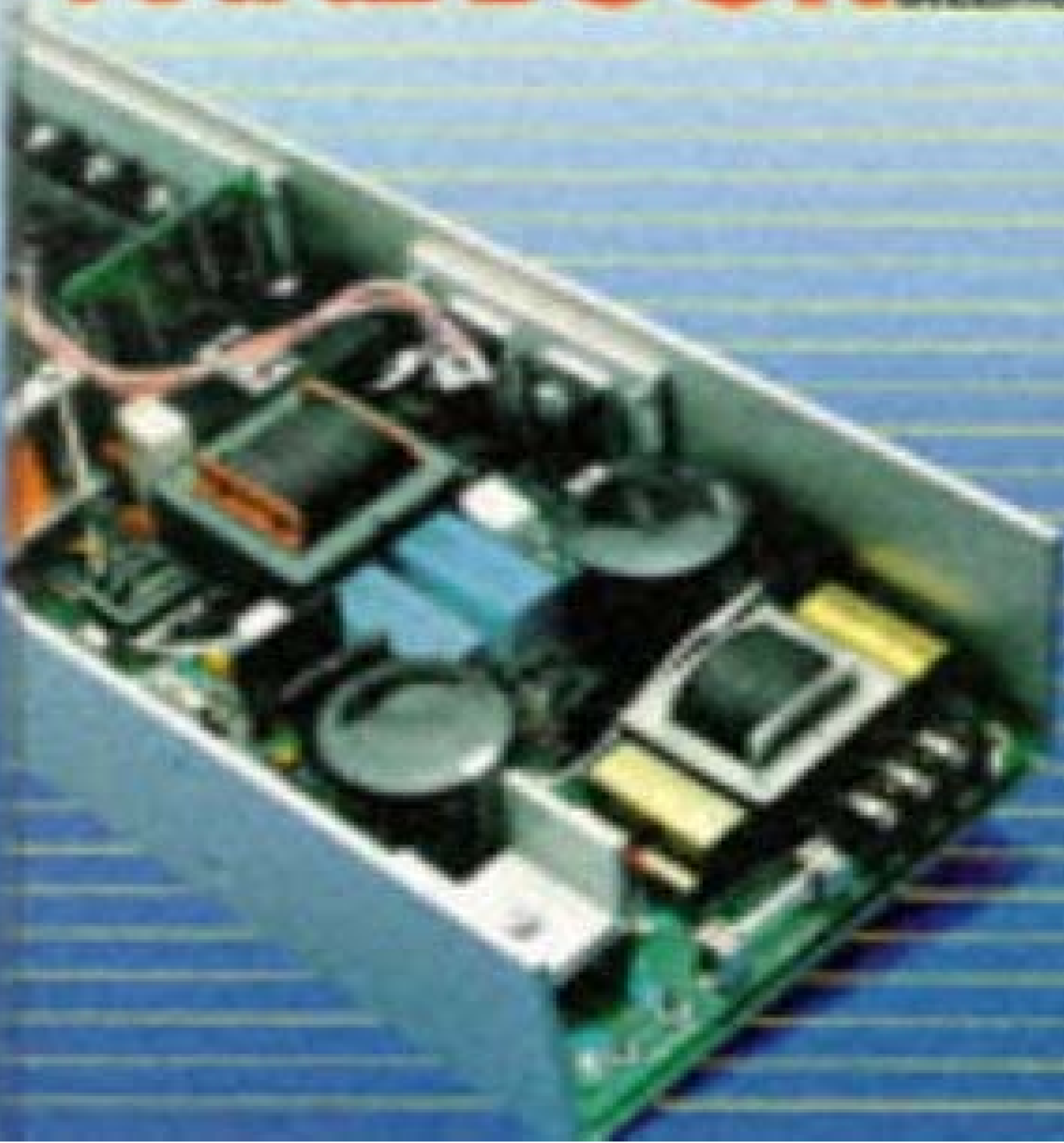
SWITCHMODE POWER SUPPLY HANDBOOK

KEITH BILLINGS



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Keith H. Billings, C.Eng., M.I.E.E.
Vice President, Engineering
Hammond Manufacturing Company, Ltd.

