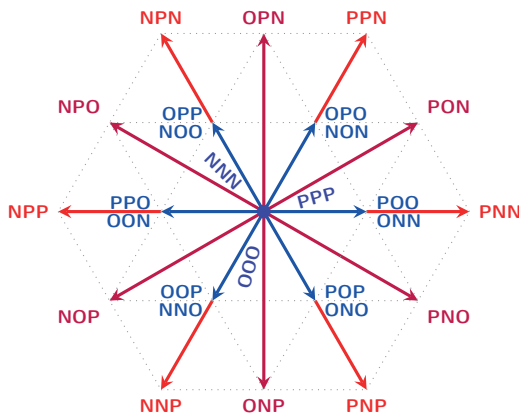


Xinbo Cai

Optimum Control of Electrical Drives and Power Converters

Computational Efficient Optimum Control for Three-Level-Inverters with DC-link Capacitance Balancing





Lehrstuhl für Elektrische Antriebssysteme und Leistungselektronik
der **Technischen Universität München**

Computational Efficient Optimum Control for Three-Level-Inverters with DC-link Capacitance Balancing

Xinbo Cai

Vollständiger Abdruck der von der Fakultät für Elektrotechnik und Informationstechnik
der Technischen Universität München zur Erlangung des akademischen Grades eines

Doktor-Ingenieurs

genehmigten Dissertation.

Vorsitzender:

Prof. Dr.-Ing. Georg Sigl

Prüfer der Dissertation:

1. Prof. Dr.-Ing. Dr. h.c. Ralph Kennel
2. Prof. Dianguo Xu, Ph.D.

Die Dissertation wurde am 18.06.2018 bei der Technischen Universität München eingereicht und durch die Fakultät für Elektrotechnik und Informationstechnik am 07.12.2018 angenommen.

Berichte aus der Elektronik

Xinbo Cai

**Optimum Control of Electrical Drives
and Power Converters**

Computational Efficient Optimum Control for
Three-Level-Inverters with DC-link Capacitance Balancing

Shaker Verlag
Düren 2021

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.

Zugl.: München, Techn. Univ., Diss., 2019

Copyright Shaker Verlag 2021

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-7981-4

ISSN 1436-3801

Shaker Verlag GmbH • Am Langen Graben 15a • 52353 Düren

Phone: 0049/2421/99011-0 • Telefax: 0049/2421/99011-9

Internet: www.shaker.de • e-mail: info@shaker.de

I have a personal philosophy in life: If somebody else can do something that I'm doing, they should do it. And what I want to do is find things that would represent a unique contribution to the world - the contribution that only I, and my portfolio of talents, can make happen. Those are my priorities in life.

Neil deGrasse Tyson (1958-)

Acknowledgment

The research work in this dissertation has been carried out during the years 2014-2017 at the Institute for Electrical Drive Systems and Power Electronics (EAL), Technische Universität München (TUM).

First of all, I would like to thank my supervisor, Prof. Dr-Ing. Ralph Kennel, for all his inspiring guidance, constant encouragement, and support during my study. I really appreciated the freedom during all the stages of my work.

I would also like to thank Prof. Dr-Ing Dianguo Xu, one of the most respectable specialists in the field of power electronics and drives for reviewing and co-examining my dissertation.

An extraordinary gratitude goes out to Shanghai STEP Electric Corporation. In particular, I would like to thank Mr. Defa Ji, the chief executive officer (CEO) of the company, not only for providing the funding which allowed me to undertake this research but also for giving me the opportunity to study abroad.

I also had very fruitful discussions and collaborations with many of my colleagues at EAL, which made my work possible and pleasant. I would especially like to thank Dr-Ing Zhenbin Zhang with whom I worked closely and published several papers. Many thanks to Mr. Dietmar Schuster for his help in my constructing process of the testbench. Those people, such as Dr-Ing. Fengxiang Wang, Dr-Ing. Zhe Chen, Hui Sun, Darshan Manoharan, Guangye Si, Hui Fang, Junxiao Wang, Wei Tian, Xiaonan Gao, Xicai Liu, etc., also deserve thanks for helping me.

The partial financial support of the China scholarship council (CSC) is gratefully acknowledged.

Thanks to all my family for their support.

Munich, Germany
Tuesday 17th April, 2018

Abstract

This work belongs to the optimization of control methods for power converters and electrical drives. Main contributions are as follows: an analytical solution of both continuous and discrete optimum control for power converters and drives is given, focusing on computational efficiency and enhanced performance; a new DC-link voltage balancing method using the deadbeat control concept for three-level neutral point clamped converters is proposed, which is suitable for the control applications using space vector modulation; a simple and effective neutral-point voltage balancing technique is proposed within the model predictive control framework for three-level neutral point clamped converters, which decouples the neutral point voltage balance control and targets current tracking; a fixed gain filter is proposed to estimate the position, velocity, and acceleration in angular motion, with computational efficiency and less tuning effort.

Index Terms— Optimum control, predictive control, fixed gain filter, current control, power converters, electrical drives.

