 18.2 <i>Snubber Circuit (with Load Line Shaping)</i> 18.3 <i>Operating Principles</i> 18.4 <i>Establishing Snubber Component Values by Empirical Methods</i> 18.5 <i>Establishing Snubber Component Values by Calculation</i> 18.6 <i>Turn-Off Dissipation in Transistor Q1</i> 18.7 <i>Snubber Resistor Values</i> 18.8 <i>Dissipation in Snubber Resistor</i> 18.9 <i>Miller Current Effects</i> 18.10 <i>The Weaving Low-Loss Snubber Diode</i> 18.11 <i>“Ideal” Drive Circuits for High-Voltage Bipolar Transistors</i> 18.12 <i>Problems</i>	

<b>19. CROSS CONDUCTION</b>	<b>1.145</b>
19.1 <i>Introduction</i> 19.2 <i>Preventing Cross Conduction</i> 19.3 <i>Cross-Coupled Inhibit</i> 19.4 <i>Circuit Operation</i> 19.5 <i>Problems</i>	
<b>20. OUTPUT FILTERS</b>	<b>1.149</b>
20.1 <i>Introduction</i> 20.2 <i>Basic Requirements</i> 20.3 <i>Parasitic Effects in Switchmode Output Filters</i> 20.4 <i>Two-Stage Filters</i> 20.5 <i>High-Frequency Choke Example</i> 20.6 <i>Resonant Filters</i> 20.7 <i>Resonant Filter Example</i> 20.8 <i>Common-Mode Noise Filters</i> 20.9 <i>Selecting Component Values for Output Filters</i> 20.10 <i>Main Output Inductor Values (Buck Regulators)</i> 20.11 <i>Design Example</i> 20.12 <i>Output Capacitor Value</i> 20.13 <i>Problems</i>	
<b>21. POWER FAILURE WARNING CIRCUITS</b>	<b>1.161</b>
21.1 <i>Introduction</i> 21.2 <i>Power Failure and Brownout</i> 21.3 <i>Simple Power Failure Warning Circuits</i> 21.4 <i>Dynamic Power Failure Warning Circuits</i> 21.5 <i>Independent Power Failure Warning Module</i> 21.6 <i>Power Failure Warning in Flyback Converters</i> 21.7 <i>Fast Power Failure Warning Circuits</i> 21.8 <i>Problems</i>	
<b>22. CENTERING (ADJUSTMENT TO CENTER) OF AUXILIARY OUTPUT VOLTAGES ON MULTIPLE-OUTPUT CONVERTERS</b>	<b>1.171</b>
22.1 <i>Introduction</i> 22.2 <i>Example</i> 22.3 <i>Saturable Reactor Voltage Adjustment</i> 22.4 <i>Reactor Design</i> 22.5 <i>Problems</i>	
<b>23. AUXILIARY SUPPLY SYSTEMS</b>	<b>1.175</b>
23.1 <i>Introduction</i> 23.2 <i>60-Hz Line Transformers</i> 23.3 <i>Auxiliary Converters</i> 23.4 <i>Operating Principles</i> 23.5 <i>Stabilized Auxiliary Converters</i> 23.6 <i>High-Efficiency Auxiliary Supplies</i> 23.7 <i>Auxiliary Supplies Derived from Main Converter Transformer</i> 23.8 <i>Problems</i> 23.9 <i>Low Noise Distributed Auxiliary Converters</i> 23.10 <i>Block Diagram of a Distributed Auxiliary Power System</i> 23.11 <i>Block 1, Rectifier and Linear Regulator</i> 23.12 <i>Block 2, Sine Wave Inverter</i> 23.13 <i>Output Modules</i> 23.14 <i>Sine Wave Inverter Transformer Design</i> 23.15 <i>Reducing Common Mode Noise</i>	
<b>24. PARALLEL OPERATION OF VOLTAGE-STABILIZED POWER SUPPLIES</b>	<b>1.195</b>
24.1 <i>Introduction</i> 24.2 <i>Master-Slave Operation</i> 24.3 <i>Voltage-Controlled Current Sources</i> 24.4 <i>Forced Current Sharing</i> 24.5 <i>Parallel Redundant Operation</i> 24.6 <i>Problems</i>	

## PART 2 DESIGN: THEORY AND PRACTICE

<b>1. MULTIPLE-OUTPUT FLYBACK SWITCHMODE POWER SUPPLIES</b>	<b>2.3</b>
1.1 <i>Introduction</i> 1.2 <i>Expected Performance</i> 1.3 <i>Operating Modes</i> 1.4 <i>Operating Principles</i> 1.5 <i>Energy Storage Phase</i> 1.6 <i>Energy Transfer Modes (Flyback Phase)</i> 1.7 <i>Factors Defining Operating Modes</i>	



1.8	<i>Transfer Function Anomaly</i>	1.9	<i>Transformer Throughput Capability</i>
1.10	<i>Specification Notes</i>	1.11	<i>Specification Example for a 110-W Direct-Off-Line Flyback Power Supply</i>
1.12	<i>Problems</i>		
<b>2.</b>	<b>FLYBACK TRANSFORMER DESIGN</b>	<b>2.17</b>	
2.1	<i>Introduction</i>	2.2	<i>Core Parameters and the Effect of an Air Gap</i>
2.3	<i>General Design Considerations</i>	2.4	<i>Design Example for a 110-W Flyback Transformer</i>
2.5	<i>Flyback Transformer Saturation and Transient Effects</i>		
2.6	<i>Conclusions</i>	2.7	<i>Problems</i>
<b>3.</b>	<b>REDUCING TRANSISTOR SWITCHING STRESS</b>	<b>2.33</b>	
3.1	<i>Introduction</i>	3.2	<i>Self-Tracking Voltage Clamp</i>
3.3	<i>Flyback Converter “Snubber” Networks</i>	3.4	<i>Problems</i>
<b>4.</b>	<b>SELECTING POWER COMPONENTS FOR FLYBACK CONVERTERS</b>	<b>2.39</b>	
4.1	<i>Introduction</i>	4.2	<i>Primary Components</i>
4.3	<i>Secondary Power Components</i>	4.4	<i>Output Capacitors</i>
4.5	<i>Capacitor Life</i>	4.6	<i>General Conclusions Concerning Flyback Converter Components</i>
4.7	<i>Problems</i>		
<b>5.</b>	<b>THE DIAGONAL HALF-BRIDGE FLYBACK CONVERTER</b>	<b>2.47</b>	
5.1	<i>Introduction</i>	5.2	<i>Operating Principle</i>
5.3	<i>Useful Properties</i>	5.4	<i>Transformer Design</i>
5.5	<i>Drive Circuitry</i>	5.6	<i>Operating Frequency</i>
5.7	<i>Snubber Components</i>	5.8	<i>Problems</i>
<b>6.</b>	<b>SELF-OSCILLATING DIRECT-OFF-LINE FLYBACK CONVERTERS</b>	<b>2.53</b>	
6.1	<i>Introduction</i>	6.2	<i>Classes of Operation</i>
6.3	<i>General Operating Principles</i>	6.4	<i>Isolated Self-Oscillating Flyback Converters</i>
6.5	<i>Control Circuit (Brief Description)</i>	6.6	<i>Squegging</i>
6.7	<i>Summary of the Major Parameters for Self-Oscillating Flyback Converters</i>	6.8	<i>Problems</i>
<b>7.</b>	<b>APPLYING CURRENT-MODE CONTROL TO FLYBACK CONVERTERS</b>	<b>2.61</b>	
7.1	<i>Introduction</i>	7.2	<i>Power Limiting and Current-Mode Control as Applied to the Self-Oscillating Flyback Converter</i>
7.3	<i>Voltage Control Loop</i>	7.4	<i>Input Ripple Rejection</i>
7.5	<i>Using Field-Effect Transistors in Variable-Frequency Flyback Converters</i>	7.6	<i>Problems</i>
<b>8.</b>	<b>DIRECT-OFF-LINE SINGLE-ENDED FORWARD CONVERTERS</b>	<b>2.67</b>	
8.1	<i>Introduction</i>	8.2	<i>Operating Principles</i>
8.3	<i>Limiting Factors for the Value of the Output Choke</i>	8.4	<i>Multiple Outputs</i>
8.5	<i>Energy Recovery Winding (P2)</i>	8.6	<i>Advantages</i>
8.7	<i>Disadvantages</i>	8.8	<i>Problems</i>
<b>9.</b>	<b>TRANSFORMER DESIGN FOR FORWARD CONVERTERS</b>	<b>2.73</b>	
9.1	<i>Introduction</i>	9.2	<i>Transformer Design Example</i>
9.3	<i>Selecting Power Transistors</i>	9.4	<i>Final Design Notes</i>
9.5	<i>Transformer Saturation</i>	9.6	<i>Conclusions</i>