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For more than four years of
quiet encouragement

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PART 3 APPLIED DESIGN

ACKNOWLEDGEMENTS

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, and 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 this work, but worthy of special mention is my former engineering colleague and friend Rodney Weaving, who not only spent many hundreds of hours carefully checking the original manuscript and calculations, but also made many useful suggestions. Without his endorsement I do not think I would have had the courage to put this into print. I am also grateful to Betty Magee, who transcribed my dictation onto computer diskette for further word processing; Hammond Manufacturing Co., Ltd., of Guelph, Ontario, who generously provided illustrating equipment and encouragement; Gordon (Ed) Bloom, president of Bloom Associates, Inc., for his helpful suggestions; Unitrode and Lloyd H. Dixon, Jr., for permission to reproduce his work on "The Right-Half-Plane Zero"; the editors and staff of McGraw-Hill Publishing Company, who added the "professional touch"; and finally Line Donald of Douglas J. Donald (illustration and design), Guelph, Ontario, who produced the more than three hundred camera-ready illustrations and diagrams. Her professional skill has greatly enhanced this presentation.

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 $2 \times \hat{B}$. 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.

Basic Entities

Unit symbol	Unit name	Quantity	Quantity symbol	Dimensions
kg	Kilogram	Mass	m	M
m	Meter	Length	l	L
s	Second	Time	t	T
A	Ampere	Electric current	I	Q/T^{-1}
K	Kelvin	Temperature	T	θ

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	S · s
Charge	Q	coulombs	C	A · s
Current	I	amperes	A	V/Ω
Energy	U	joules	J	W · s
Impedance	Z	ohms	Ω	—
Inductance, self-	L	henries	H	Wb/A
Potential difference	V	volts	V	Wb/s
Power, real (active)	P	watts	W	$VI \cos \theta$
power, apparent	S	voltamperes	VA	V · A
Reactance	X	ohms	Ω	—
Resistance	R	ohms	Ω	V/A
Resistivity, volume	ρ	ohm-centimeters cubed	Ω-cm^3	$\frac{R \cdot A}{l}$
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	V · s
Flux density	B	teslas	T	Wb/m
Permeability	μ	henries per meter	H/m	V · s/A · m
Other				
Angular velocity	ω	radians per second	rad/s	$2 \pi f$
Area	A	centimeters squared	cm^2	—
Frequency	f	hertz	Hz	cycles/s
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	minimum cross-sectional area of pole (transformer)	cm^2
A_{cp}	area of center pole (of core)	cm^2
ac	alternating current	A
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 ($A_w \times A_e$)	cm^4
A_{pe}	effective area product ($A_{wb} \times A_e$)	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
B	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 (joules/in^3/°C)	Ws/°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
DC	direct (nonvarying) current or voltage	A or V
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	
$\lvert e\rvert$	emf (magnitude of emf only)	V
E	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_a	current density (in wire)	A/cm^2
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_{wc}	capacitive reactance, 1/2 πfC (complex #)	Ω
j_{wl}	inductive reactance, 2 πfL (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
l	length (length of magnetic path)	cm
l_e	effective path length	cm

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

Variable	Parameter	Unit
l_g	total length of air gap (in core)	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 or magnetic path (or core)	cm
L_p	primary inductance	mH
L_s	secondary inductance	mH
M_{lt}	mean length per turn	cm
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 (on 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}	input power	W
P_{id}	total internal dissipation	W
P_{out}	output power	W
P_{q1}	power dissipated in transistor Q1	W
P_q	heat energy (joules)	j
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-h}	thermal resistance, case to heat exchanger	°C/W
R_{h-a}	thermal resistance, heat exchanger to free air	°C/W
R_{ha}	thermal resistance of heat exchanger	°C/W
R_{j-c}	thermal resistance, junction to case	°C/W
rms	square root of the mean of the square of all the harmonic components	V or I
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, hot spot to free air	°C/W

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

Variable	Parameter	Unit
R_{th}	thermal resistance	°C/W
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}	nonconducting "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 interferance voltage, rms	Vrms
V_{in}	input voltage	V
V_l	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
$V_{\mathrm{p-p}}$	ripple voltage, peak–peak value	V
V_{ref}	reference voltage	V
V_{rms}	root mean square voltage	Vrms
V_{sat}	saturation voltage	V
W_{in}	true input power ($VI \cos \theta$, or VA × P_f, heating effect)	W
W_{out}	true output power ($VI \cos \theta$, or VA × P_f, heating effect)	W
W_j	heat dissipation at junction, J/s	W
X_c	capacitive reactance ($1/2 \pi fC$)	Ω
X_L	inductive reactance ($2 \pi fL$)	Ω

