Herausgeber:
Univ.-Prof. Dr.-Ing. habil. Dr. h.c.
Kay Hameyer

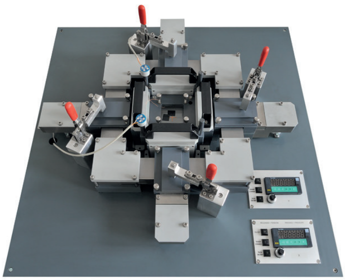
Institut für Elektrische Maschinen

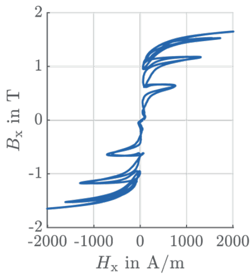
RWTH AACHEN UNIVERSITY

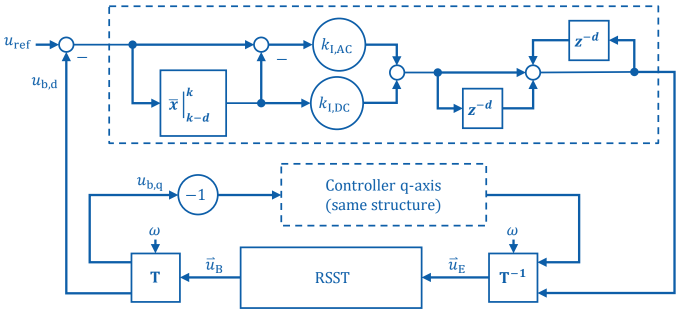
Aachener Schriftenreihe zur Elektromagnetischen Energiewandlung

Andreas Christian Thul

Application of the Principles of Field-Oriented Control for the Measurement and Metrological Characterization of Soft-Magnetic Steel at Rotating Magnetization







SHAKER VERLAG

Band 43

Application of the Principles of Field-Oriented Control for the Measurement and Metrological Characterization of Soft-Magnetic Steel at Rotating Magnetization

Von der Fakultät für Elektrotechnik und Informationstechnik der Rheinisch-Westfälischen Technischen Hochschule Aachen zur Erlangung des akademischen Grades eines Doktors der Ingenieurwissenschaften genehmigte Dissertation

vorgelegt von

Diplom-Ingenieur
Andreas Christian Thul

aus Mönchengladbach

Berichter: Univ.-Prof. Dr.-Ing. habil. Dr. h. c. Kay Hameyer
Prof. D.Sc. Anouar Belahcen

Tag der mündlichen Prüfung: 16. August 2021

Aachener Schriftenreihe zur
Elektromagnetischen Energiewandlung

Band 43

Andreas Christian Thul

Application of the Principles of Field-Oriented Control for the Measurement and Metrological Characterization of Soft-Magnetic Steel at Rotating Magnetization

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.: D 82 (Diss. RWTH Aachen University, 2021)

Aachener Schriftenreihe zur Elektromagnetischen Energiewandlung

Herausgeber:

Univ.-Prof. Dr.-Ing. habil. Dr. h.c. Kay Hameyer
Institut für Elektrische Maschinen
RWTH Aachen
52056 Aachen

Printed in Germany.

ISBN 978-3-8440-8161-9
ISSN 1861-3799

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

Motivation, Goal and Task of the Dissertation

A better understanding of the magnetic circuit behavior and controlling the magnetic material properties are some of the key prerequisites which have facilitated the continuous development and improvement of modern, highly utilized electrical machines and their applications. Concurrently, increased utilization, manufacturing and changed operating conditions will also have an influence on the magnetic material. Modeling the behavior of soft magnetic materials used in electrical machines relies on suitable measurements which are able to determine magnetic properties under conditions similar to those occurring in electrical machines. One example for such conditions is to generate a rotating magnetization and apply mechanical stress to the sample material during the measurement. The behavior of the magnetic circuit for such measurements is strongly influenced by the nonlinear magnetic properties of the sample and its shape. Simultaneously, a sufficient reduction or control of the flux density harmonics is important to obtain valid measurement results. To overcome these difficulties, a control strategy is developed by applying the principles of field-oriented control known from electrical machines and considering the specific operating conditions of the measurement device.

