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Vector Control of Three-Phase AC Machines

System Development in the Practice

Second Edition

Springer

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ISSN 1612-1287 ISSN 1860-4676 (electronic)
Power Systems
ISBN 978-3-662-46914-9 ISBN 978-3-662-46915-6 (eBook)
DOI 10.1007/978-3-662-46915-6

Library of Congress Control Number: 2015936679

Springer Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer-Verlag GmbH Berlin Heidelberg is part of Springer Science+Business Media
(www.springer.com)

Dedicated to my parents, my wife and my son

Nguyen Phung Quang

To my mother in grateful memory

Jörg-Andreas Dittrich

Preface to the Second Edition

The authors could perceive in the years following the publication of the first edition, that the book has been received very favourably worldwide thanks to the engineering-friendly balance between theoretically complicated interrelations and practice-relevant design guidelines. Since the first edition in 2008, more than 5 years have passed, and the technological development has not been idle. With respect to nonlinear control structures, many new developments have been introduced. This is the motivation for the authors to incorporate the new knowledge into the second edition, so that the book would not only be maintained in a timely manner, but also reflect the *state of the art* in the field.

In this second edition, the concept of degree of freedom in vector modulation is introduced in Sect. 2.6 to complete the inverter control topic. Especially, the concept of flatness-based controller design for systems with three-phase AC machines is presented in an easy to understand and pragmatical way. The idea of flatness-based control is presented first in Sect. 3.6.2. Then the flat property of the machine types IM, DFIM and PMSM is proved. Because the authors see themselves as bridge builders between theory and practice, the representation of theoretically complicated contexts which are not easily understood by engineers in the practice is deliberately dispensed with. The concreted designs are introduced in Sects. 9.2.2 for IM, 9.3.2 for PMSM and 11.3 for DFIM. To complete the topic, the important design of the so-called rest-to-rest trajectory for flatness-based tracking control, is presented succinctly in Appendix A.5.

The authors dedicate this second edition to their highly revered teacher Prof. Dr.-Ing. habil. Dr. E.h. Rolf Schönfeld, founder of the Dresden School of *Automated Electrical Drives* at TU Dresden. If he were still alive, he would have celebrated his 80th birthday on June 27, 2014.

The authors wish to thank the German Academic Exchange Service (DAAD) and Prof. Uwe Füssel of TU Dresden for the support in editing this second edition. The authors are grateful for any comments, suggestions for improvement, which should be addressed to N.P. Quang.

Hanoi
Zürich
Summer 2014

Nguyen Phung Quang
Jörg-Andreas Dittrich

Preface to the First Edition

This book covers the area of vector control of three-phase AC machines, in particular induction motors with squirrel-cage rotor (IM), permanent excited synchronous motors (PMSM) and doubly-fed induction machines (DFIM), from the viewpoint of the practical design and development.

The German editions of this book, published in 1993 and 1999 by expert verlag, had been well received by the readers thanks to their practice-oriented and engineer-friendly approach. This experience was motivation for the authors to address now a broader audience with this revised and extended English-language edition. The new chapters take account of the recent developments in AC drive technology on the research side as well as on the application side by dedicating appropriate room for doubly-fed induction machine control and nonlinear drive control.

The book has its clear focus on motor control with the mechanical system and its superposed control loops—speed and position—providing the necessary interface to the machine-specific control functions. The latter form the core of a drive control system and may be divided into two groups:

1. Basic algorithms like space vector modulation, current control and rotor flux estimation.
2. Advanced algorithms like parameter identification, parameter adaptation, optimal state variable control and nonlinear control.

A control system with only the first group implemented may already work satisfactorily. Integration of the second group can improve the system parameters significantly, optimize utilization of machine and frequency converter and support maintenance and commissioning.

After a summary of the basic structure of a field-oriented controlled three-phase AC drive as well as of a grid voltage-oriented controlled wind power plant in Chap. 1, the inverter control by space vector modulation is extensively discussed in Chap. 2 with the help of numerous examples to illustrate the practical application. Based on the basic machine equations, the continuous and the discrete machine models of IM, PMSM and DFIM are derived in Chap. 3. The nonlinearities of the machine models are shown here. Chapter 4 answers some questions regarding feedback acquisition and the practical implementation of field-oriented control. The design of vectorial two-dimensional current controllers using the discrete models is then discussed in detail in Chap. 5 in connection with other essential problems like control variable limitation. Several alternative controller configurations are introduced.

