Power Semiconductor Drives

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The operations of man participate in the character of their author; they are diminutive, but energetic during the short period of their existence: whilst those of nature, acting over vast spaces, and unlimited by time, are ever pursuing their silent and resistless career.

Charles Babbage Esq. A.M.

Lucasian Professor of Mathematics in the
University of Cambridge and member of several Academies
On the Economy of Machinery and Manufactures

Preface

This book is concerned with dc and ac electric motor drives and the speed and positional control systems that may be devised by using them. The power sources considered are also both dc and ac. Power semiconductor converters of various types are located between motor and source.

We hope that the book will be useful both to practicing engineers and to university students. At the University of Toronto this material is discussed in the final semester of the undergraduate course in electrical engineering. It is fully covered by graduate students in an advanced course.

The reader is assumed to have a sound basic knowledge of electric machines and of power semiconductor circuits. On this assumption, the text is designed to provide an analysis of the steady-state operation of drive systems that permits the specification of suitable converters and machines for the systems envisaged. Transient operation is glanced at but not discussed in detail because the full analysis of stability and response demands a text of its own.

After an introductory chapter that deals with the kind of mechanical systems that may need to be driven the chapters that follow are concerned with particular combinations of machines and power sources. In the worked examples in the text and the problems at the end of each chapter an effort has been made to illustrate the practical details that complicate system design. Problems in which these details are neglected for the sake of simplicity, or in which more are included in the interest of verisimilitude, can readily be prepared by the instructor, to whom solutions to the problems in the text will be supplied by the authors on request. All worked examples and the problems have been solved on a hand calculator. A programmable model is essential for some of them because numerical solution of some equations is necessary.

The semiconductor devices commonly used for converters in drive systems are the diode, the reverse-blocking triode thyristor (which, on the North American continent, at least, has arrogated to itself the generic title of "thyristor"), the triac, and power transistors. The last two types of device perform functions in the power circuit that may be performed equally well by one or more thyristors, and it is usually the power level of the circuit that determines which devices shall be used. In this text only converters with thyristors and diodes are illustrated. When gating signals are shown in a diagram they are appropriate for thyristors. It must be understood, however, that under some circumstances other types of device would be selected. Such change would not modify the operation of the power circuits, which are the subject matter of the book.

Superscripts 1 to 7 in the text refer to the Bibliography.

We must acknowledge our indebtedness to two persons who have helped us greatly. Professor Richard Bonert has used the draft for teaching and taken part in many helpful discussions. Dr. Timothy Miller, Manager of the Adjustable Speed Drives Program in the Research and Development Center of the General Electrical Company, has read and commented in detail on the draft of the text. The errors and inadequacies that remain in the book must be attributed only to the authors. We must also express our gratitude to Mrs. Amelia Ma for many hours of patient and accurate text entry and editing.

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Symbols

In general, upper-case letters are used for direct or constant quantities or for rms values of alternating quantities. Lower-case letters are used for instantaneous values of variables.

A bar over a lower-case symbol ($\bar{a}$) means average value. A bar over an upper-case symbol ($\bar{A}$) means phasor or phasor operator value.

A "hat" over a lower-case symbol ($\hat{a}$) means peak value.

A "prime" added to a symbol (a') means "referred to the stator" (except for I_a' and I_M', for which see list).

A numerical subscript (a_2) indicates harmonic order.

Subscript *sh* (A_{sh}) indicates desired (should) value of a variable.

Subscript *is* (A_{is}) indicates actual value of a variable.

Subscript *R* (A_R) indicates rms or resistive value of a quantity.

Many other subscripts are defined in the following list.

