Power Electronics

Other Macmillan titles of related interest

- W. A. Atherton, *From Compass to Computer*
B. R. Bannister and D. G. Whitehead, *Fundamentals of Modern Digital Systems*
G. B. Clayton, *Data Converters*
G. B. Clayton, *Experiments with Operational Amplifiers*
J. C. Cluley, *Transducers for Microprocessor Systems*
R. F. W. Coates, *Modern Communication Systems*, second edition
A. R. Daniels, *Introduction to Electrical Machines*
C. W. Davidson, *Transmission Lines for Communication*
J. D. Edwards, *Electrical Machines – An Introduction to Principles and Characteristics*
M. Goodge, *Semiconductor Device Technology*
B. A. Gregory, *An Introduction to Electrical Instrumentation and Measurement Systems*, second edition
Paul A. Lynn, *An Introduction to the Analysis and Processing of Signals*, second edition
Paul A. Lynn, *Electronic Signals and Systems*
S. A. Marshall, *Introduction to Control Theory*
A. G. Martin and F. W. Stephenson, *Linear Microelectronic Systems*
J. E. Parton, S. J. T. Owen and M. S. Raven, *Applied Electromagnetics*, second edition
M. Ramamoorthy, *An Introduction to Thyristors and their Applications*
Douglas A. Ross, *Optoelectronic Devices and Optical Imaging Techniques*
Trevor J. Terrell, *Introduction to Digital Filters*
M. J. Usher, *Sensors and Transducers*
G. Williams, *An Introduction to Electrical Circuit Theory*

Power Electronics

Devices, Drivers and Applications

B.W. Williams

B.Sc., Dip.Eng., B.Eng., M.Sc., Ph.D., D.I.C.

Professor of Electrical Engineering

Department of Electrical and Electronic Engineering

Heriot-Watt University, Edinburgh

M
MACMILLAN

© B. W. Williams 1987

All rights reserved. No reproduction, copy or transmission of this publication may be made without written permission.

No paragraph of this publication may be reproduced, copied or transmitted save with written permission or in accordance with the provisions of the Copyright Act 1956 (as amended).

Any person who does any unauthorised act in relation to this publication may be liable to criminal prosecution and civil claims for damages.

First published 1987

Published by
MACMILLAN EDUCATION LTD
Houndmills, Basingstoke, Hampshire RG21 2XS
and London
Companies and representatives
throughout the world

British Library Cataloguing in Publication Data
Williams, B. W.

Power electronics: devices, drivers and
applications.

1. Power semiconductors

I. Title

621.3815'2 TK7871.85

ISBN 978-0-333-39662-9 ISBN 978-1-349-18525-2 (eBook)

DOI 10.1007/978-1-349-18525-2

Contents

<i>Preface</i>	<i>viii</i>
<i>Acknowledgements</i>	<i>ix</i>
<i>List of Symbols</i>	<i>x</i>
PART 1: DEVICES	1
1 Basic Semiconductor Physics and Technology	3
1.1 Processes forming pn junctions	4
1.2 The masking process	6
2 The pn Junction	8
2.1 The pn junction under forward bias (steady state)	8
2.2 The pn junction under reverse bias (steady state)	9
2.3 Thermal effects	12
2.4 Piecewise-linear junction diode model	13
3 Power Switching Devices and their Static Electrical Characteristics	16
3.1 The power diode	16
3.2 Power switching semiconductor transistors	23
3.3 The thyristor	36
3.4 The field-controlled thyristor (fct)	50
4 Electrical Ratings and Characteristics of Power Semiconductor Switching Devices	53
4.1 General maximum ratings of power semiconductor devices	53
4.2 The fast-recovery diode	55
4.3 The bipolar, high-voltage, power switching npn transistor	59
4.4 The power mosfet	70
4.5 The thyristor	78

