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Springer-Verlag
Berlin Heidelberg New York Tokyo

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With 270 Figures

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Completely revised and enlarged edition of the German book
„Regelung in der elektrischen Antriebstechnik", Teubner, Stuttgart 1974.
Translated by the author in cooperation with R. M. Davis and R. S. Bowes

ISBN 3-540-13650-9 Springer-Verlag Berlin Heidelberg New York Tokyo
ISBN 0-387-13650-9 Springer-Verlag New York Heidelberg Berlin Tokyo

Library of Congress Cataloging in Publication Data.
Leonhard, Werner, 1926– . Control of Electrical Drives.
Translation of: Regelung in der elektrischen Antriebstechnik.
Bibliography: p. Includes Index. 1. Electric driving. 2. Electric controllers.
3. Electronic controllers. I. Title.
TK4058.L4313 1984 621.46'2 84-14141

Typesetting: Graphischer Betrieb Konrad Triltsch, Würzburg.
Offsetprinting: Brüder Hartmann, Berlin. Bookbinding: B. Helm, Berlin
2061/3020-5 4 3 2 1 0

EESES

Electric Energy Systems and Engineering Series

Editors: J. G. Kassakian · D. H. Naunin

Introduction to the Electric Energy Systems and Engineering Series

Concerns for the continued supply and efficient use of energy have recently become important forces shaping our lives. Because of the influence which energy issues have on the economy, international relations, national security, and individual well-being, it is necessary that there exists a reliable, available and accurate source of information on energy in the broadest sense. Since a major form of energy is electrical, this new book series titled *Electric Energy Systems and Engineering* has been launched to provide such an information base in this important area.

The series coverage will include the following areas and their interaction and coordination: generation, transmission, distribution, conversion, storage, utilization, economics.

Although the series is to include introductory and background volumes, special emphasis will be placed on: new technologies, new adaptations of old technologies, materials and components, measurement techniques, control – including the application of microprocessors in control systems, analysis and planning methodologies, simulation, relationship to, and interaction with, other disciplines.

The aim of this series is to provide a comprehensive source of information for the developer, planner, or user of electrical energy. It will also serve as a visible and accessible forum for the publication of selected research results and monographs of timely interest. The series is expected to contain introductory level material of a tutorial nature, as well as advanced texts and references for graduate students, engineers and scientists.

The editors hope that this series will fill a gap and find interested readers.

John G. Kassakian · Dietrich H. Naunin

Preface

Electrical drives play an important role as electromechanical energy converters in transportation and most production processes. The ease of controlling electrical drives is an important aspect for meeting the increasing demands by the user with respect to flexibility and precision, caused by technological progress in industry.

Conversely, the control of electrical drives has in the past provided strong incentives to control engineering in general, leading to the development of new control structures and their introduction to other areas of control. This is due to stringent operating conditions and widely varying specifications – a drive may alternately require control of torque, acceleration, speed or position – and the fact that most electric drives have – in contrast to chemical or thermal processes – well defined structures and consistent dynamic characteristics.

During the last few years the field of controlled electrical drives has experienced rapid expansion caused mainly by the advances of semiconductors in the form of power electronics as well as analogue and digital signal electronics, eventually culminating in microelectronics and microprocessors. The introduction of electronically switched solid-state power converters has renewed the search for ac motor drives, not subject to the limitations of the mechanical commutator of dc drives; this has created new and difficult control problems. On the other hand, the fast response of electronic power switching devices and their limited overload capacity have made the inclusion of protective control functions essential. The present phase of evolution is likely to continue for many more years; a new steady-state is not yet in sight.

This book, originally published in 1974 in German, was an outcome of lectures the author held for a number of years at the Technical University Braunschweig. In its updated English version it characterizes the present state of the art without laying claim to complete coverage of the field. Many interesting details have been omitted, which is not necessarily a disadvantage since details are often bound for early obsolescence. In selecting and presenting the material, didactic view points have also been considered.

A prerequisite for the reader is a basic knowledge of power electronics, electrical machines and control engineering, as taught in most under-graduate electrical engineering courses; for additional facts recourse is made to special literature. However the text should be sufficiently self contained to be useful also for non-experts wishing to extend or refresh their knowledge of controlled electrical drives.