With Chap. 6 the focus passes to the group of advanced control algorithms by attending to problems like determining the machine parameters by calculation from name-plate data and automatic offline parameter identification. Chapter 7 brings the complex of parameter adaptation yet one step further discussing methods of online adaptation of the rotor time constant of IM, an important issue to achieve high utilization of the motor. Questions of energy efficient operation gain increasing importance, especially for high-power drives. Chapter 8 has its emphasis on these problems, particularly addressing issues like efficiency and torque optimal control strategies under consideration of state variable limitations.

Control applications for AC drives usually feature linear algorithms in spite of the machine itself being characterized by a nonlinear process model and of nonlinear operating states (limitation of state variables) to master. Control approaches which take into account system nonlinearities from the outset may fare better in a number of circumstances. One such approach, the exact linearization method, is introduced in Chap. 9 and further deepened for DFIM applications in Chap. 11. Before that, Chap. 10 introduces control concepts for the electrical system of wind power plants with DFIM, an application that has gained widespread importance in recent years.

While compiling this book, the authors had been dedicated to expose the problems as close as possible oriented on practical and implementation-related requirements. The theoretical background is detailed as much as needed to understand the subjects; numerous equations, figures, diagrams and appendices support the detailed description of the design processes.

The book is the result of the research and development practice of the authors over more than 15 years. We hope to provide the readers not only with approaches, but also with reproducible and useful solutions for their systems and problems. The authors will be grateful for any hints and inputs to improve further editions. Please confer with N.P. Quang for remarks regarding Chapters 1–3, 4.1–4.3, 5, 6.1, 6.3, 9–12, and J.-A. Dittrich for Chapters 2.5.3, 3.1.2, 4.4, 6.2, 6.4, 7, 8.

The authors wish to thank the lector of Springer Verlag, Dr. Ch. Baumann, for his friendly and dedicated cooperation for editing this book.

Hanoi — Nguyen Phung Quang
Zürich — Jörg-Andreas Dittrich
Winter 2008

Contents

Formula Symbols and Abbreviations

$\mathbf{A}$	System matrix
$\mathbf{B}$	Input matrix
$\mathbf{C}$	Output matrix
dq	Field synchronous or rotor flux-oriented coordinate system
E	Sensitivity function
$\mathrm{E_I}$, $\mathrm{E_R}$	Imaginary, real part of the sensitivity function
$\mathbf{e}_N$	Vector of grid voltage
$\mathbf{f}$	General analytical vector function
f_p, f_r, f_s	Pulse, rotor, stator frequency
F	Analytical function (formula symbol only used for flatness-based design)
G	Transfer function
G_{fe}	Iron loss conductance
$\mathbf{H}$, $\mathbf{h}$	Input matrix, input vector of discrete system
$\mathbf{h}$	General analytical vector function
$\mathbf{i}_\mu$	Vector of magnetizing current running through L_m
$\mathbf{i}_m$	Vector of magnetizing current
i_{md}, i_{mq}	dq components of the magnetizing current
$\mathbf{i}_N$, $\mathbf{i}_T$, $\mathbf{i}_F$	Vectors of grid, transformer and filter current
$\mathbf{i}_s$, $\mathbf{i}_r$	Vector of stator, rotor current
i_{sd}, i_{sq}, i_{rd}, i_{rq}	dq components of the stator, rotor current
$i_{s\alpha}$, $i_{s\beta}$	$\alpha\beta$ components of the stator current
i_{su}, i_{sv}, i_{sw}	Stator current of phases u, v, w
J	Torque of inertia
$\mathbf{K}$	Feedback matrix, state feedback matrix
$L_f g$	Lie derivation of the scalar function $g(\mathbf{x})$ along the trajectory $\mathbf{f}(\mathbf{x})$
L_m, L_r, L_s	Mutual, rotor, stator inductance
L_{sd}, L_{sq}	d axis, q axis inductance
$L_{\sigma r}$, $L_{\sigma s}$	Rotor-side, stator-side leakage inductance
m_M, m_G	Motor torque, generator torque

