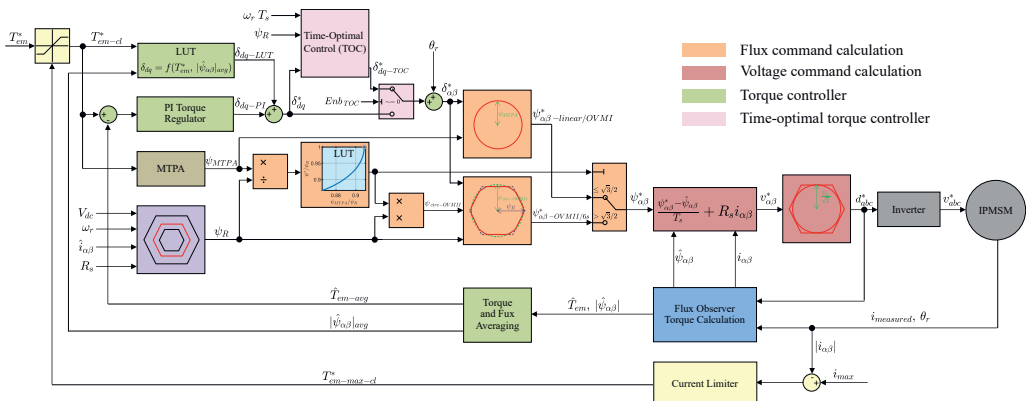


Forschungsberichte Elektrische Antriebstechnik und Aktorik

Hrsg.: Prof. Dr.-Ing. Dieter Gerling

Hadi El Khatib

Deadbeat Flux and Torque Control in the Linear, Overmodulation, and Six-Step Regions for Automotive Traction Applications



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Vollständiger Abdruck der von der Fakultät für Elektro- und Informationstechnik der Universität der Bundeswehr München zur Erlangung des akademischen Grades eines

Doktor-Ingenieurs (Dr.-Ing.)

genehmigte Dissertation.

Prüfungsvorsitzender:

Prof. Dr.-Ing. habil. Thomas Weyh

Gutachter:

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2. Prof. Dr.-Ing. Joachim Böcker

Die Dissertation wurde am 5.12.2022 bei der Universität der Bundeswehr München eingereicht und durch die Fakultät für Elektro- und Informationstechnik am 25.5.2023 angenommen. Die mündliche Prüfung fand am 15.9.2023 statt.

Forschungsberichte Elektrische Antriebstechnik und Aktorik

Band 54

Hadi El Khatib

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Overmodulation, and Six-Step Regions for
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Shaker Verlag
Düren 2023

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, Univ. der Bundeswehr, Diss., 2023

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Printed in Germany.

ISBN 978-3-8440-9319-3

ISSN 1863-0707

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

Abstract

Six-step modulation offers notable advantages over the conventional Space Vector Pulse Width Modulation (SVPWM) in the flux-weakening region. It enhances the torque capability of the machine and guarantees maximum power performance by maximizing battery voltage utilization, a critical component of electric cars due to its high cost. Moreover, the system's efficiency is enhanced by reducing the phase current required for flux weakening and minimizing switching losses. Conversely, under identical operational requirements, it becomes feasible to downsize the battery capacity and/or machine/inverter ratings, leading to cost, weight, and space savings.

This thesis introduces an enhanced Deadbeat Flux Vector Controller (DBFC) as a one single control law capable of operating interior permanent magnet synchronous machines (IPMSMs) across the entire torque-speed range. Stable operation in the full voltage modulation range, including SVPWM, overmodulation (I and II), and six-step, is achieved through precise tracking of various flux trajectories. DBFC enables a continuous and seamless transition between the different operating regions, with the modulation index varying linearly with speed in the constant torque region. With this proposed strategy, undesirable torque dynamics, stability problems, and increased computational efforts, associated with using multiple control laws are completely avoided.

A comprehensive analysis of DBFC's transient performance at the maximum voltage limit (six-step) is conducted. A time-optimal torque control algorithm is developed to achieve the fastest possible torque response, significantly reducing the settling time, particularly when operating at the voltage limit (six-step). The torque can be controlled with high accuracy and high robustness to machine parameter variations. DBFC allows for the control of the instantaneous flux vector, encompassing both steady-state and transient flux trajectories, without requiring trade-offs between steady-state six-step behavior and excellent transient performance. The proposed controller offers significant advantages over conventional Field-Oriented Control (FOC) and it is simpler to implement.

If operation in overmodulation, including six-step, is not desirable based on the application and requirements, another variant of the classical Direct Torque Controller (DTC) can be employed. The operation of the Deadbeat-Direct Torque and Flux Controller (DB-DTFC) is extended to the second flux weakening region by the Square-Root Condition (SRC), ensuring robust and reliable maximum-torque-per-flux (MTPF) operation with a circular flux trajectory. A robust Gopinath flux linkage observer is implemented and evaluated since the flux is a controlled variable for both DBFC and DB-DTFC.

Simulation and experimental results are provided to validate the proposed control strategies, which have been implemented on an automotive microcontroller with a high-power, high-performance automotive traction machine.