Controlled electrical drives consist of several parts, the electrical machine, the power converter, the control equipment and the mechanical load, all of which are dealt with in varying depths. A brief resumé of mechanics and of thermal effects in electrical machines is presented in Chaps. 1–4 which would be skipped by the more experienced reader. Chaps. 5–9 deal with dc drives which are today the standard solution when controlled drives are required. This part of the text also contains an introduction to line-commutated converters as used for the supply of dc machines. AC drives are introduced in Chap. 10, beginning with a general dynamic model of the symmetrical induction motor, valid in both the steady-state and transient condition. This is followed in Chap. 11 by an overview of static converters to be employed for ac drives. The control aspects are discussed in Chaps. 12–14 with emphasis on high dynamic performance drives, where microprocessors are proving invaluable in disentangling the multivariate interactions present in ac machines. Chapter 15 finally describes some of the problems connected with the industrial application of drives. This cannot by any means cover the wide field of special situations with which the designer is confronted in practice but some more frequent features of drive system applications are explained there. It should become sufficiently clear that the design of a controlled drive, in particular at larger power ratings, cannot stop at the motor shaft but often entails an analysis of the whole electromechanical system.

In view of the fact that this book is a translation and extension of an application-orientated text in another language, there are inevitably problems with regard to symbols, the drawing of circuit diagrams etc. After thorough consultations with competent advisors and the publisher, a compromise solution was adopted, using symbols recommended by IEE wherever possible but retaining the authors usage where confusion would otherwise arise with his readers at home. A list of the symbols is compiled following the table of contents. The underlying principle employed is that time varying quantities are usually denoted by lower case latin letters, while capital letters are applied to parameters, average quantities, phasors etc; greek letters are used predominantly for angles, angular frequencies etc. A certain amount of overlap is unavoidable, since the number of available symbols is limited. Also the list of references still exhibits a strong continental bias, eventhough an attempt has been made to balance it with titles in english language. The list is certainly by no means complete but it contains the information readily available to the author. Direct references in the text have been used sparingly. It is hoped that the reader is willing to accept these shortcomings with the necessary patience and understanding.

The author wishes to express his sincere gratitude to two English colleagues, R. M. Davis of Nottingham University and S. R. Bowes of the University of Bristol who have given help and encouragement to start the work of updating and translating the original German text and who have spent considerable time and effort in reviewing and improving the initial rough translation; without their assistance the work could not have been completed. Anyone who has undertaken the task of smoothing the translation of a foreign text can appreciate how tedious and time-consuming this can be. Thanks are also due to the editors of this Springer Series, Prof. J. G. Kassakian and Prof. D. H. Naunin, and the publisher for their cooperation and continued encouragement.

Brunswick, October 1984 Werner Leonhard

Abbreviations and Symbols

1. Equations

All equations comprise physical variables described by the product of a unit and a dimensionless number, which depends on the choice of the unit.

Some variables are nondimensional due to their nature or because of normalization (p. u.).

2. Characterization by Style of Writing

$i(t)$, $u(t)$, etc.	instantaneous values
$\bar{i}$, I_d, $\bar{u}$, U_d, etc.	average values
I, U, etc.	RMS-values
$\underline{I}$, $\underline{U}$, etc.	complex phasors for sinusoidal variables
$\underline{i}(t)$, $\underline{u}(t)$, etc.	complex time-variable vectors, used with multiphase systems
$\underline{i}^*(t)$, $\underline{u}^*(t)$, $\underline{I}^*$, $\underline{U}^*$	conjugate complex vectors or phasors
${}^1\underline{i}(t)$, ${}^1\underline{u}(t)$, etc.	vectors in special coordinate systems
$I(s) = L(i(t))$ etc.	Laplace transforms

3. Symbols

Abbreviation	*Variable*	*Unit*
$a(t)$	– current distribution	A/m
	– linear acceleration	m/s^2
	– nondimensional factor	
A	area	m^2
b	nondimensional field factor	
B	magnetic flux density	T
C	– electrical capacity	F
	– thermal storage capacity	J = Ws
D	damping ratio	
$e(t)$, E, $\underline{E}$	induced voltage, e.m.f.	V
f	– frequency	Hz = 1/s
	– force	N
$F(s)$	transfer function	
g	gravitational constant	m/s^2
$g(t)$	unit impulse response	