Zusammenfassung

Diese Arbeit befasst sich mit der Optimierung von Regelungsverfahren für Stromrichter und elektrische Antriebe. Die wesentlichen Beiträge der Dissertation sind folgende: Eine analytische Betrachtung von kontinuierlichen als auch diskreten optimalen Regelungen für Stromrichter und Antriebe; dabei wird trotz deutlich reduzierter Rechenleistung ein verbessertes Regelungsergebnis erzielt. Ein neues Konzept zur Regelung der Zwischenkreismittelpunktspannung für Dreipunkt-NPC-Umrichter wird auf Basis eines Deadbeat-Algorithmus vorgeschlagen; dieser Ansatz ist für Regelungen mit Raumzeitmodulation (PWM) geeignet. Weiterhin wird eine einfache und trotzdem wirkungsvolle Regelung der Zwischenkreismittelpunktspannung nach dem Konzept der modellprädiktiven Regelung vorgeschlagen. Dieser Ansatz ermöglicht die Entkopplung von Mittelpunktspannung und Statorströmen. Ein Filter mit konstanten Parametern wird vorgeschlagen, um die Position, die Geschwindigkeit und die Beschleunigung der Rotationsbewegung abzuschätzen. Dieser Ansatz benötigt weniger Rechenleistung und verringert somit den Verarbeitungsaufwand.

Index Terms— Optimale Steuerung, prädiktive Regelung, Filter mit konstanter parameter, Aktuelle Kontrolle, Stromrichter, Elektrische Antriebs.

Contents

Acknowledgment	I
Abstract	III
Zusammenfassung	V
1 Introduction	1
1.1 Research motivation	1
1.1.1 Computational burden	2
1.1.2 Control algorithm	2
1.1.3 Converters	3
1.1.4 Observer and filter	4
1.2 Contributions	4
1.3 Outline	5
2 Background and preliminaries	7
2.1 Nomenclature	7
2.2 Mathematical basics	8
2.2.1 Coordinate transformation	8
2.2.2 Discretization of analog systems	9
2.2.3 Normalization values	11
2.3 Converters	13
2.3.1 Two-level inverter	13
2.3.2 Three-level neutral point clamped inverter	15
2.4 Induction motor	17
2.4.1 Complex representation of induction motor	18
2.4.2 State space representation in dq frame	18
2.4.3 State space representation in $\alpha\beta$ frame	18
2.4.4 Mechanical model	19
2.5 Permanent magnet synchronous motor	19
2.6 Classical control techniques	20
2.6.1 Field oriented control	20
2.6.2 Direct torque flux control	22
2.6.3 Model predictive control	24
3 Optimum control	27

3.1	Motivation	27
3.2	Optimization formulation and solution	29
	3.2.1 Linear system dynamics	29
	3.2.2 Principle problem	30
	3.2.3 Solution of the principle problem	30
3.3	Continuous-control solution of optimum control	31
	3.3.1 Solution of the state transition	32
	3.3.2 Solution of continuous optimum control	32
	3.3.3 Continuous optimum control within constraints	33
	3.3.4 Relationship between COC and DBC	34
3.4	Discrete-control solution of optimum control	34
	3.4.1 Single vector optimum	34
	3.4.2 Two vectors optimum	35
	3.4.3 Multiple vectors optimum	36
3.5	Optimum current control for SPMSM	36
	3.5.1 Unconstrained solution with COC	37
	3.5.2 Constrained solution	38
	3.5.3 Two vectors optimum solution	39
3.6	Experimental results and analysis	39
	3.6.1 Experimental setup	41
	3.6.2 Assessment of control dynamics and steady-state performance	42
	3.6.3 Assessment of disturbance rejection capabilities	43
	3.6.4 Assessment of parameter robustness	43
	3.6.5 Assessment of performance under constraint	45
	3.6.6 Assessment of computation burden	46
3.7	Summary	48
4	Voltage balance of NPC	49
4.1	Neutral Point Current	49
4.2	DBC of neutral-point voltage balance for SVM	51
	4.2.1 Motivation	51
	4.2.2 Space vector based modulation of the three-level NPC	52
	4.2.3 Conventional deadbeat controller design	57
	4.2.4 Case application: Deadbeat controller for neutral-Point voltage balance	58
	4.2.5 Simulation Results	59
	4.2.6 Experimental Results	61
	4.2.7 Summary	62
4.3	Decoupled neutral-point voltage balance for MPC	63
	4.3.1 Motivation	63
	4.3.2 Conventional FCS-MPC controller	65
	4.3.3 Proposed decoupled FCS-MPC controller	66
	4.3.4 Simulation verification	67
	4.3.5 Experimental verification	70
	4.3.6 Summary	76

5	Observers and filters	79
5.1	Luenberger observer	79
5.2	Kalman filter	80
5.2.1	Introduction	80
5.2.2	case study: angular motion system	82
5.3	Fixed gain filter for angular motion system	83
5.3.1	Motivation	83
5.3.2	Gain of the FGF	85
5.3.3	Stability analysis	88
5.3.4	Simulation Assessment	92
5.3.5	Experimental Assessment	96
5.3.6	Summary	100
5.4	Relationship of FGF and Luenberger observer	102
6	Conclusions and future work	105
6.1	Summary	105
6.2	Outlook	106
Appendices		
A	Nomenclature and Abbreviations	107
A.1	Abbreviations	107
A.2	Nomenclatures	110
B	Testbench	113
B.1	Real-time system	113
B.2	Gate driver board	114
B.3	Three-level inverter	116
B.4	DC source	116
B.5	Induction machine	117
B.6	Permanent magnet synchronous motor	117
C	Three level NPC SVPWM	119
C.1	Calculation of triangle 1	119
C.2	Calculation of triangle 2	127
C.3	Calculation of triangle 3	131
C.4	Calculation of triangle 4	139
List of Figures		145
List of Tables		149
Bibliography		149