5	Cooling of Power Switching Semiconductor Devices	90
5.1	Thermal resistances	91
5.2	Modes of power dissipation	93
5.3	Average power dissipation	98
5.4	Power losses from manufacturers' data sheets	98
5.5	Heat-sinking design cases	100
PART 2:	DRIVERS	111
6	Load Considerations	113
6.1	The resistive load	113
6.2	The inductive load	116
7	Driving the Transistor, and its Protection	124
7.1	Application of the power mosfet	124
7.2	Application of the bipolar transistor	133
7.3	Transistor combinations	151
7.4	Appendix: Turn-off switching-aid circuit analysis	154
8	Driving the Thyristor, and its Protection	159
8.1	Gate drive circuits	160
8.2	Gate drive design	162
8.3	Drive design for gto's	164
8.4	Thyristor switching-aid circuits	164
8.5	Switching-aid circuit for the gto thyristor	170
8.6	Appendix: Turn-off snubber circuit analysis	170
9	Switching-aid Circuits with Energy Recovery	173
9.1	Energy recovery for turn-on snubber circuits	173
9.2	Energy recovery for turn-off snubber circuits	177
9.3	Unified turn-on and turn-off snubber circuit energy recovery	184
10	Series and Parallel Device Operation and Protection	187
10.1	Parallel and series operation of power devices	187
10.2	Protection	198
PART 3:	APPLICATIONS	213
11	Naturally Commutating Converters	215
11.1	Single-phase uncontrolled converter circuits	216
11.2	Single-phase half-controlled converter	224

Contents

vii

11.3	Single-phase controlled thyristor converter circuits	227
11.4	Three-phase uncontrolled converter circuits	233
11.5	Three-phase half-controlled converter	239
11.6	Three-phase controlled thyristor converter circuits	239
12	AC Voltage Regulators	249
12.1	Single-phase ac regulator	249
12.2	Three-phase ac regulator	251
12.3	Integral cycle control	256
12.4	Single-phase transformer tap changer	258
12.5	Cycloconverter	259
12.6	Load efficiency and supply current power factor	259
13	Thyristor Forced Commutated DC Choppers	264
13.1	A thyristor reverse impressed voltage commutated dc chopper	266
13.2	A thyristor current impulse displacement commutated dc chopper	270
13.3	Other cid and riv commutation circuits	277
13.4	Comparison between the cid and riv commutation processes	279
14	Static Power Inverters	282
14.1	Voltage-fed inverter bridge topologies	283
14.2	Controlled current-sourced inverters	304
15	Switched-mode Power Supplies	309
15.1	The forward converter	309
15.2	The flyback converter	314
15.3	Comparison of basic converters	321
15.4	Multiple-switch, balanced, isolated converters	324
	<i>Bibliography</i>	330
	<i>Index</i>	332

Preface

The objective of this book is to bridge the gap between semiconductor device theory and device application in the area of power electronics. The majority of existing books concentrate on one aspect at the expense of the other. They either analyse semiconductor physics and material aspects of devices without including any applications or, at the other end of the spectrum, they consider device applications with the device being treated as a 'black box'.

This book specifically considers high-power devices and in particular how a device's structure and construction are related to its terminal electrical and thermal characteristics. Only then, armed with an understanding of device characteristics, is it possible to select the correct device for a given application.

Emphasis is placed on the circuitry required to use power devices rather than treating them as ideal switches or considering just one device type. The structure and electrical characteristics of a device are related to its driving and protection requirements for a particular type of application.

The book is in three parts. Part 1 covers power device electrical and thermal characteristics and how they relate to a device's physical structure. Devices considered include the thyristor, gto, mosfet and bipolar transistor. Part 2 describes device driving and protection techniques and the final part gives a general selection of power electronic applications. Application areas other than those dominated by thyristors have been considered; in particular the growing area of switched-mode power supplies has been introduced.

The book gives a fundamental, yet detailed education in the art of power electronics. Since a basic knowledge of semiconductor physics and circuit techniques is assumed, it is a specialist subject book intended for university and polytechnic students, as well as for practising engineers wishing to broaden their understanding of power electronics. Non-trivial worked examples and problems have been included for the student, and each chapter has a specific reading list.

B. W. W.

Acknowledgements

I would like to thank Motorola, International Rectifier and Siemens, who have permitted use of their published material. I am indebted to Elizabeth Boden who has not been content with just typing the manuscript but has attempted to eliminate those errors of grammar and punctuation that I tend to overlook.