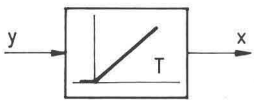
G	– weight	N
	– gain	
h	airgap	m
$i(t), I, \underline{I}$	current	A
J	inertia	kg m^2
k	nondimensional factor	
K	torsional stiffness	Nm/rad
l	length	m
L	inductance	H
$m(t)$	torque	Nm
M	– mass	kg
	– mutual inductance	H
N	number of turns	
$p(t), P$	power	W
Q	reactive power	VA
r	radius	m
R	resistance	Ω
	speed, rev/min	1/min
$s=\sigma+j\omega$	Laplace variable	rad/s
s, x	distance	m
S	slip	
t	time	s
T	time constant	s
$u(t), U, \underline{U}$	voltage	V
$v(t)$	– velocity	m/s
	– unit ramp response	
V	volume	m^3
$w(t)$	unit step response	
x	control variable	
y	actuating variable	
z	disturbance variable	
$z=e^{sT}$	discrete Laplace variable	
Y	admittance	$1/\Omega = S$
Z	impedance	Ω
α	– coefficient of heat transfer	$W/m^2\,°C$
	– firing angle	
	– angular acceleration	
$\alpha, \beta, \delta, \zeta, \xi, \lambda, \mu, \varrho$ etc.	angular coordinates	rad
$\gamma = 2\pi/3$		
δ	load angle	
Δ	difference operator	
ε	angle of rotation	
$\varkappa$	coupling factor	
η	efficiency	
ϑ	temperature	°C
	absolute temperature	K
Θ	magnetomotive force, m.m.f.	A

μ_0	coefficient of permeability	H/m
ν	integer number	
σ	leakage factor	
$\tau = \int \omega \, dt, \omega t$	normalized time, angle	
φ	phase shift	
$\cos \varphi$	power factor	
Φ	magnetic flux	Wb = Vs
ψ	flux linkage	Wb = Vs
ω	angular frequency	Rad/s

4. Indices

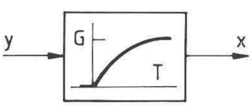
i_a	armature current
i_e	exciting current
u_F	field voltage
i_S	stator current
i_R	rotor current
i_{Sd}, i_{Sq}	direct and quadrature components of stator current
i_{Rd}, i_{Rq}	direct and quadrature component of rotor current
i_m	magnetizing current
i_{mR}	magnetizing current representing rotor flux
m_d	driving torque
m_L	load torque
m_p	pull-out torque
S_p	pull-out slip

5. Graphical Symbols



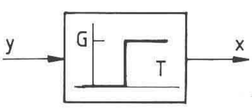
$$x(t) = \frac{1}{T} \int y \, dt$$

integrator



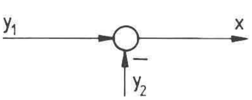
$$T \frac{dx}{dt} + x = G y$$

first order lag



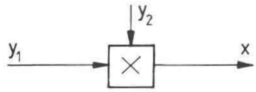
$$x(t) = G y (t - T)$$

delay

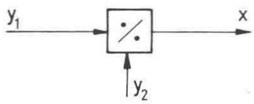


$$x = y_1 - y_2$$

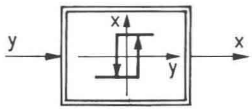
summing point



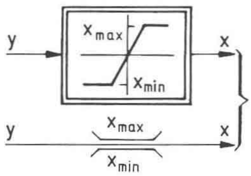
$x = y_1 \, y_2$ multiplication



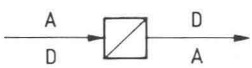
$x = y_1 / y_2$ division



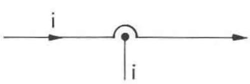
$x = f(y)$ nonlinearity



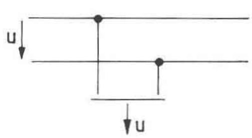
$x = y$ for $x_{min} < y < x_{max}$
$x = x_{min}$ for $y \leq x_{min}$ limiter
$x = x_{max}$ for $y \geq x_{max}$



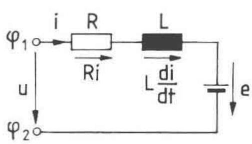
A/D- or *DA*-converter



current sensor



voltage sensor



$$u = R\,i + L\frac{di}{dt} + e$$

The voltage arrows indicating voltage sources (u, e) or voltage drops $\left(R\,i,\ L\frac{di}{dt}\right)$ represent the differences of potential, $u = \varphi_1 - \varphi_2$. They point from the higher to the lower assumed potential. Hence the voltages in any closed mesh have zero sum. $\Sigma\, u = 0$.