<b>10. DIAGONAL HALF-BRIDGE FORWARD CONVERTERS</b>	<b>2.83</b>
10.1 <i>Introduction</i> 10.2 <i>Operating Principles</i>	
<b>11. TRANSFORMER DESIGN FOR DIAGONAL HALF-BRIDGE FORWARD CONVERTERS</b>	<b>2.87</b>
11.1 <i>General Considerations</i> 11.2 <i>Design Notes</i>	
<b>12. HALF-BRIDGE PUSH-PULL DUTY-RATIO-CONTROLLED CONVERTERS</b>	<b>2.93</b>
12.1 <i>Introduction</i> 12.2 <i>Operating Principles</i> 12.3 <i>System Advantages</i> 12.4 <i>Problem Areas</i> 12.5 <i>Current-Mode Control and Subharmonic Ripple</i> 12.6 <i>Cross-Conduction Prevention</i> 12.7 <i>Snubber Components (Half-Bridge)</i> 12.8 <i>Soft Start</i> 12.9 <i>Transformer Design</i> 12.10 <i>Optimum Flux Density</i> 12.11 <i>Transient Conditions</i> 12.12 <i>Calculating Primary Turns</i> 12.13 <i>Calculate Minimum Primary Turns</i> 12.14 <i>Calculate Secondary Turns</i> 12.15 <i>Control and Drive Circuits</i> 12.16 <i>Flux Doubling Effect</i> 12.17 <i>Problems</i>	
<b>13. BRIDGE CONVERTERS</b>	<b>2.105</b>
13.1 <i>Introduction</i> 13.2 <i>Operating Principles</i> 13.3 <i>Transformer Design (Full Bridge)</i> 13.4 <i>Transformer Design Example</i> 13.5 <i>Staircase Saturation</i> 13.6 <i>Transient Saturation Effects</i> 13.7 <i>Forced Flux Density Balancing</i> 13.8 <i>Problems</i>	
<b>14. LOW-POWER SELF-OSCILLATING AUXILIARY CONVERTERS</b>	<b>2.117</b>
14.1 <i>Introduction</i> 14.2 <i>General Operating Principles</i> 14.3 <i>Operating Principle, Single-Transformer Converters</i> 14.4 <i>Transformer Design</i>	
<b>15. SINGLE-TRANSFORMER TWO-TRANSISTOR SELF-OSCILLATING CONVERTERS</b>	<b>2.123</b>
15.1 <i>Introduction</i> 15.2 <i>Operating Principles (Gain-Limited Switching)</i> 15.3 <i>Defining the Switching Current</i> 15.4 <i>Choosing Core Materials</i> 15.5 <i>Transformer Design (Saturating-Core-Type Converters)</i> 15.6 <i>Problems</i>	
<b>16. TWO-TRANSFORMER SELF-OSCILLATING CONVERTERS</b>	<b>2.135</b>
16.1 <i>Introduction</i> 16.2 <i>Operating Principles</i> 16.3 <i>Saturated Drive Transformer Design</i> 16.4 <i>Selecting Core Size and Material</i> 16.5 <i>Main Power Transformer Design</i> 16.6 <i>Problems</i>	
<b>17. THE DC-TO-DC TRANSFORMER CONCEPT</b>	<b>2.141</b>
17.1 <i>Introduction</i> 17.2 <i>Basic Principles of the DC-to-DC Transformer Concept</i> 17.3 <i>DC-to-DC Transformer Example</i> 17.4 <i>Problems</i>	
<b>18. MULTIPLE-OUTPUT COMPOUND REGULATING SYSTEMS</b>	<b>2.145</b>
18.1 <i>Introduction</i> 18.2 <i>Buck Regulator, Cascaded with a DC-to-DC Transformer</i> 18.3 <i>Operating Principles</i> 18.4 <i>Buck Regulator Section</i>	

18.5 *DC Transformer Section* 18.6 *Synchronized Compound Regulators*  
18.7 *Compound Regulators with Secondary Post Regulators* 18.8 *Problems*

**19. DUTY-RATIO-CONTROLLED PUSH-PULL CONVERTERS 2.151**

19.1 *Introduction* 19.2 *Operating Principles* 19.3 *Snubber Components*  
19.4 *Staircase Saturation in Push-Pull Converters* 19.5 *Flux Density Balancing*  
19.6 *Push-Pull Transformer Design (General Considerations)*  
19.7 *Flux Doubling* 19.8 *Push-Pull Transformer Design Example*  
19.9 *Problems*

**20. DC-TO-DC SWITCHING REGULATORS 2.163**

20.1 *Introduction* 20.2 *Operating Principles* 20.3 *Control and Drive Circuits*  
20.4 *Inductor Design for Switching Regulators* 20.5 *Inductor Design Example*  
20.6 *General Performance Parameters* 20.7 *The Ripple Regulator* 20.8 *Problems*