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

Variable	Parameter	Unit
ρ	volume resistivity of copper (at 0°C = 1.588 $\mu\Omega/cm^3$)	$\mu\Omega$-cm^3
ρ_{tc}	resistivity of copper at t_c °C ($R_{\mathrm{cu}} = \frac{\rho_{tc} \cdot l}{A}$	$\mu\Omega$-cm^3
μ_0	magnetic field constant ($4 \pi \times 10^{-7}$ H/m)	Vs/Am
μ_r	relative permeability (of core)	
μ_x	effective permeability (after gap is introduced)	
η	efficiency (power output/power input × 100%)	%
Δ	a small increment (change); also skin thickness, mm	mm
$\Delta\Phi$	a small change in total flux	Φ
φ	effective conductor height	mm
Φ	total magnetic flux, Wb	Vs
$\approx$	approximatly equal to	
α	proportional to	
ω	angular velocity ($\omega = 2 \pi f$)	rad/s
0V	zero voltage reference line (often the common output)	V
$1-D$	1 − duty ratio (the "off" period)	s
π	physical constant (3.1416)	
$\lvert x \rvert$	magnitude of function (x) only	

ABBREVIATIONS

ac	alternating current
AIEE	American Institute of Electrical Engineers
AWG	American wire gauge
B/H	(curve) hysteresis loop of magnetic material.
CISPR	Comité International Spécial des Perturbations Radioélectriques
CSA	Canadian Standards Association
dB	decibels (logarithmic ratio of power or voltage)
DC	direct (nonvarying) current or voltage
DCCT	direct-current current transformers
e.g.	exemplia gratis
emf	electromotive force
EMI	electromagnetic interference
ESL	effective series inductance
ESR	effective series resistance
FCC	Federal Communications Commission
FET	field-effect transistor
HCR	heavily cold-reduced
HRC	high rupture capacity
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
LC	(filter) a low-pass filter consisting of a series inductor and shunt capacitor
LED	light-emitting diode
LISN	line impedance stabilization network
mmf	magnetomotive force (magnetic potential, ampere-turns)
MLT	mean length (of wire) per turn

MOV	metal oxide varistor
MPP	molybdenum Permalloy powder
MTBF	mean time before/between failure(s)
NTC	negative temperature coefficient
"on"	conducting (working) state of device (circuit)
"off"	nonconducting (nonworking) state of device (circuit)
OVP	overvoltage protection (circuit)
PARD	periodic and random deviations (see glossary)
pcb	printed circuit board
PFS	power failure sense/signal
p–p	peak-to-peak value (ripple voltage/current)
PTFE	polytetrafluoroethylene
PVC	polyvinyl chloride
PWM	pulse-width modulation
RF	radio frequency
RFI	radio-frequency interference
rms	root mean square
RHP	right-half-plane (zero), a zero located in the right half of the complex *s*-plane
+s	positive remote sensing (terminal, line)
−s	negative remote sensing (terminal, line)
SCR	silicon controlled rectifier
SMPS	switchmode power supply
SOA	safe operating area
SR	saturable reactor (see glossary)
TTL	transistor-transistor logic
UL	Underwriters' Laboratories
UPS	uninterruptible power supply
UVP	undervoltage protection (circuit)
VDE	Verband Deutscher Elektrotechniker

SWITCHMODE
POWER SUPPLY
HANDBOOK

P • A • R • T • 1

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

CHAPTER 1

COMMON REQUIREMENTS: AN OVERVIEW

1.1 INTRODUCTION

The "direct-off-line" switchmode supply is so called because it takes its power input directly from the ac power lines, without using the rather large low-frequency (60 to 50 Hz) isolation transformer normally found in linear power supplies.

Although the various switchmode conversion techniques are often very different in terms of circuit design, they have, over many years, developed very similar basic functional characteristics which have become generally accepted industry standards.

Further, the need to satisfy various national and international safety, electromagnetic compatibility, and line transient requirements has forced the adoption of relatively standard techniques for track and component spacing, noise filter design, and transient protection. The prudent designer will be familiar with all these agency needs before proceeding with a design. Many otherwise sound designs have failed as a result of their inability to satisfy safety agency standards.

Many of the requirements outlined in this section will be common to all switching supplies, irrespective of the design strategy or circuit. Although the functions tend to remain the same for all units, the circuit techniques used to obtain them may be quite different. There are many ways of meeting these needs, and there will usually be a best approach for a particular application.

The designer must also consider all the minor facets of the specification before deciding on a design strategy. Failure to consider at an early stage some very minor system requirement could completely negate a design approach—for example, power good and power failure indicators and signals, which require an auxiliary supply irrespective of the converter action, would completely negate a design approach which does not provide this auxiliary supply when the converter is inhibited! It can often prove to be very difficult to provide for some minor neglected need at the end of the design and development exercise.