Contents

Introduction

Energy is the basis of any technical and industrial development. As long as only human and animal labour is available, a main prerequisite for social progress and general welfare is lacking. The mean energy consumption per capita in a country is thus an indicator of its state of technical development, exhibiting differences of up to two orders of magnitudes between highly industrialized and not yet developed countries.

In latent form, energy is ubiquitous (fossile and nuclear fuels, hydro and tidal energy, solar and wind energy, geothermal energy etc.); however, it must be developed and made available at the point of consumption in suitable form, for example chemical, mechanical or thermal, and at an acceptable price. This creates problems of transporting the energy from the place of origin to the point of demand and of converting it into its final physical form. In many cases, these problems are best solved with an electrical intermediate stage because electricity can be

- generated from primary energy (chemical energy in fossile fuel, potential hydro energy, nuclear energy) in relatively efficient central generating stations,
- transported with low losses over long distance and distributed simply and at acceptable cost,
- converted into any final form at the point of destination.

This flexibility is unmatched by any other form of energy.

Of particular importance is the mechanical nature of energy which is needed in widely varying power ratings wherever physical activities take place, involving the transportation of goods and people or industrial production processes. For this final conversion at the point of utilization, electro-mechanical devices in the form of electrical drives are well suited; it is estimated, that about 60% of the electricity generated in an industrial country is eventually converted to mechanical energy. This predominance is due to several aspects:

- Electric drives are available for any power, from $\ll 1$ W for electronic watches to $> 10^8$ W for driving pumps in hydro storage plants.
- They cover a wide range of torque and speed, $> 10^6$ Nm, for a rolling mill motor, $> 10^5$ 1/min, for a centrifuge drive.
- Electric drives are adaptable to almost any operating conditions such as forced air ventilation or totally enclosed, submerged in liquids, exposed to explosive or radioactive environments. Since electric motors do not require hazardous fuels and do not emit exhaust fumes, electrical drives have no

detrimental effect on their immediate environment. The noise level is low compared with other types of prime movers.

- Electric drives are operable at a moment's notice and can be fully loaded immediately. There is no need to refuel, nor warm-up the motor. The service requirements are very modest, as compared with other prime movers.
- Electrical motors have low no-load losses and exhibit high efficiency; they normally have a considerable short time overload capacity.
- Electrical drives are easily controllable. The steady state characteristics can be reshaped almost at will, so that traction motors do not require speed-changing gears. High dynamic performance is achieved by electronic control.
- Electrical drives can be designed to operate indefinitely in all four quadrants of the torque-speed-plane without requiring a special reversing gear (Fig. 0.1). During braking, i.e. when operating in quadrants 2 or 4, the drive is normally regenerating, feeding power back to the line. A comparison with combustion engines or turbines makes this feature look particularly attractive.

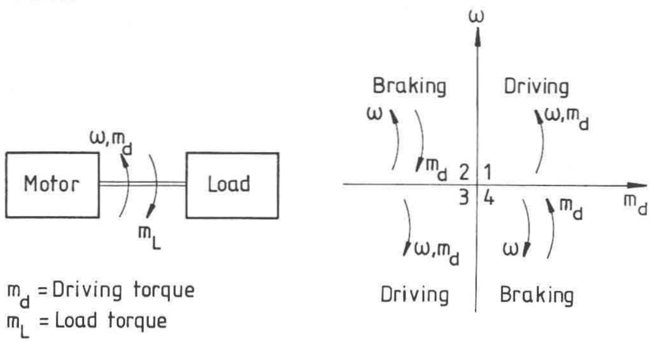


Fig. 0.1. Operating modes of an electric drive

- The rotational symmetry of electrical machines and (with most motors) the smooth torque result in quiet operation with little vibrations. Since there are no elevated temperatures causing material fatigue, long operating life can be expected.
- Electrical motors are built in a variety of designs to make them compatible with the load; they may be foot or flange mounted, or the motor may have an external rotor etc. Machine-tools which formerly had a single drive shaft and complicated mechanical internal gearing can now be driven by a multitude of individually controlled motors producing the mechanical power exactly where, when and in what form it is needed. This has removed constraints from machine tool designers.
  In special cases, such as propulsion of vehicles, linear electric drives are also available.

As would be expected, this long list of remarkable characteristics is supplemented by disadvantages of electric drives which limit or preclude their use.