$\mathbf{N}$	Nonlinear coupling matrix
p_{Cu}	Copper loss
p_v	Total loss
$p_{v,fe}$, p_{Fe}	Iron loss
P	Analytical function (formula symbol only used for flatness-based design)
Q	Analytical function (formula symbol only used for flatness-based design)
$\mathbf{R}_I$, $\mathbf{R}_{IN}$	Two-dimensional current controller
R_F, R_D	Filter resistance, inductor resistance
R_{fe}	Iron loss resistance
R_r, R_s	Rotor, stator resistance
$R_\psi R$	Flux controller
$\mathbf{r}$	Vector of relative difference orders
r	Relative difference order
$\mathbf{s}$	Complex power
S	Loss function
s	Slip
T	Sampling period Time from the beginning to the end of a movement along a trajectory
T_p	Pulse period
T_r, T_s	Rotor, stator time constant
T_{sd}, T_{sq}	d axis, q axis time constant
t_0, t_E	Starting, ending time
t_D	Protection time
t_{on}, t_{off}	Turn-on, turn-off time
t_r	Transfer ratio
t_u, t_v, t_w	Switching time of inverter leg IGBTs
$\mathbf{u}$	Input vector
$\mathbf{u}_0, \mathbf{u}_1, \ldots, \mathbf{u}_7$	Standard voltage vectors of inverter
U_{DC}	DC link voltage
$\mathbf{u}_N$	Vector of grid voltage
$\mathbf{u}_{N0}$	Neutral point voltage
$\mathbf{u}_s$, $\mathbf{u}_r$	Vector of stator, rotor voltage
u_{sd}, u_{sq}, u_{rd}, u_{rq}	dq components of the stator, rotor voltage
$u_{s\alpha}$, $u_{s\beta}$	$\alpha\beta$ components of the stator voltage
$\mathbf{V}$	Pre-filter matrix
$\mathbf{w}$	Input vector
$\mathbf{x}$	State vector
$\mathbf{x}_w$	Control error or control difference
$\mathbf{y}$	Output vector
$\mathbf{Z}$	State vector
z_p	Number of pole pairs
$\underline{Z}_s$	Complex resistance or impedance

$\alpha\beta$	Stator-fixed coordinate system
$\mathbf{\Phi}$	Transition or system matrix of discrete system
$\boldsymbol{\psi}_\mu$	Main flux linkage
$\boldsymbol{\psi}_p$, $\boldsymbol{\psi}_r$, $\boldsymbol{\psi}_s$	Vector of pole, rotor, stator flux
$\boldsymbol{\psi}'_r$, $\boldsymbol{\psi}'_s$	Vector of rotor, stator flux in terms of L_m
ψ'_{sd}, ψ'_{sq}, ψ'_{rd}, ψ'_{rq}	dq components of the stator, rotor flux
ψ'_{rd}, ψ'_{rq}, $\psi'_{r\alpha}$, $\psi'_{r\beta}$	Components of $\boldsymbol{\psi}'_r$
ψ'_{sd}, ψ'_{sq}	Components of $\boldsymbol{\psi}'_s$
λ_i	Eigenvalue
$\omega, \omega_r, \omega_s$	Mechanical rotor velocity, rotor and stator circuit velocity
ϑ, ϑ_s	Rotor angle, angle of flux-oriented coordinate system
σ	Total leakage factor
φ	Angle between vectors of stator or grid voltage and stator current
μC, μP	Microcontroller, microprocessor
ADC	Analog to Digital Converter
CAPCOM	Capture/Compare register
DFIM	Doubly-Fed Induction Machine
DSP	Digital Signal Processor
DTC	Direct Torque Control
EKF	Extended Kalman Filter
FAT	Finite Adjustment Time
FPT	Flux, Power factor and Torque Calculation
GC	Grid-side Converter or Front-end Converter
IE	Incremental Encoder
IGBT	Insulated Gate Bipolar Transistor
IM	Induction Machine
KF	Kalman Filter
MIMO	Multi Input–Multi Output
MISO	Multi Input–Single Output
MRAS	Model Reference Adaptive System
NFO	Natural Field Orientation
PLL	Phase Locked Loop
PMSM	Permanent Magnet Excited Synchronous Machine
PWM	Pulse-Width Modulation
SISO	Single Input–Single Output
VFC	Voltage to Frequency Converter
VSI	Voltage Source Inverter