The remainder of Chap. 1 gives an overview of the basic input and output functions most often required by the user or specified by national or international standards. They will assist in the checking or development of the initial specification, and all should be considered before moving to the design stage.

1.2 INPUT TRANSIENT VOLTAGE PROTECTION

Both artificial and naturally occurring electrical phenomena cause very large transient voltages on all but fully conditioned supply lines from time to time.

IEEE Standard 587–1980 shows the results of an investigation of this phenomenon at various locations. These are classified as low-stress class A, medium-stress class B, and high-stress class C locations. Most power supplies will be in low- and medium-risk locations, where stress levels may reach 6000 V at up to 3000 A.

Power supplies are often required to protect themselves and the end equipment from these stress conditions. To meet this need requires special protection devices. (See Part 1, Chap. 2.)

1.3 ELECTROMAGNETIC COMPATIBILITY

Input Filters

Switching power supplies are electrically noisy, and to meet the requirements of the various national and international RFI (radio-frequency interference) regulations for conducted-mode noise, a differential- and common-mode noise filter is normally fitted in series with the line inputs. The attenuation factor required from this noise filter depends on the power supply size, operating frequency, power supply design, application, and environment.

For domestic and office equipments, such as personal computers, VDUs, and so on, the more stringent regulations apply, and FCC class B or similar limits would normally be applied. For industrial applications, the less severe FCC class A or similar limits would apply. (See Part 1, Chap. 3.)

It is important to appreciate that it is very difficult to cure a badly designed supply by fitting filters. The need for minimum noise coupling must be considered at all stages of the design; some good guidelines are covered in Part 1, Chaps. 3 and 4.

1.4 DIFFERENTIAL-MODE NOISE

Differential-mode noise refers to the component of high-frequency electrical noise between any two supply or output lines. For example, this would be measured between the live and neutral input lines or between the positive and negative output lines.

1.5 COMMON-MODE NOISE

For the line input, common-mode noise refers to that component of electrical noise that exists between both supply lines (in common) and the earth (ground) return.

For the outputs, the position is more complicated, as various configurations of isolated and nonisolated connections are possible. In general, output common-mode noise refers to the electrical noise between any output and some common point, usually the chassis or common return line.

Some specifications, notably those applying to medical electronics, severely limit the amount of ground return current permitted between either supply line and the earth (ground) return. A ground return current normally flows through the filter capacitors and leakage capacitance to ground, even if the insulation is perfect. The return current limitation can have a significant effect on the design of the supply and the size of input filter capacitors. In any event, capacitors in excess of 0.01 μF between the live line and ground are not permitted by many safety standards.

1.6 FARADAY SCREENS

High-frequency conducted-mode noise (noise conducted along the supply or output leads) is normally caused by capacitively coupled currents in the ground plane or between input and output circuits. For this reason, high-voltage switching devices should not be mounted on the chassis. Where this cannot be avoided, a Faraday screen should be fitted between the noise source and the ground plane, or at least the capacitance to the chassis should be minimized.

To reduce input-to-output noise coupling in isolating transformers, Faraday screens should be fitted. These should not be confused with the more familiar safety screens. (See Part 1, Chap. 4.)

1.7 INPUT FUSE SELECTION

This is an often neglected part of power supply design. Modern fuse technology makes available a wide range of fuses designed to satisfy closely defined parameters. Voltages, inrush currents, continuous currents, and let-through energy (I^2t ratings) should all be considered. (See Part 1, Chap. 5.)

Where units are dual-input-voltage-rated, it may be necessary to use a lower fuse rating for the higher input voltage condition. Standard, medium-speed glass cartridge fuses are universally available and are best used where possible. For line input applications, the current rating should take into account the 0.6 to 0.7 power factor of the capacitive input filter used in most switchmode systems.

For best protection the input fuse should have the minimum rating that will reliably sustain the inrush current and maximum operating currents of the supply at minimum line inputs. However, it should be noted that the rated fuse current given in the fuse manufacturer's data is for a limited service life, typically a thousand hours operation. For long fuse life, the normal power supply current should be well below the maximum fuse rating; the larger the margin, the longer the fuse life.

Fuse selection is therefore a compromise between long life and full protection. Users should be aware that fuses tend to age and should be replaced at routine servicing periods. For maximum safety during fuse replacement, the live input is normally fused at a point after the input switch.

To satisfy safety agency requirements and maintain maximum protection, when fuses are replaced, a fuse of the same type and rating must be used.