**21. HIGH-FREQUENCY SATURABLE REACTOR POWER REGULATOR (MAGNETIC DUTY RATIO CONTROL) 2.177**

21.1 *Introduction* 21.2 *Operating Principles* 21.3 *The Saturable Reactor Power Regulator Principle*  
21.4 *The Saturable Reactor Power Regulator Application* 21.5 *Saturable Reactor Quality Factors* 21.6 *Selecting Suitable Core Materials*  
21.7 *Controlling the Saturable Reactor* 21.8 *Current Limiting the Saturable Reactor Regulator*  
21.9 *Push-Pull Saturable Reactor Secondary Power Control Circuit* 21.10 *Some Advantages of the Saturable Reactor Regulator*  
21.11 *Some Limiting Factors in Saturable Reactor Regulators* 21.12 *The Case for Constant-Voltage or Constant-Current Reset (High-Frequency Instability Considerations)*  
21.13 *Saturable Reactor Design* 21.14 *Design Example* 21.15 *Problems*

**22. CONSTANT-CURRENT POWER SUPPLIES 2.193**

22.1 *Introduction* 22.2 *Constant-Voltage Supplies* 22.3 *Constant-Current Supplies* 22.4 *Compliance Voltage* 22.5 *Problems*

**23. VARIABLE LINEAR POWER SUPPLIES 2.197**

23.1 *Introduction* 23.2 *Basic Operation (Power Section)* 23.3 *Drive Circuit*  
23.4 *Maximum Transistor Dissipation* 23.5 *Distribution of Power Losses*  
23.6 *Voltage Control and Current Limit Circuit* 23.7 *Control Circuit*  
23.8 *Problems*

**24. SWITCHMODE VARIABLE POWER SUPPLIES 2.207**

24.1 *Introduction* 24.2 *Variable Switchmode Techniques* 24.3 *Special Properties of Flyback Converters*  
24.4 *Operating Principles* 24.5 *Practical Limiting Factors* 24.6 *Practical Design Compromises* 24.7 *Initial Conditions*  
24.8 *The Diagonal Half Bridge* 24.9 *Block Schematic Diagram (General Description)*  
24.10 *Overall System Operating Principles* 24.11 *Individual Block Functions* 24.12 *Primary Power Limiting* 24.13 *Conclusions*

**25. SWITCHMODE VARIABLE POWER SUPPLY TRANSFORMER DESIGN 2.223**

25.1 *Design Steps* 25.2 *Variable-Frequency Mode* 25.3 *Problems*

**PART 3 APPLIED DESIGN****1. INDUCTORS AND CHOKES IN SWITCHMODE SUPPLIES 3.3**

1.1 *Introduction* 1.2 *Simple Inductors* 1.3 *Common-Mode Line-Filter Inductors* 1.4 *Design Example of a Common-Mode Line-Filter Inductor (Using a Ferrite E Core and Graphical Design Method)* 1.5 *Calculating Inductance (for Common-Mode Inductors Wound on Ferrite E Cores)* 1.6 *Series-Mode Line-Input-Filter Inductors* 1.7 *Chokes (Inductors with DC Bias)* 1.8 *Design Example of a Gapped Ferrite E-Core Choke (Using an Empirical Method)* 1.9 *Design Example of Chokes for Buck and Boost Converters (by Area Product Graphical Methods and by Calculation)* 1.10 *Choke Design Example for a Buck Regulator (Using a Ferrite E Core and Graphical AP Design Method)* 1.11 *Ferrite and Iron Powder Rod Chokes* 1.12 *Problems*

**2. HIGH-CURRENT CHOKES USING IRON POWDER CORES 3.29**

2.1 *Introduction* 2.2 *Energy Storage Chokes* 2.3 *Core Permeability* 2.4 *Gapping Iron Powder E Cores* 2.5 *Methods Used to Design Iron Powder E-Core Chokes (Graphical Area Product Method)* 2.6 *Example of Iron Powder E-Core Choke Design (Using the Graphical Area Product Method)*

**3. CHOKE DESIGN USING IRON POWDER TOROIDAL CORES 3.41**

3.1 *Introduction* 3.2 *Preferred Design Approach (Toroids)* 3.3 *Swinging Chokes* 3.4 *Winding Options* 3.5 *Design Example (Option A)* 3.6 *Design Example (Option B)* 3.7 *Design Example (Option C)* 3.8 *Core Loss* 3.9 *Total Dissipation and Temperature Rise* 3.10 *Linear (Toroidal) Choke Design*  
 Appendix 3.A, *Derivation of Area Product Equations*  
 Appendix 3.B, *Derivation of Packing and Resistance Factors*  
 Appendix 3.C, *Derivation of Nomogram 3.3.1*

**4. SWITCHMODE TRANSFORMER DESIGN (GENERAL PRINCIPLES) 3.63**

4.1 *Introduction* 4.2 *Transformer Size (General Considerations)* 4.3 *Optimum Efficiency* 4.4 *Optimum Core Size and Flux Density Swing* 4.5 *Calculating Core Size in Terms of Area Product* 4.6 *Primary Area Factor  $K_p$*  4.7 *Winding Packing Factor* 4.8 *Rms Current Factor  $K_i$*  4.9 *The Effect of Frequency on Transformer Size* 4.10 *Flux Density Swing  $\Delta b$*  4.11 *The Impact of Agency Specifications on Transformer Size* 4.12 *Calculation of Primary Turns* 4.13 *Calculating Secondary Turns* 4.14 *Half Turns* 4.15 *Wire Sizes* 4.16 *Skin Effects and Optimum Wire Thickness* 4.17 *Winding Topology* 4.18 *Temperature Rise* 4.19 *Efficiency* 4.20 *Higher Temperature Rise Designs* 4.21 *Eliminating Breakdown Stress in Bifilar Windings* 4.22 *RFI Screens and Safety Screens* 4.23 *Transformer Half-Turn Techniques* 4.24 *Transformer Finishing and Vacuum Impregnation* 4.25 *Problems*  
 Appendix 4.A, *Derivation of Area Product Equations for Transformer Design*  
 Appendix 4.B, *Skin and Proximity Effects in High-Frequency Transformer Windings*