Major Scientific Contributions

In order to obtain a well-funded knowledge base for the control design process, the dynamic interaction between excitation and measured voltage is analyzed. Special attention is given to the impact of nonlinearities and magnetic circuit geometry on said relations. A transient time domain circuit model capable of simulating the nonlinearities of

the measurement is implemented.

The basic control problem of generating a circular rotating magnetization inside the sample is formulated in field-oriented equations and compared to common field-oriented control variations used for rotating electrical machines. Then, the influence of the discussed nonlinearities on the control problem is examined. Based on the results of this analysis, a field-oriented control strategy capable of sufficiently suppressing unwanted flux density harmonics over a wide range of the flux density, is derived. The control strategy is analyzed theoretically and numerically by using the developed model.

A modified coordinate transformation between physical and field-oriented quantities is introduced. With this transformation it is possible to use the same control strategy to generate elliptical and uniaxial magnetizations as well. It is shown that the modified transformation principle can map any rotating flux density distribution with periodically changing amplitude to the circular case. Therefore, the control strategy can be used to generate a wide variety of flux density distributions without changing the basic control structure.

The control strategy is applied to a rotational single sheet tester capable of generating two-dimensional mechanical stress inside the sample. The functionality of the developed control is validated. The influence of different mechanical stress combinations for axial, circular and elliptical flux density distributions on the measurement results is shown.

Danksagung

Diese Arbeit ist im Rahmen meiner Tätigkeit als wissenschaftlicher Mitarbeiter am Institut für elektrische Maschinen der RWTH Aachen entstanden. Zuallererst möchte ich meinem Doktorvater Professor Kay Hameyer für die hervorragende Betreuung meiner Arbeit danken. Für Ihre Unterstützung, Ihren Rat und die viele Zeit und Geduld, die Sie dafür aufgebracht haben, bin ich Ihnen sehr dankbar. Professor Anouar Belahcen danke ich herzlich für das Interesse an dieser Arbeit und die Übernahme des Koreferats.

Die Entwicklung und der Aufbau des in der Arbeit untersuchten Messsystems erfolgte gemeinsam mit der Firma Brockhaus Messtechnik im Forschungsvorhaben *Zweidimensionale Charakterisierung von Elektroblechen unter realen magnetischen und mechanischen Bedingungen einer rotierenden elektrischen Maschine*, welches freundlicherweise durch das Zentrale Innovationsprogramm Mitlelstand (ZIM) gefördert worden ist (Förderkennzeichen KF3464501DF4). Für die Unterstütung und die gute Zusammenarbeit danke ich der Firma Brockhaus sehr. Im Besonderen gilt mein Dank hier Patrick Denke und Dr. Piotr Klimczyk, mit denen ich dieses Projekt gemeinsam bearbeiten durfte.

Der viele fachliche Austausch, die Einblicke in andere Themengebiete und die gegenseitige Unterstützung haben die Arbeit am Institut angenehm und abwechslungsreich gemacht und wesentlich zum Gelingen meiner Promotion beigetragen. Dafür möchte ich allen Kolleginnen und Kollegen am IEM, aber auch meinen studentischen Abschlussarbeitern und Hilfkräften herzlich danken. Im Besonderen seien an dieser

Stelle Stefan Böhmer, Christian Krüttgen, Benedikt Schauerte, Nora Leuning, Fabian Müller und Oliver Knie genannt. Außerdem möchte ich mich bei Petra Jonas-Astor, Isabel Mainz und Denise Boukamp für die viele Hilfe bedanken, die ich von ihnen erhalten habe.

Zu guter Letzt gilt mein Dank meiner Familie, meinem Bruder Simon und meinen Eltern Christa und Bernd. Ihr standet mir zu jeder Zeit mit Rat, Ermunterung und Hilfe zur Seite.

Acknowledgment

This thesis was written during my employment as research associate at the Institute of Electrical Machines of the RWTH Aachen University. I would like to specially thank Professor Kay Hameyer for his excellent supervision of my thesis. I am thankful for your support, your advice and the time and patience you spent providing them. I also cordially thank Professor Anouar Belahcen for the interest in this work and kindly co-reviewing my thesis.