1.8 LINE RECTIFICATION AND CAPACITOR INPUT FILTERS

Rectifier capacitor input filters have become almost universal for direct-off-line switchmode power supplies. In such systems the line input is directly rectified into a large electrolytic reservoir capacitor.

Although this circuit is small, efficient, and low-cost, it has the disadvantage of demanding short, high-current pulses at the peak of the applied sine-wave input, causing excessive line I^2r losses, harmonic distortion, and a low power factor.

In some applications (e.g., shipboard equipment), this current distortion cannot be tolerated, and special low-distortion input circuits must be used. (See Part 1, Chap. 6.)

1.9 INRUSH LIMITING

Inrush limiting reduces the current flowing into the input terminals when the supply is first switched on. It should not be confused with "soft start," which is a separate function controlling the way the power converter starts its switching action.

In the interests of minimum size and weight, most switchmode supplies will use semiconductor rectifiers and low-impedance input electrolytics in a capacitive input filter configuration. Such systems have an inherently low input resistance; also, because the capacitors are initially discharged, very large surge currents would occur at switch-on if such filters were switched directly to the line input.

Hence, it is normal practice to provide some form of current inrush limiting on power supplies that have capacitive input filters. This inrush limiting typically takes the form of a resistive limiting device in series with the supply lines. In high-power systems, the limiting resistance would normally be removed (shorted out) by an SCR, triac, or switch when the input reservoir and/or filter capacitor has been fully charged. In low-power systems, NTC thermistors are often used as limiting devices.

The selection of the inrush-limiting resistance value is usually a compromise between acceptable inrush current amplitude and start-up delay time. Negative temperature coefficient thermistors are often used in low-power applications, but it should be noted that thermistors will not always give full inrush limiting. For example, if, after the power supply has been running long enough for the thermistor to heat up, the input is turned rapidly off and back on again, the thermistor will still be hot and hence low-resistance, and the inrush current will be large. The published specification should reflect this effect, as it is up to the user to decide whether this limitation will cause any operational problems. Since even with a hot NTC the inrush current will not normally be damaging to the supply, thermistors are usually acceptable and are often used for low-power applications. (See Part 1, Chap. 7.)

1.10 START-UP METHODS

In direct-off-line switchmode supplies, the elimination of the low-frequency (50 to 60 Hz) transformer can present problems with system start-up. The difficulty usually stems from the fact that the high-frequency power transformer cannot be used for auxiliary supplies until the converter has started. Suitable start-up circuits are discussed in Part 1, Chap. 8.

1.11 SOFT START

Soft start is the term used to describe a low-stress start-up action, normally applied to the pulse-width-modulated converter to reduce transformer and output capacitor stress and to reduce the surge on the input circuits when the converter action starts.

Ideally, the input reservoir capacitors should be fully charged before converter action commences; hence, the converter start-up should be delayed for several line cycles, then start with a narrow pulse and a progressively increasing pulse width until the output is established.

There are, in fact, a number of reasons why the pulse width should be narrow when the converter starts and progressively increase during the start-up phase. There will often be considerable capacitance on the output lines, and this should be charged slowly so that it does not reflect an excessive transient back to the supply lines. Further, where a push-pull action is applied to the main transformer, flux doubling and possible saturation of the core may occur if a wide pulse is applied to the transformer for the first half cycle of operation. (See Part 3, Chap. 7.) Finally, since an inductor will invariably appear somewhere in series with the current path, it may be impossible to prevent voltage overshoot on the output if this inductor current is allowed to rise to a high value during the start-up phase. (See Part 1, Chap. 10.)

1.12 START-UP OVERVOLTAGE PREVENTION

When the power supply is first switched on, the control and regulator circuits are not in their normal working condition (unless they were previously energized by some auxiliary supply).

As a result of the limited output range of the control and driver circuits, the large-signal slew rate may be very nonlinear and slow. Hence, during the start-up phase, a "race" condition can exist between the establishment of the output voltages and correct operation of the control circuits. This can result in excessive output voltage overshoot.

Additional fast-acting voltage clamping circuits may be required to prevent overshoot during the start-up phase, a need often overlooked in the past by designers of both discrete and integrated control circuits. (See Part 1, Chap. 10.)

1.13 OUTPUT OVERVOLTAGE PROTECTION

Loss of voltage control can result in excessive output voltages in both linear and switchmode supplies. In the linear supply (and some switching regulators), there is a direct DC link between input and output circuits, so that a short circuit of the power control device results in a large and uncontrolled output. Such circuits