<b>5. OPTIMUM 150-W TRANSFORMER DESIGN EXAMPLE USING NOMOGRAMS</b>	<b>3.105</b>
<i>5.1 Introduction 5.2 Core Size and Optimum Flux Density Swing 5.3 Core and Bobbin Parameters 5.4 Calculate Primary Turns 5.5 Calculate Primary Wire Size 5.6 Primary Skin Effects 5.7 Secondary Turns 5.8 Secondary Wire Size 5.9 Secondary Skin Effects 5.10 Design Notes 5.11 Design Confirmation 5.12 Primary Copper Loss 5.13 Secondary Copper Loss 5.14 Core Loss 5.15 Temperature Rise 5.16 Efficiency</i>	
<b>6. TRANSFORMER STAIRCASE SATURATION</b>	<b>3.111</b>
<i>6.1 Introduction 6.2 Methods of Reducing Staircase Saturation Effects 6.3 Forced Flux Balancing in Duty-Ratio-Controlled Push-Pull Converters 6.4 Staircase Saturation Problems in Current-Mode Control Systems 6.5 Problems</i>	
<b>7. FLUX DOUBLING</b>	<b>3.117</b>
<b>8. STABILITY AND CONTROL-LOOP COMPENSATION IN SMPS</b>	<b>3.119</b>
<i>8.1 Introduction 8.2 Some Causes of Instability in Switchmode Supplies 8.3 Methods of Stabilizing the Loop 8.4 Stability Testing Methods 8.5 Test Procedure 8.6 Transient Testing Analysis 8.7 Bode Plots 8.8 Measurement Procedures for Bode Plots of Closed-Loop Power Supply Systems 8.9 Test Equipment for Bode Plot Measurement 8.10 Test Techniques 8.11 Measurement Procedures for Bode Plots of Open-Loop Power Supply Systems 8.12 Establishing Optimum Compensation Characteristic by the "Difference Method" 8.13 Some Causes of Stubborn Instability 8.14 Problems</i>	
<b>9. THE RIGHT-HALF-PLANE ZERO</b>	<b>3.133</b>
<i>9.1 Introduction 9.2 Explanation of the Dynamics of the Right-Half-Plane Zero 9.3 The Right-Half-Plane Zero—A Simplified Explanation 9.4 Problems</i>	
<b>10. CURRENT-MODE CONTROL</b>	<b>3.139</b>
<i>10.1 Introduction 10.2 The Principles of Current-Mode Control 10.3 Converting Current-Mode Control to Voltage Control 10.4 Performance of the Complete Energy Transfer Current-Modecontrolled Flyback Converter 10.5 The Advantages of Current-Mode Control in Continuous-Inductor-Current Converter Topologies 10.6 Slope Compensation 10.7 Advantages of Current-Mode Control in Continuous-Inductor-Current-Mode Buck Regulators 10.8 Disadvantages Intrinsic to Current-Mode Control 10.9 Flux Balancing in Push-Pull Topologies When Using Current-Mode Control 10.10 Asymmetry Caused by Charge Imbalance in Current-Mode-Controlled Half-Bridge Converters and Other Topologies Using DC Blocking Capacitors 10.11 Summary 10.12 Problems</i>	
<b>11. OPTOCOUPLEDERS</b>	<b>3.157</b>
<i>11.1 Introduction 11.2 Optocoupler Interface Circuit 11.3 Stability and Noise Sensitivity 11.4 Problems</i>	

<b>12. RIPPLE CURRENT RATINGS FOR ELECTROLYTIC CAPACITORS IN SWITCHMODE POWER SUPPLIES</b>	<b>3.163</b>
<i>12.1 Introduction 12.2 Establishing Capacitor RMS Ripple Current Ratings From Published Data 12.3 Establishing the Effective RMS Ripple Current in Switchmode Output-Filter Capacitor Applications 12.4 Recommended Test Procedures 12.5 Problems</i>	
<b>13. NONINDUCTIVE CURRENT SHUNTS</b>	<b>3.169</b>
<i>13.1 Introduction 13.2 Current Shunts 13.3 Resistance/Inductance Ratio of a Simple Shunt 13.4 Measurement Error 13.5 Construction of Low-Inductance Current Shunts 13.6 Problems</i>	
<b>14. CURRENT TRANSFORMERS</b>	<b>3.173</b>
<i>14.1 Introduction 14.2 Types of Current Transformers 14.3 Core Size and Magnetizing Current (All Types) 14.4 Current Transformer Design Procedure 14.5 Unidirectional Current Transformer Design Example 14.6 Type 2, Current Transformers (for Alternating Current) Push-Pull Applications) 14.7 Type 3, Flyback-Type Current Transformers 14.8 Type 4, DC Current Transformers (Dcct) 14.9 Using Current Transformers in Flyback Converters</i>	
<b>15. CURRENT PROBES FOR MEASUREMENT PURPOSES</b>	<b>3.189</b>
<i>15.1 Introduction 15.2 Special-Purpose Current Probes 15.3 The Design of Current Probes for Unidirectional (Discontinuous) Current Pulse Measurements 15.4 Select Core Size 15.5 Calculate Required Core Area 15.6 Check Magnetization Current Error 15.7 Current Probes in Applications with DC and AC Currents 15.8 High-Frequency AC Current Probes 15.9 Low-Frequency AC Current Probes 15.10 Problems</i>	
<b>16. THERMAL MANAGEMENT (IN SWITCHMODE POWER SUPPLIES)</b>	<b>3.197</b>
<i>16.1 Introduction 16.2 The Effect of High Temperatures on Semiconductor Life and Power Supply Failure Rates 16.3 The Infinite Heat Sink, Heat Exchangers, Thermal Shunts, and Their Electrical Analogues 16.4 The Thermal Circuit and Equivalent Electrical Analogue 16.5 Heat Capacity <math>C_j</math> (Analogous to Capacitance C) 16.6 Calculating Junction Temperature 16.7 Calculating the Heat Sink Size 16.8 Methods of Optimizing Thermal Conductivity Paths, and Where to Use "Thermal Conductive Joint Compound" 16.9 Convection, Radiation, or Conduction? 16.10 Heat Exchanger Efficiency 16.11 The Effect of Input Power on Thermal Resistance 16.12 Thermal Resistance and Heat Exchanger Area 16.13 Forced-Air Cooling 16.14 Problems</i>	

## PART 4 SUPPLEMENTARY

<b>1. ACTIVE POWER FACTOR CORRECTION</b>	<b>4.3</b>
<i>1.1 Introduction 1.2 Power Factor Correction Basics, Myths, and Facts 1.3 Passive Power Factor Correction 1.4 Active Power Factor Correction 1.5 More Regulator Topologies 1.6 Buck Regulators 1.7 Combinations of</i>	

*Converters* 1.8 *Integrated Circuits for Power Factor Control* 1.9 *Typical IC Control System* 1.10 *Applied Design* 1.11 *Choice of Control IC* 1.12 *Power Factor Control Section* 1.13 *Buck Section Drive Stage* 1.14 *Power Components*  
 Appendix 1.A, *Boost Choke for Power Factor Correction: Design Example*