The measurement system investigated in this thesis was designed and built in cooperation with Brockhaus Measurements during a joint research project called *Zweidimensionale Charakterisierung von Elektroblechen unter realen magnetischen und mechanischen Bedingungen einer rotierenden elektrischen Maschine.* The Central Innovation Programme for small and medium-sized enterprises (ZIM) has kindly funded this project (grant number KF3464501DF4). I would like to thank Brockhaus Measurements for the support and the fruitful cooperation during the project. In particular, my thanks go to Dr. Piotr Klimczyk and Patrick Denke, with whom I worked together on this project.

During the time at the IEM I could gather many insights into other topics. The scientific exchange and mutual support among the colleagues at the IEM lead to a pleasant atmosphere and made work exciting as well. Those conditions were important contributions for me to complete my dissertation. For this I would like to cordially thank all colleagues at the IEM, and the students I supervised as well. In particular, I would like to mention Stefan Böhmer, Christian Krüttgen, Benedikt Schauerte, Nora Leuning, Fabian Müller and Oliver Knie in this context. I also would like to thank Petra Jonas-Astor, Isabel Mainz and Denise Boukamp for all the help they provided.

Last but not least, I am very grateful to my family, my brother Simon and my parents Christa and Bernd. You gave me encouragement, advice and help, at any time.

Contents

List of acronyms

FE	finite-element
FEA	finite-element analysis
FEM	finite-element method
FOC	field-oriented control
IEEE	Institute of Electrical and Electronics Engineers
IEM	Institute of Electrical Machines
IM	induction machine
PMSM	permanent magnet synchronous machine
RMS	root mean square
RPT	rotational power loss tester
RSST	rotational single-sheet tester
RWTH	Rheinisch-Westfälische Technische Hochschule
SM	synchronous machine
SST	single-sheet tester

List of symbols

Latin letters

$\mathbf{J}$	1/s	coordinate transformation derivative matrix
$\mathbf{K}$		flux linkage coupling matrix
$\mathbf{L}$	H	self inductance matrix
$\mathbf{M}$	H	mutual inductance matrix
$\mathbf{T}_\theta$		static rotation matrix
$\mathbf{T}_{\mathrm{ax}}$		elliptic stretching matrix
$\mathbf{T}$		generalized transformation matrix
$\mathbf{T}_{\mathrm{dq}}$		transformation matrix to rotating coordinate system
$\mathbf{X}$	H^{-1}	inverse mutual inductance matrix
A	m^2	coil cross-section
B	T	magnetic flux density, magnetic induction
F		form factor of a signal
F	N	force
F_{m}		modified form factor
G		transfer function (Laplace domain)
H	A/m	magnetic field strength
K		flux linkage coupling factor
L	H	self inductance
M	H	mutual inductance
R	Ω	ohmic resistance
T	s	time constant or characteristic time
T_{N}	s	reset time (PI controller)
T_{n}	s	time between controller cycles
T_{p}	s	sample time for one period of data
W		number of turns
X	H^{-1}	inverse mutual inductance

e		error signal or control difference
f	Hz	frequency
i	A	electric current
k_c		controller gain (PI controller)
n		controller cycle index
p		number of data points per period
t	s	time
u	V	electric voltage

Greek letters

r_{ax}	rad	ratio between major and minor axis diameter for elliptical magnetization
Ψ	Vs	flux linkage
α	rad	space vector angle
γ	rad	transformation angle
ϵ		relative deviation of a quantity
θ	rad	angle of the major semi axis for elliptical magnetization or magnetization direction in the uniaxial case
μ	Vs/(Am)	magnetic permeability
ν		order of a harmonic
π		number $\pi = 3.141\,592\,6\ldots$
ω	1/s	angular frequency

Indices and superscripts

ax	axis related
B	flux density measurement coils
d	direct (d) axis
E	excitation coils
H	field strength measurement coils
q	quadrature (q) axis

ref.	reference value
dyn	transient quantity
∞	stationary quantity
x	x magnetization axis
y	y magnetization axis

Notations

$\overrightarrow{x}$	vectorial quantity
$\overline{x}$	dc component of a periodic quantity
$\widetilde{x}$	ac component of a periodic quantity
$\{x\}$	array containing one period of data