VOLUME TWO

Power Supplies for Electronic Equipment

Linear and Switched Supplies

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PREFACE

The power supply is an essential part of every electronic equipment. In its simplest form it may consist of no more than a transformer, rectifier, and smoothing circuit, but frequently much more sophisticated arrangements are required, especially in the industrial field of computers, digital instruments, d.c. amplifiers, etc.

Since the introduction of transistors and other semiconductor devices in in the late 1940s, the interest in all types of power supplies, including d.c. inverters and converters, has grown considerably. The advantages of ruggedness and higher overall efficiency in using semiconductor devices when compared with the earlier valve counterparts are well known, and are particularly beneficial as greater emphasis is now placed on reliability, size and weight reduction, and portability.

Numerous papers have been published, often dealing with one particular aspect of the subject. Many of the references are not readily available and tracking down information often proves a time-consuming undertaking. While working in the field during the past twelve years, I have frequently been faced with the unenviable task of wading through vast amounts of material in order to extract the required reference.

These two volumes, therefore, are an attempt to present up-to-date available material and to give the necessary references. The basic theory is supported by circuit analysis and, in many cases, is followed by a detailed design procedure. Many practical examples are given to provide the reader with reliable and ready-to-use circuits.

They aim to supply the need for a comprehensive study of the subject for the use of all grades of electronic engineers, technicians, and students at universities and technical colleges.

Patent Protection

Some of the circuits, semiconductor devices, and arrangements described here are subject to Patent protection. Anybody wishing to make use of the above should obtain the permission of the Patentee.

JR Nowicki

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SYMBOLS

a *or* A	anode terminal
A	cross-sectional area of core
av *or* AV	average
b *or* B	base terminal
B	flux density
B_M	maximum operating flux density
B_S	saturation flux density
BO	breakover
BR	breakdown
c *or* C	collector terminal
c or C	capacitance
$C_{b'c}$	transistor base-collector capacitance
$C_{b'e}$	transistor base-emitter capacitance
C_o *or* C_{out}	output capacitance
C_{TC}	capacitance of collector depletion layer
C_{TE}	capacitance of emitter depletion layer
CC	constant current
CV	constant voltage
d	delay *or* duty cycle
D	diode
e *or* E	emitter terminal
e	instantaneous voltage
E	applied voltage
E_{dc}	d.c. output voltage
E_{max}	maximum applied voltage
E_s	energy stored
E_t	transferred energy
E_D	forward voltage drop across thyristor
E_K	voltage drop due to copper loss
E_T	transformer output voltage
$E_{T(max)}$	maximum sine-wave output voltage of the transformer
$E_{T(rms)}$	r.m.s. value of the transformer output voltage
f	frequency
f_{low}	low frequency
f_{max}	maximum frequency of oscillations

f_o	optimum frequency
f_r	ripple frequency
f_T	transition frequency (common product of emitter gain and bandwidth)
f_1	frequency of unity current-transfer ratio modulus
g *or* G	gate terminal
g_m	mutual conductance of transistor
G_m	mutual conductance of stage
h_{FB} and h_{FE}	static value of forward current-transfer ratio with output held constant
H	henry
H	magnetising field strength
H_s	value of magnetising field strength at saturation
H_0	intrinsic strength of magnetising field
Hz	hertz
i	instantaneous current
i_{av}	average value of a.c. current
i_{pk}	peak value of a.c. current
i_r	instantaneous reverse current
i_{rms}	r.m.s. value of a.c. current
i_C	instantaneous value of capacitor current
i_F	instantaneous forward current
I_{av}	total average current
$I_{b(min)}$	minimum base current
$I_{b(pk)}$	peak base current
I_c	r.m.s. value of collector current *or* total capacitor current
$I_{c(rms)}$	r.m.s. value of capacitor current
I_{dc}	d.c. value of total current
I_i	input current *or* inverse current
$I_{i(max)}$	maximum inverse current
I_m	magnetising current
I_{mag}	r.m.s. value of transformer primary magnetising current
I_o *or* I_{out}	output current
I_{on}	initial switch-on current
$I_{o/c}$	sum of magnetising current and core loss components of transformer with either primary or secondary open-circuited
I_{pk}	peak current
I_{rms}	r.m.s. value of current
I_B	base current
$I_{B(on)}$	base current of saturated transistor
$I_{B(off)}$	reverse base current during switch-off transition
I_C	total collector current
I_{CBO}	collector cut-off current (emitter open-circuited)