<b>2. THE MERITS AND LIMITATIONS OF HARD SWITCHING AND FULLY RESONANT SWITCHMODE POWER SUPPLIES</b>	<b>4.69</b>
<i>2.1 Introduction</i> <i>2.2 Advantages and Limitations of Hard Switching Methods</i> <i>2.3 Fully Resonant Switching Systems</i> <i>2.4 Current Fed Parallel Resonant Ballast</i> <i>2.5 Wound Component Design</i> <i>2.6 Conclusions</i>	
<b>3. QUASI-RESONANT SWITCHING CONVERTERS</b>	<b>4.87</b>
<i>3.1 Introduction</i> <i>3.2 Hard Switching Methods</i> <i>3.3 Fully Resonant Methods</i> <i>3.4 Quasi-Resonant Systems</i> <i>3.5 The Power Section of a Full-Bridge, Quasi-Resonant, Zero-Voltage Transition, Phase-Shift Modulated, 10-kW Converter</i> <i>3.6 Q1-Q4 Bridge FET Drive Timing</i> <i>3.7 Power Switching Sequence</i> <i>3.8 Optimum Conditions for Zero Voltage Switching</i> <i>3.9 Establishing the Optimum Resonant Inductance (<math>L_{re}</math>)</i> <i>3.10 Transformer Leakage Inductance</i> <i>3.11 Output Rectifier Snubbing</i> <i>3.12 Switching Speed and Transition Periods</i> <i>3.13 Primary and Secondary Power Circuits</i> <i>3.14 Power Waveforms and Power Transfer Conditions</i> <i>3.15 Basic FET Drive Principles</i> <i>3.16 Modulation and Control Circuits</i> <i>3.17 Switching Asymmetry in the Power Stage FETs</i> <i>3.18 Control ICs</i>	
<b>4. A FULLY RESONANT SELF-OSCILLATING CURRENT FED FET TYPE SINE WAVE INVERTER</b>	<b>4.123</b>
<i>4.1 Introduction</i> <i>4.2 Basic FET Resonant Inverter</i> <i>4.3 Starting the FET Inverter</i> <i>4.4 Improved Gate Drive</i> <i>4.5 Other Methods of Starting</i> <i>4.6 Auxiliary Supply</i> <i>4.7 Summary</i>	
<b>5. A SINGLE CONTROL WIDE RANGE SINE WAVE OSCILLATOR</b>	<b>4.133</b>
<i>5.1 Introduction</i> <i>5.2 Frequency and Amplitude Control Theory</i> <i>5.3 Operating Theory for the Wide Range Sine Wave VCO</i> <i>5.4 Circuit Performance</i>	
<b>Glossary</b>	<b>G.1</b>
<b>References</b>	<b>R.1</b>
<b>Index</b>	<b>I.1</b>

---

# PREFACE

---

When Keith Billings wrote the first edition of *Switchmode Power Supply Handbook* over twenty years ago, he was aware that many engineers had expressed the desire for a general handbook on the subject. He responded to this need with a practical, easy-to-read explanation of many of the techniques in common use, together with some of the latest developments. The author has drawn upon his own experience of the questions most often asked by students and junior engineers to address the subject in the most straightforward way, giving explicit design examples which do not assume any previous knowledge of the subject. In particular, the design of the wound components is covered very fully, since these are critical to the final performance but tend to be rather poorly understood.

In the third edition Keith continues the easily assimilated, nonacademic treatment, using the simplified theory and mathematical analysis that was so well received in the previous editions, waiving the fully rigorous approach in the interests of simplicity. As a result, this latest edition should once again appeal to students, junior engineers, and interested non-specialist users, as well as practicing professional power supply engineers.

The new edition covers the subject from simple system explanations (with typical specifications and performance parameters) to the final component, thermal, and circuit design and evaluation, and now includes new material related to resonant and quasi-resonant systems and highly efficient, high power, phase shift-modulated switching converters.

As before, to simplify the design approach, considerable use has been made of nomograms, many of which have been developed by the author, originally for his own use. Some of the more academic supporting theory is covered in the chapter appendixes, and those who wish to go further should read these and the many excellent specialized books and papers mentioned in the references.

Since the seventies, switchmode power supply design has developed from a somewhat neglected “black art” to a precise engineering science. The rapid advances in electronic component miniaturization and space exploration have led to an ever-increasing need for small, efficient, power processing equipment. In recent years this need has caught and focused the attention of some of the world’s most competent electronic engineers. As a result of intensive research and development, there have been many new innovations with a bewildering array of topologies.

As yet, there is no single “ideal” system that meets all needs. Each topology lays claim to various advantages and limitations, and the power supply designer’s skill and experience is still needed to match the specification requirements to the most suitable topology to define the preferred technique for a particular application.

The modern switchmode power supply will often be a small part of a more complex processing system. Hence, as well as supplying the necessary voltages and currents for the user’s equipment, it will often provide many other ancillary functions—for example, power good signals (showing when all outputs are within their specified limits), power failure warning signals (giving advanced warning of line failure), and overtemperature protection, which will shut the system down before damage can occur. Further, it may respond to an external signal demand for power on or power off. Power limit and current limit circuitry will protect the supply and load from fault conditions. Overvoltage protection is often provided to protect sensitive loads from overvoltage conditions, and in some special applications, synchronization of the switching frequency to an external clock will be provided. Hence, the power supply designer must understand and meet many needs.



To utilize or specify a modern power processing system more effectively, the user should be familiar with the advantages and limitations of the many techniques available. With this information, the system engineer can specify the power supply requirements so that the most cost-effective and reliable system may be designed to meet these needs. Very often a small change in specification or rearrangement of the power distribution system will allow the power supply designer to produce a much more reliable and cost-effective solution to the user's needs. Hence, to produce the most reliable and cost-effective design, the development of the specification should be an interactive exercise between the power supply designer and the user.

Very often, power supply specifications have inflexible and often artificial boundaries and limitations. These unrealistic specifications usually result in overspecified requirements and hence an overdesigned supply. This in turn can entail high cost, high complexity, and lower reliability. The power supply user who takes the trouble to understand the limitations and advantages of modern switchmode techniques will be in a far better position to specify and obtain reliable and cost-effective solutions to power supply requirements.

The book is presented in four parts:

Part 1, "Functional Requirements Common to Most Direct-Off-Line Switchmode Power Supplies," covers, in simple terms, the requirements which tend to be common to any supply intended for operation direct from the ac line supply. It gives details of the various techniques in common use, highlighting their major advantages and limitations, together with typical applications. In this new edition, Chapter 23 has been expanded to include a current-fed, self-oscillating, resonant sine wave inverter adapted to providing multiple distributed independently isolated auxiliary supplies for a large system. The need for semi-stabilized outputs with very low noise are addressed by a linear pre-regulator that also affords current limiting and the use of sine wave power distribution for low system noise.