Acknowledgment

First and foremost, I am extremely grateful to Audi AG for funding this project and to the Bundeswehr University Munich for providing an exceptional research environment.

I would like to express my sincere gratitude to Prof. Dr.-Ing. Dieter Gerling for offering me this great research opportunity. In addition to the guidance, continuous support, and sage advice, Professor Gerling granted me the autonomy to explore and implement my own ideas throughout the research project. I would also like to express my deepest appreciation to Prof. Dr.-Ing. Joachim Böcker for being the second examiner of this thesis and for the insightful comments and suggestions.

I am deeply indebted to Dr.-Ing. Michael Saur whose inspiration led me into the realm of control of electric drives. I had the pleasure of working with him for more than three years. He provided invaluable support that helped guide this entire project. Without him, I would not have been able to complete this research.

I extend my thanks to Dr.-Ing. Benjamin Grothmann for reviewing this thesis and for his support in extending the PhD project. Special thanks to Dr. Daniel Gaona for motivating me at the beginning of my PhD project and for the valuable and fruitful discussions. Thanks should also go to Emebet Gebeyehu Gedlu, Mario Peña, and Gerardo Pantoja for the great teamwork and the wonderful time at Audi. I would like to extend my sincere thanks to Dr.-Ing. Andreas Joerg, Nils Conzelmann, Martin Adam, and all the Audi colleagues for the invaluable collaboration.

Many thanks to Dr.-Ing. Johann Mayer. The door to his office was always open whenever I needed help. I also thank Dr.-Ing. Harald Hofmann and the rest of the EAA colleagues at the Bundeswehr University Munich for their support.

Words cannot express my gratitude to my parents, my sisters, my future wife Afnan, and the rest of my family for their unconditional love and support. I owe you everything.

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Nomenclature

Symbols

v	Stator voltage	$[V]$
i	Stator current	$[A]$
ψ	Flux linkage	$[Vs]$
T_{em}	Electromagnetic torque	$[Nm]$
ω_{rm}	Mechanical angular speed of the rotor	$[rad/s]$
ω_r	Electrical angular speed of the rotor	$[rad/s]$
n_{rm}	Mechanical angular speed of the rotor (revolutions per minute)	$[min^{-1}]$
L	Inductance	$[H]$
ψ_{pm}	Permanent-magnet flux linkage	$[Vs]$
R_s	Stator resistance	$[\Omega]$
R_i	Iron-loss resistance	$[\Omega]$
P	Number of poles	
V_{dc}	Dc-link voltage	$[V]$
I_{dc}	Dc-link current	$[A]$
ψ_R	Circumradius of the flux hexagon	$[Vs]$
MI	Modulation index	
R_ψ	Average flux magnitude normalized to ψ_R	
V_1	Peak magnitude of the fundamental phase voltage	$[V]$
f_1	Fundamental electrical frequency	$[Hz]$
f_s	Switching frequency	$[Hz]$
N_p	Pulse number	
θ	Angle referred to the $\alpha - axis$	$[rad]$
δ	Angle referred to the $d - axis$	$[rad]$
θ_r	Rotor position	$[rad]$
t	Time (continuous)	$[s]$
T_s	Sampling time	$[s]$
k	Current sample (discrete)	

K_p, K_i	Coefficients of the proportional and integral terms	
$S_{a,b,c}$	Switching states of the three-phase voltage source inverter	
ΔT_{em}	Change in the electromagnetic torque	$[Nm]$
M	Slope of the differential torque line	
B	q-intercept of the differential torque line	$[Vs]$
$-x, -y$	Flux circle center coordinates	$[Vs]$
n_{opt}	Optimal number of time steps to achieve TOC	
P_{cu}	Copper losses	$[W]$
P_i	Iron losses	$[W]$
f_{abc}	Stationary three-phase reference frame	
$f_{\alpha\beta}$	Stationary two-phase reference frame	
f_{dq}	Synchronous two-phase reference frame	
j	Unit imaginary number	
$\odot$	Operating point ($x \in \mathbb{N}^*$)	
$\hat{x}$	Estimated parameter	
x^*	Commanded variable	

Acronyms and Abbreviations

AC	Alternating current
CM	Current model
CO	Current observer
CVC	Current vector control
DB-DTFC	Deadbeat-direct torque and flux control
DBFC	Deadbeat flux vector control
DC	Direct current
DSC	Direct self control
DTC	Direct torque control
EV	Electric vehicle
FO	Flux observer
FW	Flux weakening
HIL	Hardware in the loop
IGBT	Insulated-gate bipolar transistor
IPMSM	Interior permanent magnet synchronous machine
LPF	Low-pass filter
LUT	Lookup table
MOSFET	Metal-oxide-semiconductor field-effect transistor

MTPA	Maximum torque per ampere
MTPF/V	Maximum torque per flux/voltage
MTPL	Maximum torque per loss
OPP	Optimized pulse pattern
OMV	Overmodulation
PI	Proportional–integral controller
PWM	Pulse width modulation
RMS	Root mean square
SR	Square root condition
SVM	Space vector modulation
TOC	Time optimal control
VATC	Voltage angle torque control
VM	Voltage model