I_{CEO}	collector cut-off current (base open-circuited)
I_D	diode current
I_E	emitter current
I_f	feedback current
I_F *or* $I_{F(AV)}$	forward current *or* average forward current
I_{FG}	thyristor forward gate current
I_{FGM}	thyristor peak forward gate current
I_G	thyristor gate current
I_H	thyristor holding current (d.c.)
I_{IN}	average supply current
I_L	load current
I_L	thyristor latching current
I_L	value of inductive current
I_M	magnetising current
I_R	continuous d.c. reverse leakage current
I_R	current flowing through the resistor R *or* collector load current
I_T	thyristor continuous (d.c.) on-state current
$I_{T(AV)}$	average value of anode current
I_V	tunnel diode valley point current
I_Z	current through voltage regulator diode after breakdown
I_{Zs}	specified current through voltage regulator diode after breakdown
K	constant
l	length of magnetic path
l_c	length of flux path in core
l_g	length of air gap
L	inductance
L_{crit}	value of critical inductance
L_p	inductance of primary
L_t	inductance of winding N_t
n	number $1, 2, 3, \ldots, n$
N_b	number of turns in base winding
N_f	number of turns in feedback winding
N_h	number of turns in heater winding
N_i	number of turns in ignition winding
N_p	number of turns in primary winding
N_s	number of turns in secondary winding
N_t	number of turns in control winding
p	percentage change
P	steady-state dissipation
P_c	collector dissipation
$P_{c(max)}$	maximum collector dissipation

$P_{c(transient)}$	collector transient dissipation
P_f	power delivered by feedback winding
P_i	input power
$P_{i(av)}$	average input power
P_K	transformer copper loss
P_o *or* P_{out}	output power
P_p	pulse power
$P_{p(max)}$	maximum permissible pulse power
P_s	steady-state dissipation
$P_{s(max)}$	maximum permissible steady-state dissipation
$P_{tot(max)}$	maximum total dissipation
P_F	forward power loss *or* total power absorbed by drive circuit
$P_{F(AV)}$	average forward power loss
P_R	power dissipated in resistor R *or* power drawn from the supply by bias chain
Q	charge *or* charge remaining in the device after time t
Q_e	extracted charge
Q_f	charge extracted during forward recovery time
Q_i	initial charge
Q_m *or* Q_{max}	maximum charge
Q_{min}	minimum charge
Q_r	charge extracted during reverse recovery time
Q_t	total charge extracted
r_b	transistor base resistance of equivalent T circuit
r_{bb}	internal base resistance of transistor
r_e	internal emitter resistance of transistor
r_p *or* R_p	winding resistance of transformer primary
r_s *or* R_s	winding resistance of transformer secondary
r_{tot}	total winding resistance of transformer
r_B	base resistance of unijunction transistor
r_{BB}	interbase resistance of unijunction transistor
r_Z	dynamic resistance of voltage regulator diode
r_{Zs}	dynamic resistance at specified current
R	resistance
R_b *or* R_B	external base resistance
R_{bb}	sum of internal and external base resistances
R_{ext}	external circuit resistance
R_o	transistor input resistance obtained by drawing tangent to input characteristics *or* output resistance
R_{th}	thermal resistance
$R_{th(c-a)}$	thermal resistance case-to-ambient
$R_{th(effective)}$	effective thermal resistance
$R_{th(h)}$	thermal resistance of heat sink

$R_{th(i)}$	contact thermal resistance
$R_{th(j-a)}$ *or* $R_{th(j-amb)}$	thermal resistance junction-to-ambient
$R_{th(j-c)}$ *or* $R_{th(j-case)}$	thermal resistance junction-to-case
$R_{th(j-mb)}$	thermal resistance junction-to-mounting base
$R_{th(s)}$	steady-state thermal resistance
$R_{th(s-r)}$	thermal resistance for permissible temperature rise
$R_{th(t)}$	transient thermal resistance
R_B	equivalent transistor input resistance
R_{BX}	total input resistance of compound transistor
R_{CE}	collector-emitter resistance of transistor
$R_{CE(sat)}$	saturation resistance of transistor
R_G	thyristor gate resistance
R_L	load resistance
R_V	variable resistance
S	stabilisation factor
S_p	stabilisation factor of pre-stabilising stage
S_F	fractional change coefficient
S_T	total temperature coefficient
S_{TR}	temperature coefficient of transistor
S_Z	temperature coefficient of voltage regulator diode
SCR	thyristor
SW	switch
t	time
t_d	delay time
t_{com}	commutation period
t_{cond}	conduction period
t_f	fall time
t_{fr}	forward recovery time
t_{off}	turn-off time *or* duration of off time
t_{on}	turn-on time *or* duration of on time
t_p	pulse duration *or* time of half-cycle
t_r	rise time
t_{rr}	reverse recovery time
t_s	storage time
T	transformer
T	temperature *or* periodic time
T_a *or* T_{amb}	ambient temperature
$T_{amb(max)}$	maximum ambient temperature
T_c *or* T_{case}	case temperature
T_{eq}	equivalent time
T_j	junction temperature