Part 2, "Design, Theory and Practice," considers the selection of power components and transformer designs for many well-known converter circuits. It is primarily intended to assist practicing power supply engineers in developing conservatively rated prototypes with more speed and minimum effort. It provides examples, information, and design theory sufficient for a general understanding and the initial design of the more practical switchmode power supplies. However, to produce fully optimized designs, the reader will need to become conversant with the more specialized information presented in Part 3 and the many references.

Part 3, "Applied Design," deals with many of the more general engineering requirements of switchmode systems, such as transformer design, choke design, input filters, RFI control, snubber circuits, thermal design, and much more.

Part 4, "Supplementary," looks at a number of selected topics that may be of more interest to power supply professionals.

The first topic covers the design of an active power factor correction system. The power distribution industry is becoming more concerned with the increasing level of harmonic content caused by non-corrected electronic equipment and in particular electronic ballasts for fluorescent lighting. Active power factor correction is still a relatively new addition to the power supply designer's tasks. It is difficult to display waveforms and design power inductors, due to the dynamic behavior of the boost topology, with its low- and high-frequency requirements. This part should help remove some of the mystery regarding this subject.

In most switchmode power supplies, it is the wound components that mainly control the efficiency and performance. Switching devices will work efficiently only if leakage inductances are small and good coupling is provided between input and output windings. The designer has considerable control over the wound components, but it requires considerable

knowledge and skill to overcome the many practical and engineering problems encountered in their design. The author has therefore concentrated on the wound components, and provided many worked examples. To develop a full working knowledge of this critical area, the reader should refer to the more rigorous transformer design information given in Part 3, and the many references.

The advances in resonant and semi-resonant converters have focused much attention on these promising techniques. An examination of the pros and cons of a fully resonant technique is demonstrated by the design of a resonant fluorescent ballast. The principles demonstrated are applicable to many other fully resonant systems.

A quasi-resonant system is demonstrated by the design of a high-power, full bridge converter that uses both semi-resonant techniques and phase shift modulation to achieve very high efficiency and low noise. This section includes a step-by-step analysis of each stage of operation of the circuit during the progress of the switching cycle.

In Part 4 Chapters 4 and 5, co-author Taylor Morey shows a current fed, self-oscillating, fully resonant inverter using power MOSFETs. This version has the advantage of near ideal zero voltage switching transitions that result in harmonic free waveforms of high purity. He also shows a variable frequency sine wave oscillator, implemented with operational transconductance amplifiers. In this design the frequency can be adjusted with a single manual control, or electronically swept over a wide range from milliHertz to hundreds of kiloHertz.

No single work can do full justice to this vast and rapidly developing subject. The reader's attention is directed to the Reference section where many related books and papers will be found that extend the range of knowledge well beyond the scope of this book. It is hoped that this new edition will at least partly fill the need for a more general handbook on the subject.

---

## **ACKNOWLEDGMENTS**

---

No man is an island. We progress not only by our own efforts, but also by utilizing the work of those around us and by building on the foundations of those who went before. The reference section is an attempt to acknowledge this. I have no doubt that many more works should have been mentioned. I sincerely apologize for any omissions; it is often difficult to remember the original source.

I am grateful to the many who have contributed to the third edition, but worthy of special mention is my engineering colleague and co-author Taylor Morey, who spent hundreds of hours carefully checking the new manuscript and calculations and also contributed to this edition with Part 4, Chapters 4 and 5. I also thank Unitrode and Lloyd H. Dixon, Jr., for permission to reproduce his work on "The Right-Half-Plane Zero" and Texas Instruments for permission to reproduce application information. We also recognize the editors and staff of McGraw-Hill Publishing Company, who added much to this work.

—Keith Billings

---

# UNITS, SYMBOLS, DIMENSIONS, AND ABBREVIATIONS USED IN THIS BOOK

---

## Units, Symbols, and Dimensions

In general, the units and symbols used in this book conform to the International Standard (SI) System. However, to yield convenient solutions, the equations are often dimensionally modified to convenient multiples or submultiples. (The preferred dimensions are shown following each equation.)

The imperial system is used for thermal calculations, because most thermal information is still presented in this form. Dimensions are in inches (1 in = 25.4 mm) and temperatures are in degrees Celsius, except for radiant heat calculations, which use the absolute Kelvin temperature scale.

Some graphs and equations in the magnetics sections use CGS units where this is common practice. Many manufacturers still provide magnetic information in CGS units; for example, magnetic field strength is shown in oersted(s) rather than At/m. (1 At/m =  $12.57 \times 10^{-3}$  Oe.)

It is industry standard practice to show core loss in terms of milliwatts per gram, with “peak flux density  $\hat{B}$ ” as a parameter. (Because these graphs were developed for conventional push-pull transformer applications, symmetrical flux density swing about zero is assumed.) Hence, loss graphs assume a peak-to-peak swing of  $2\hat{B}$ . To prevent confusion, when nonsymmetrical flux excursions are considered in this book, the term “peak flux density  $\hat{B}$ ” is used only to indicate peak values. The term “flux density swing  $\Delta B$ ” is used to indicate total peak-to-peak excursion.

### Fundamental SI Quantities

Quantity name	Quantity symbol	Unit name	Unit symbol
Mass	<i>m</i>	Kilogram	kg
Length	<i>l</i>	Meter	m
Time	<i>t</i>	Second	s
Electric current	<i>I</i>	Ampere	A
Temperature	<i>T</i>	Kelvin	K

**Multiples and Submultiples of Units Are Limited to the Following Range**

Symbol prefix	Prefix name	Power multiple
M	mega-	$10^6$
k	kilo-	$10^3$
m	milli-	$10^{-3}$
$\mu$	micro-	$10^{-6}$
n	nano-	$10^{-9}$
p	pico-	$10^{-12}$

**Symbols for Physical Quantities**

Quantity	Quantity symbol	Unit name	Unit symbol	Formula
<i>Electric</i>				
Capacitance	$C$	farads	F	Ss
Charge	$Q$	coulombs	C	As
Current	$I$	amperes	A	$V/\Omega$
Energy	$U$	joules	J	Ws
Impedance	$Z$	ohms	$\Omega$	—
Inductance, self-	$L$	henries	H	Wb/A
Potential difference	$V$	volts	V	Wb/s
Power, real (active)	$P$	watts	W	$VI \cos \theta$
Power, apparent	$S$	volt amperes	VA	VA
Reactance	$X$	ohms	$\Omega$	—
Resistance	$R$	ohms	$\Omega$	V/A
Resistivity, volume	$\rho$	ohm-centimeters	$\Omega\text{-cm}$	$\frac{R \cdot A}{l}$
<i>Magnetic</i>				
Field strength	$H$	amperes per meter	A/m	—
Field strength (CGS)	$H$	oersteds	Oe	$4\pi(10^{-3})\text{A/m}$
Flux	$\Phi$	webers	Wb	Vs
Flux density	$B$	teslas	T	Wb/s
Permeability	$\mu$	henries per meter	H/m	Vs/A/m
<i>Other</i>				
Angular velocity	$\omega$	radians per second	rad/s	$2\pi f$
Area	$A$	centimeters squared	$\text{cm}^2$	—
Frequency	$f$	hertz	Hz	$\text{s}^{-1}$
Length	$l$	centimeters	cm	—
Skin thickness	$\Delta$	millimeters	mm	—
Temperature	$T$	degrees Celsius	$^{\circ}\text{C}$	—
Temperature, absolute	$T$	kelvins	K	—
Time	$t$	seconds	s	—
Winding height	$\phi$	millimeters	mm	—

