KEITH BILLINGS
TAYLOR MOREY

SWITCHMODE POWER SUPPLY HANDBOOK

THIRD EDITION

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Third Edition

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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).

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PART 3 APPLIED DESIGN

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 preregulator 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 = 12.57×10^{-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 ΔB" is used to indicate total peak-to-peak excursion.

Fundamental SI Quantities

Quantity name	Quantity symbol	Unit name	Unit symbol
Mass	m	Kilogram	kg
Length	l	Meter	m
Time	t	Second	s
Electric current	I	Ampere	A
Temperature	T	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}
μ	micro-	10^{-6}
n	nano-	10^{-9}
p	pico-	10^{-12}

Symbols for Physical Quantities

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

Symbols for Mathematical Variables Used in This Book

Variable	Parameter	Unit
A	area	cm^2
A	gain (without feedback)	dB
A'	gain (with feedback)	dB
A_c	cross-sectional area of center pole (transformer core)	cm^2
A_{cp}	area of center pole (transformer core)	cm^2
A_e	effective area (of core)	cm^2
A_g	area of air gap (in core)	cm^2
A_L	inductance factor (inductance of a single turn)	nH
A_m	minimum area of core	cm^2
A_n	attenuation factor	—
A_p	area of center pole (of core)	cm^2
$A_{p'}$	area of primary winding	cm^2
AP	area product of core ($A_w A_e$)	cm^4
AP_e	effective area product ($A_{wb} A_e$)	cm^4
A_r	resistance factor (bobbin); also attenuation factor	—
A_w	winding window area (of core)	cm^2
A_{wb}	winding window area (of bobbin)	cm^2
A_{we}	effective area of copper in winding (total)	cm^2
A_{wp}	primary winding window area	cm^2
A_s	surface area	cm^2
A_x	area of copper (for a single wire)	cm^2
B	magnetic flux density	mT
$\hat{B}$	peak magnetic flux density	mT
β	feedback factor	—
ΔB	small change in B	mT
ΔB_{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	μF
C_c	leakage (parasitic) capacitance	pF
cfm	cubic feet per minute (of air flow)	cfm
C_h	heat (storage) capacity	Ws/in^3/°C
C_k	interelectrode capacitance	pF
C_p	parasitic coupling capacitance	pF
D	duty ratio (t_{on}/t_p)	
d'	duty cycle ($t_{\mathrm{on}}/t_{\mathrm{off}}$)	
D'	$D'(1 - D)$ = "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 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
$\mathbf{e}$	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
ΔH	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
ΔI	small change in current	A
I^2R	resistive power loss	W
J	current density (in wire)	A/cm^2
$-j\omega C$	capacitive reactance, (complex #)	Ω
$j\omega L$	inductive reactance, (complex #)	Ω
K'	copper utilization factor (topology factor)	
K_m	material constant	
K_p	primary area factor	
K_t	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	μH
L_{Ls}	secondary leakage inductance	μH
L_{LT}	total (transformer) leakage inductance	μH
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)	μs
P_c	power dissipated in core	W
P_f	power factor (ratio true power/VA)	—
P_{in}	true input power (VI cos θ, 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 θ, 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^2 by radiation)	W J/s
R	resistance	Ω
r	radius (or wire)	mm
R_{Cu}	DC resistance of wound component at specified temperature	Ω
R_e	effective DC resistance of transformer winding	Ω
$R_{c\text{–}h}$	thermal resistance, case to heat exchanger	°C/W
$R_{h\text{–}a}$	thermal resistance, heat exchanger to free air	°C/W
$R_{j\text{–}c}$	thermal resistance, junction to case	°C/W
R_o	total thermal resistance	°C/W
R_s	effective resistance of prime source or network	Ω
R_{sf}	effective source resistance factor ($R_{sf} = R_s \times W_{out}$)	Ω
RT	temperature coefficient of resistance (copper = 0.00393 at 0°C)	Ω/Ω/°C
RT_{cm}	resistance of wire in Ω/cm at temp T, °C	Ω/cm
R_θ	thermal resistance (of heat-conducting path)	°C/W
$R_{\theta ja}$	thermal resistance, junction hot spot to free air	°C/W

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

Variable	Parameter	Unit
R_w	effective resistance of wound component at frequency f	Ω
R_x	resistance factor of bobbin	
S_f	scaling factor	
T	temperature in degrees Celsius	°C
t	time	s
T_{amb}	ambient temperature (of air)	°C
T_c	temperature of copper (winding)	°C
t_d	time delay period	s
T_{ds}	temperature of surface (diode)	°C
t_f	fall time (time required for voltage or current decay)	μs
T_h	temperature of heat exchanger surface	°C
t_p	total period (of time), i.e., duration of single cycle	μs
t_{off}	non-conducting "off" time period	μs
t_{on}	conducting "on" time period	μs
ΔT	small change in temperature	°C
ΔT_a	small temperature rise (above ambient)	°C
Δt	small increment of time	μs
T_r	temperature rise (above ambient)	°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	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_t	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_{out}	output voltage	V
V_p	peak voltage or primary voltage	V
$V_{p\text{–}p}$	ripple voltage, peak-peak value	V
V_{ref}	reference voltage	V
V_{rms}	root mean square voltage	Vrms
V_{sat}	saturation voltage	V
X_c	capacitive reactance	Ω
X_L	inductive reactance	Ω
ρ	volume resistivity of copper (at 0°C = 1.588 $\mu\Omega$-cm)	$\mu\Omega$-cm
ρ_{tc}	resistivity of copper at t_c °C	$\mu\Omega$-cm
μ_0	permeability of space ($4\pi\, 10^{-7}$ H/m)	Vs/Am
μ_r	relative permeability (of core)	

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