$T_{j(max)}$	maximum junction temperature
T_{mb}	mounting base temperature
T_n	temperature of *n* degrees Kelvin
T_r	reference temperature
T_s	source temperature
T_{s-r}	permissible temperature rise
TR	transistor
U_p	utility factor of transformer primary
U_s	utility factor of transformer secondary
v	instantaneous value of voltage
v_{pk}	peak value of instantaneous voltage
v_F	instantaneous value of forward voltage
v_R	instantaneous value of reverse voltage
V_{bb}	voltage applied to base of transistor
V_{be}	minimum value of base-emitter voltage
V_{cc}	supply voltage
V_d	forward voltage drop across rectifier diode
V_f	feedback voltage
V_{fr}	forward recovery voltage
V_i *or* V_{in}	input voltage
V_i	ignition voltage
V_h	heater voltage
V_o *or* V_{out}	output voltage
$V_{o/c}$	open-circuit voltage
V_p	peak point voltage *or* primary voltage
V_s	secondary voltage
$V_{s/c}$	short-circuit test voltage
V_x	voltage across ballast reactance
V_{BB}	unijunction interbase voltage *or* d.c. base-supply voltage
V_{BE}	base-emitter voltage
V_{BEM}	maximum base-emitter voltage
V_{BO}	breakover voltage
$V_{(BR)}$	breakdown voltage
$V_{(BR)CBO}$	breakdown voltage collector-to-base (emitter open-circuited)
$V_{(BR)CEO}$	breakdown voltage collector-to-base (emitter and base short-circuited)
$V_{(BR)R}$	reverse breakdown voltage
V_C	collector voltage
V_{CE}	collector-to-emitter voltage (d.c.)
$V_{CE(pk)}$	peak value of collector-to-emitter voltage
$V_{CE(sat)}$	collector-to-emitter saturation voltage

V_{CEM}	maximum rated peak collector voltage
V_D	forward voltage drop of p-n junction *or* forward voltage drop of rectifier diode
V_E	emitter voltage
V_{EB}	emitter-base voltage (d.c.)
V_F	d.c. forward voltage
V_L	voltage across lamp
V_R	d.c. reverse voltage *or* ripple voltage
V_{RR}	applied repetitive peak reverse voltage
V_{RRM}	repetitive peak reverse voltage
V_{R_p}	voltage drop across resistance of primary winding
V_{RB}	voltage drop across external base resistor
V_{RS}	voltage drop across resistance of secondary winding
V_{RSM}	maximum non-repetitive reverse voltage rating
V_{RW}	crest working voltage rating of rectifier diode
V_{RWM}	crest (peak) working reverse voltage
V_T	thyristor voltage between anode and cathode
V_Z	voltage across voltage regulator diode after breakdown *or* voltage regulator (Zener) diode operating voltage
V_{Zs}	specified reference voltage at specified current I_{Zs}
V_0	intercept voltage of tangent to forward characteristic
VA_s	secondary volt-ampere rating
W	watt
$W_{o/c}$	transformer copper loss and core loss open-circuit test
$W_{s/c}$	transformer copper loss and core loss short-circuit test
W_R	reverse switching transient power loss
X_L	reactance of ballast choke
α	turns for 1 mH (Ferroxcube cores)
β	h_{FE}, transistor current gain
δ	differential
η	efficiency
η_f	efficiency as function of frequency f
θ	angle in degrees
μ	permeability of core material
τ	time constant *or* rise time
τ_s	carrier storage time coefficient of switching transistor
ϕ	magnetic flux *or* angle in degrees
ϕ_{pk}	peak value of magnetic flux
ϕ_s	magnetic flux at saturation
ω	angular frequency, $2\pi f$
ω_t	product of gain and bandwidth
Ω	ohm

CONTENTS

CHAPTER 1. LINEAR POWER SUPPLIES

Power supplies can be defined as circuits which transform electrical input power, either a.c. or d.c., into d.c. output power. This definition distinguishes power supplies from other electronic power sources which are dealt with elsewhere under the following headings: d.c.-to-a.c. inverters, d.c.-to-d.c. converters, and static inverters. The term *power supply* is commonly used when referring to an electronic stabilising circuit. The term *linear power supply* denotes a circuit which obeys a proportional control with continuous regulation following resistive d.c. load line.

Stabilising circuits, employing voltage regulator (Zener) diodes and transistors, can be arranged in many ways. Voltage regulator diodes are basically shunt stabilisers, whereas transistors can be connected as either shunt or series elements.

The basic function of stabilising circuits is to eliminate or to substantially reduce the characteristic variations of a.c. mains supplies and suppress the mains-borne interference.

Stabilising circuits may also be needed to cope with variations in d.c. supplies derived from primary cells or rechargeable accumulators where the output voltage not only depends on the initial state of charge but also on the magnitude of the load current.

Transistor power supplies which embrace shunt and series stabilisers as well as current stabilisers are not new in principle, but are modern versions of the thermionic valve circuits (Refs. 10 to 13) which date back to the 1930s. This reference to the valve circuits is made for historical reasons only. While not intending to make any detailed comparison between valve and transistor circuits, it may be fairly said that the latter have certain obvious advantages, such as lower voltage drop, higher current rating, and the elimination of heater power supplies. These advantages are further augmented by the availability of complementary transistors which, as will be seen later, allow greater freedom in circuit design and result in many improvements.