## Symbols for Mathematical Variables Used in This Book

Variable	Parameter	Unit
$A$	area	cm <sup>2</sup>
$A$	gain (without feedback)	dB
$A'$	gain (with feedback)	dB
$A_c$	cross-sectional area of center pole (transformer core)	cm <sup>2</sup>
$A_{cp}$	area of center pole (transformer core)	cm <sup>2</sup>
$A_e$	effective area (of core)	cm <sup>2</sup>
$A_g$	area of air gap (in core)	cm <sup>2</sup>
$A_L$	inductance factor (inductance of a single turn)	nH
$A_m$	minimum area of core	cm <sup>2</sup>
$A_n$	attenuation factor	—
$A_p$	area of center pole (of core)	cm <sup>2</sup>
$A_{p'}$	area of primary winding	cm <sup>2</sup>
$AP$	area product of core ( $A_w A_e$ )	cm <sup>4</sup>
$AP_e$	effective area product ( $A_{wb} A_e$ )	cm <sup>4</sup>
$A_r$	resistance factor (bobbin); also attenuation factor	—
$A_w$	winding window area (of core)	cm <sup>2</sup>
$A_{wb}$	winding window area (of bobbin)	cm <sup>2</sup>
$A_{we}$	effective area of copper in winding (total)	cm <sup>2</sup>
$A_{wp}$	primary winding window area	cm <sup>2</sup>
$A_x$	surface area	cm <sup>2</sup>
$A_x$	area of copper (for a single wire)	cm <sup>2</sup>
$B$	magnetic flux density	mT
$\hat{B}$	peak magnetic flux density	mT
$\beta$	feedback factor	—
$\Delta B$	small change in $B$	mT
$\Delta B_{ac}$	magnetic flux density swing (p-p)	mT
$B_{dc}$	steady-state magnetic flux density (due to $H_{dc}$ )	mT
$B_{opt}$	optimum flux density swing (for minimum loss)	mT
$B_r$	remanence flux density	mT
$B_s$	saturation flux density	mT
$B_w$	peak (working) value of flux density	mT
$b_w$	useful winding width (of bobbin)	mm
$C$	capacitance	$\mu$ F
$C_c$	leakage (parasitic) capacitance	pF
$cfm$	cubic feet per minute (of air flow)	cfm
$C_h$	heat (storage) capacity	Ws/in <sup>3</sup> /°C
$C_k$	interelectrode capacitance	pF
$C_p$	parasitic coupling capacitance	pF
$D$	duty ratio ( $t_{on}/t_p$ )	
$d'$	duty cycle ( $t_{on}/t_{off}$ )	
$D'$	$D'(1 - D) = \text{"off" time}$	
$dB$	logarithmic ratio (voltage $20 \log_{10} V_1/V_2$ or power $10 \log_{10} P_1/P_2$ )	dB
$dB_m$	logarithmic power ratio with respect to 1 mW ( $10 \log_{10} P_1/1 \text{ mW}$ )	dB
$di/dt$	rate of change of current with respect to time	A/s
$di_p/dt$	rate of change of primary current with respect to time	A/s
$di_s/dt$	rate of change of secondary current with respect to time	A/s

## Symbols for Mathematical Variables Used in This Book (cont.)

Variable	Parameter	Unit
$dv/dt$	rate of change of voltage with respect to time	V/s
$d_w$	wire diameter	mm
$e$	emf, induced electromotive force (vector quantity)	V
$e'$	radiant emissivity of surface	
$ e $	emf (magnitude of emf only)	V
$U$	electrical energy	J
$f$	frequency	Hz
$F_1$	layer factor (copper)	
$F_r$	ratio of ac/DC resistance (of winding)	
$H$	magnetic field strength	Oe
$\hat{H}$	peak value of effective magnetic field strength	Oe
$h$	conductor thickness (strip) or wire diameter	mm
$H_{ac}$	magnetic field strength swing, p-p	Oe
$H_{dc}$	magnetic field strength due to Dc current	Oe
$H_{opt}$	optimum value of magnetic field strength	Oe
$H_s$	saturating value of magnetic field strength	Oe
$\Delta H$	small change in magnetic field strength	Oe
$I$	current flow (DC)	A
$I$	rms current (ac)	A
$\hat{I}$	peak current	A
$I_{ave}$	average value of current for a defined period	A
$I_{cp}$	peak collector current	A
$I_{dc}$	direct current (dependent variable)	A
$I_e$	effective input current	A
$I_i$	harmonic interference current	A
$I_L$	inductor or choke current (average)	A
$i_L$	ac inductor current	A
$I_{L(p-p)}$	ripple current p-p in choke or inductor	A
$I_{max}$	maximum value of current	A
$I_{mean}$	time-averaged current value	A
$I_{min}$	minimum value of current	A
$I_p$	primary current (in transformer)	A
$I_s$	secondary current (also snubber current)	A
$\Delta I$	small change in current	A
$I^2R$	resistive power loss	W
$J$	current density (in wire)	A/cm <sup>2</sup>
$-j\omega C$	capacitive reactance, (complex #)	$\Omega$
$j\omega L$	inductive reactance, (complex #)	$\Omega$
$K'$	copper utilization factor (topology factor)	
$K_m$	material constant	
$K_p$	primary area factor	
$K_r$	primary rms current factor	
$K_u$	packing factor (of wire)	%
$K_{ub}$	utilization factor of bobbin	
$L$	Inductance (self-inductance of wound component)	H