List of Symbols

a	device tolerance
A	anode
b	base
b_t	base transport factor
B_{sat}	saturation flux density
c	collector
C	capacitance
C_{ds}	drain-to-source capacitance
C_f	heat-sink correction factor
C_{gd}	gate-to-drain capacitance
C_{gs}	gate-to-source capacitance
C_o	snubber transfer capacitance
C_s	snubber capacitance
d	drain
e_o	output voltage
e_s	step input voltage
E	circuit voltage source
E_i	input voltage source
ESR	equivalent series resistance
f_m	maximum switching frequency
f_s	switching frequency
g	mosfet gate
G	thyristor gate

List of Symbols

xi

h	heat transfer coefficient
H_s	flux intensity at saturation
i	current
i_b	base current
i_i	input current
i_l	inductor current
i_o	output current
i_{rr}	reverse recovery current
i_T	thyristor anode current
I_a	prospective fault current
I_c	collector current
I_{cbo}	collector leakage current
$I_{c(max)}$	maximum allowable collector current
I_d	drain current
$I_{d(rms)}$	rms drain current
I_D	mean diode current
I_F	forward current
$I_{F(av)}$	average forward current
I_G	gate current
I_H	holding current
$\bar{I}_i$	mean input current
I_l	leakage current
I_L	latching current
I_o	reverse leakage current
$\bar{I}_o$	mean output current
I_p	peak let-through current
I_{rr}	peak reverse recovery current
$I_{s/b}$	second breakdown current
I_T	total current
J	junction
J_R	reverse recovery energy
k	transistor switching time ratio
K	cathode
K_{ID}	diode current form factor
K_v	voltage ripple factor
l_p	primary inductance
l_s	saturable inductance
L	inductance
L_s	linear snubber inductance

m	empirical transistor constant
M	avalanche multiplication factor
n	ratio C_s/C_o
n_i	intrinsic carrier concentration
N	turns or turns ratio
N_A	acceptor concentration
N_C	concentration
N_D	donor concentration
pd	percentage derating
P	power
P_d	average power dissipation
P_G	mean gate power
P_p	peak power
P_s	switching interval power loss
Q_G	mosfet gate charge
Q_o	diode total recovery charge
Q_R	diode reverse recovery charge
r'_b	base lateral resistance
$r(t_p)$	thermal normalising factor
R_{be}	base-to-emitter resistance
$R_{ds(on)}$	mosfet on-state resistance
R_g	gate resistance
R_L	load resistance
R_θ	thermal resistance
$R_{\theta j-c}$	thermal resistance junction-to-case
s	source
S	maximum dv/dt
SOA	safe operating area
t	time
t_a	fuse arcing time
t_c	fuse clearing time
t_d	turn-on delay time
t_D	diode conduction time
t_{fi}	current fall time
t_{fr}	diode turn-on time
t_{fv}	voltage fall time
t_m	fuse melting time
t_{off}	turn-off time

t_{on}	turn-on time
t_p	pulse width
t_q	thyristor turn-off time
t_{ri}	current rise time
t_{rr}	reverse recovery time
t_s	saturation delay time
t_T	transistor on-time
t_x	time of no conduction
T	temperature
T_a	ambient temperature
T_c	case temperature
T_j	junction temperature
T_{jmax}	maximum allowable junction temperature
T_m	main thyristor

v	voltage
$v_{be(sat)}$	base-to-emitter saturation voltage
$v_{ce(sat)}$	collector-to-emitter saturation voltage
v_D	diode on-state voltage
v_o	output voltage
V	voltage
V_a	common emitter avalanche voltage
V_{ac}	ac supply voltage
V_b	junction avalanche voltage
V_{be}	base-to-emitter voltage
V_{BF}	scr forward breakover voltage
V_{BR}	scr reverse breakdown voltage
V_c	collector voltage
V_{ce}	collector-to-emitter voltage
V_D	device voltage rating
V_{ds}	drain-to-source voltage
V_{fp}	diode turn-on peak forward voltage
V_{gs}	gate-to-source voltage
V_L	line-to-line rms voltage
V_o	mean output voltage
V_{PT}	punch-through voltage
V_r	rms output voltage
V_R	reverse applied voltage
V_{RI}	ripple voltage
V_{RM}	reverse overshoot voltage
V_s	dc supply voltage
V_{TH}	mosfet threshold voltage
V_Z	Zener voltage

w	thickness
W	energy
W_t	total loss
Z	impedance
Z_θ	thermal impedance
α	current transfer ratio
α_o	α in the linear region
β	current amplification factor
β_Q	gto turn-off gain
γ	injection efficiency
δ	duty cycle
ΔT	change in temperature
λ	thermal conductance
ξ	damping factor
ξ_m	peak electric field
σ	electrical conductivity
τ	period
ϕ	$\tan^{-1} (\omega L/R)$
Φ	zero bias potential
ω	oscillation frequency
ω_o	natural oscillation frequency
$\wedge$	peak
$\vee$	minimum