B	viscous friction constant
C	capacitance
C_{eq}	per-phase equivalent capacitance
D	distance
e, E	electromotive force (emf)
e_a, E_a	armature or per-phase stator emf
e_L	inductive emf
E_{ma}	per-phase stator emf
E_{mA}	per-phase rotor emf
E_o	excitation emf
f	force, frequency
F	magnetomotive force
f_s	stator frequency
i_a, I_a	armature or stator current
I_a'	*rotor* current referred to stator
I_A	rotor current
I_{ah}	rms harmonic current
I_c	core-loss current, capacitor current
i_D	diode current

i_f, I_f	field current
i_G	gate current
i_l	line current
I_m	imaginary part
I_{ma}, I_M	magnetizing current
I'_M	field current referred to stator
I_{NL}	no-load current
i_O	converter output current
i_p, I_p	transformer primary current
i_Q	thyristor current
I_R	rms current
I_{REF}	reference current
i_s, I_s	source current
J	rotational inertia
k	dc machine constant
K_i	current ripple factor
k_T	tachometer transfer function
k_{TR}	transducer transfer function
L	inductance
L_a	armature inductance
L_f	field inductance
L_{ls}	per-phase stator leakage inductance
L_{lr}	per-phase rotor leakage inductance
L_L	per-phase leakage inductance
L_{ms}	per-phase magnetizing inductance
m	$E_a/\sqrt{2}$ V
n	motor speed, harmonic order
n', n''	effective turns ratio
N	number of turns
N_{re}	effective rotor turns
N_{se}	effective stator turns
p	number of poles
P	active power
P_a	armature power
P_{amech}	per-phase mechanical power
P_{FL}	full-load input power
P_{FW}	friction and windage power
P_I	inverter power rating
P_{in}	input power
P_{ma}	per-phase stator power
P_{mA}	per-phase rotor power
P_{mech}	mechanical power
P_R	resistive losses
P_{SL}	stray load loss
P_o	output power

P_w	work power
PF	power factor
PF_l	supply-system power factor
PF_1	fundamental power factor
R	resistance
R_a	armature resistance
R_c	per-phase core-loss resistance
R_d	external armature-circuit resistance
Re	real part
R_{ex}	per-phase external rotor-circuit resistance
R_f	field resistance
R_{in}	per-phase motor input resistance
R_r	per-phase rotor resistance
R_s	per-phase stator resistance
s	Laplace operator, slip
S	apparent power
t	time
T	torque, air-gap torque
T_B	viscous-friction torque
T_C	coulomb friction torque
t_d	dead time
T_F	friction torque
T_J	inertia torque
T_{loss}	loss torque
T_L	load torque
t_{off}	turn-off time
t_{ON}	conduction time
T_p	periodic time
t_q	time-available for turn-off
T_s	starting torque
T_S	static friction torque
T_W	work torque
t_α	delay time
v, V	potential difference (pd)
V_a	per-phase stator terminal pd
V_A	per-phase rotor terminal pd
v_{AK}	anode-to-cathode pd
v_f, V_f	field terminal pd
v_{LK}, V_{LK}	dc link pd
v_s, V_s	source pd
v_t, V_t	armature terminal pd
v_O	converter output pd
v_p, V_p	transformer primary pd
v_R	resistive pd
v_T	tachometer or transducer pd

X_d	per-phase direct-axis reactance
X_{in}	per-phase motor input reactance
X_{lr}	per-phase rotor leakage reactance
X_{ls}	per-phase stator leakage reactance
X_L	per-phase leakage reactance
X_q	per-phase quadrature-axis reactance
X_s	per-phase synchronous reactance
X_{ms}	per-phase magnetizing reactance
Z	impedance
Z_A	per-phase rotor impedance
Z_{ex}	per-phase external rotor-circuit impedance
Z_{in}	per-phase motor input impedance
Z_{ms}	per-phase magnetizing-branch impedance
Z_s	per-phase stator impedance
α	delay angle, phase angle
β	extinction angle, rotor position
γ	conduction angle
ζ	damping factor
η	$\sin^{-1}(E_a/\sqrt{2}\ V)$ efficiency
ϑ	angular displacement, phase angle
μ	angle of overlap
v	translational speed
τ	time constant
τ_a	armature electrical time constant
τ_m	armature mechanical time constant
φ	flux per pole, impedance angle
Φ	flux per pole
ψ	phase angle
ω, Ω	angular speed, angular frequency
ω_b	base speed, base frequency
ω_f	filter resonance frequency
ω_m, Ω_m	motor angular speed
Ω_m	motor speed command
ω_n	natural frequency
ω_o	angular chopping frequency
ω_r	rotor angular frequency
Ω_r	rotor frequency command
ω_s	stator or source angular frequency
ω_{syn}	synchronous speed

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