## Symbols for Mathematical Variables Used in This Book (cont.)

Variable	Parameter	Unit
$l$	length (of magnetic path)	cm
$l_e$	effective path length	cm
$l_g$	total length in core air gap	cm
$L_{LP}$	primary leakage inductance	$\mu\text{H}$
$L_{Ls}$	secondary leakage inductance	$\mu\text{H}$
$L_{LT}$	total (transformer) leakage inductance	$\mu\text{H}$
$l_m$	mean length of wire turn or magnetic path (of core)	cm
$L_p$	primary inductance	mH
$L_s$	secondary inductance	mH
$mmf$	magnetomotive force (magnetic potential ampere-turns)	At
$N$	number of turns	
$N_{fb}$	number of turns of feedback winding	
$N_{\min}$	minimum number of turns (to prevent core saturation)	
$N_{mpp}$	minimum primary turns for p-p operation	
$N_p$	primary turns (of transformer)	
$N_s$	secondary turns (of transformer)	
$N_v$	turns per volt (of transformer)	T/V
$N_w$	number of turns (or wires) per layer	
$P$	power	W
$p$	period (of time)	$\mu\text{s}$
$P_c$	power dissipated in core	W
$P_f$	power factor (ratio true power/VA)	—
$P_{in}$	true input power ( $VI \cos \theta$ , or $VA \times P_f$ , heating effect)	W
$P_{id}$	total internal dissipation	W
$P_j$	heat dissipation at junction, J/s	W
$P_{out}$	true output power ( $VI \cos \theta$ , or $VA \times P_f$ , heating effect)	W
$P_{q1}$	power dissipated in transistor Q1	W
$P_t$	total internal dissipation	W
$P_v/N$	primary volts per turn	V/T
$P_w$	winding copper loss	W
$Q$	rate of heat flow (in watts by conduction or in J/s/in <sup>2</sup> by radiation)	W J/s
$R$	resistance	$\Omega$
$r$	radius (or wire)	mm
$R_{Cu}$	DC resistance of wound component at specified temperature	$\Omega$
$R_e$	effective DC resistance of transformer winding	$\Omega$
$R_{c-h}$	thermal resistance, case to heat exchanger	$^{\circ}\text{C}/\text{W}$
$R_{h-a}$	thermal resistance, heat exchanger to free air	$^{\circ}\text{C}/\text{W}$
$R_{j-c}$	thermal resistance, junction to case	$^{\circ}\text{C}/\text{W}$
$R_o$	total thermal resistance	$^{\circ}\text{C}/\text{W}$
$R_s$	effective resistance of prime source or network	$\Omega$
$R_{sf}$	effective source resistance factor ( $R_{sf} = R_s \times W_{out}$ )	$\Omega$
$RT$	temperature coefficient of resistance (copper = 0.00393 at 0 $^{\circ}\text{C}$ )	$\Omega/\Omega/^{\circ}\text{C}$
$RT_{cm}$	resistance of wire in $\Omega/\text{cm}$ at temp $T$ , $^{\circ}\text{C}$	$\Omega/\text{cm}$
$R_{\theta}$	thermal resistance (of heat-conducting path)	$^{\circ}\text{C}/\text{W}$
$R_{\theta ja}$	thermal resistance, junction hot spot to free air	$^{\circ}\text{C}/\text{W}$

## Symbols for Mathematical Variables Used in This Book (cont.)

Variable	Parameter	Unit
$R_w$	effective resistance of wound component at frequency $f$	$\Omega$
$R_x$	resistance factor of bobbin	
$S_f$	scaling factor	
$T$	temperature in degrees Celsius	$^{\circ}\text{C}$
$t$	time	s
$T_{\text{amb}}$	ambient temperature (of air)	$^{\circ}\text{C}$
$T_c$	temperature of copper (winding)	$^{\circ}\text{C}$
$t_d$	time delay period	s
$T_{ds}$	temperature of surface (diode)	$^{\circ}\text{C}$
$t_f$	fall time (time required for voltage or current decay)	$\mu\text{s}$
$T_h$	temperature of heat exchanger surface	$^{\circ}\text{C}$
$t_p$	total period (of time), i.e., duration of single cycle	$\mu\text{s}$
$t_{\text{off}}$	non-conducting "off" time period	$\mu\text{s}$
$t_{\text{on}}$	conducting "on" time period	$\mu\text{s}$
$\Delta T$	small change in temperature	$^{\circ}\text{C}$
$\Delta T_a$	small temperature rise (above ambient)	$^{\circ}\text{C}$
$\Delta t$	small increment of time	$\mu\text{s}$
$T_r$	temperature rise (above ambient)	$^{\circ}\text{C}$
VA	volt-ampere product (apparent power)	VA
$V_c$	transistor collector voltage	V
$V_{cc}$	supply line (voltage)	V
$V_{ce}$	voltage, collector to emitter	V
$V_{ceo}$	collector-to-emitter breakdown voltage (base open circuit)	V
$V_{cer}$	collector-to-emitter breakdown voltage (with specified base-to-emitter resistance)	V
$V_{cex}$	collector-to-emitter breakdown voltage (base reverse-biased)	V
$V_e$	effective volume of core	$\text{cm}^3$
$V_{fb}$	feedback voltage	V
$V_h$	header voltage (voltage at input of regulator)	V
$V_{hi}$	harmonic interference voltage, rms	Vrms
$V_{in}$	input voltage	V
$V_i$	voltage across inductor	V
$V_m$	mean voltage	V
$V_n$	nominal (average normal) voltage	V
$V/N$	volts per turn	V/T
$V_o$	ripple voltage	V
$V_{\text{out}}$	output voltage	V
$V_p$	peak voltage or primary voltage	V
$V_{p-p}$	ripple voltage, peak-peak value	V
$V_{\text{ref}}$	reference voltage	V
$V_{\text{rms}}$	root mean square voltage	Vrms
$V_{\text{sat}}$	saturation voltage	V
$X_c$	capacitive reactance	$\Omega$
$X_L$	inductive reactance	$\Omega$
$\rho$	volume resistivity of copper (at $0^{\circ}\text{C} = 1.588 \mu\Omega\text{-cm}$ )	$\mu\Omega\text{-cm}$
$\rho_{tc}$	resistivity of copper at $t_c$ $^{\circ}\text{C}$	$\mu\Omega\text{-cm}$
$\mu_0$	permeability of space ( $4\pi \cdot 10^{-7}$ H/m)	Vs/Am
$\mu_r$	relative permeability (of core)	



- [read online 365 Slow Cooker Suppers](#)
- [Les jongleurs de mots : de François Villon Ã Raymond Devos online](#)
- [\*\*read Mind the Gap: The New Class Divide in Britain \(3rd Revised Edition\)\*\*](#)
- [click Bunter The Sportsman \(Billy Bunter, Book 37\)](#)
- [CrÃtica de la mirada: Textos de Harun Farocki pdf, azw \(kindle\), epub, doc, mobi](#)
  
- <http://conexdx.com/library/365-Slow-Cooker-Suppers.pdf>
- <http://bestarthritiscare.com/library/Les-jongleurs-de-mots---de-Fran--ois-Villon----Raymond-Devos.pdf>
- <http://ramazotti.ru/library/Mind-the-Gap--The-New-Class-Divide-in-Britain--3rd-Revised-Edition-.pdf>
- <http://junkrobots.com/ebooks/Bunter-The-Sportsman--Billy-Bunter--Book-37-.pdf>
- <http://korplast.gr/lib/Cr--tica-de-la-mirada--Textos-de-Harun-Farocki.pdf>