

Thyristor-Based High-Power On-Load Tap Changers

Control under Harsh Load Conditions

**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
Stefan P. Engel
aus Lebach

Berichter:

Univ.-Prof. Dr. ir. Dr. h. c. Rik W. De Doncker
Univ.-Prof. Dr.-Ing. Armin Schnettler

Tag der mündlichen Prüfung: 24. November 2016

Stefan P. Engel

Thyristor-Based High-Power On-Load Tap Changers

Control under Harsh Load Conditions

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, 2016)

AACHENER BEITRÄGE DES ISEA

Herausgeber:

Univ.-Prof. Dr. ir. Dr. h.c. Rik W. De Doncker
Leiter des Instituts für Stromrichtertechnik und
Elektrische Antriebe der RWTH Aachen (ISEA)
52056 Aachen

Copyright Shaker Verlag 2017

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 978-3-8440-4986-2

ISSN 1437-675X

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen

Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9

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

Vorwort

Die vorliegende Dissertation entstand während meiner Tätigkeit als wissenschaftlicher Mitarbeiter am Institut für Stromrichtertechnik und Elektrische Antriebe (ISEA) der Rheinisch-Westfälischen Technischen Hochschule Aachen. Die Arbeit befasst sich mit thyristorbasierten Stufenschaltern für Transformatoren und deren Regelung bei verzerrten Lastströmen und gestörten Spannungen.

Bei meiner Arbeit haben mich viele liebe Menschen direkt oder indirekt unterstützt, denen ich an dieser Stelle meinen Dank aussprechen möchte.

Für die Betreuung und Unterstützung meiner Arbeit möchte ich mich sehr herzlich bei meinem Doktorvater Professor Rik W. De Doncker bedanken, insbesondere vor dem Hintergrund, dass momentan alles in Richtung DC zu gehen scheint. Ihm als Institutsleiter gilt auch mein Dank für die vielseitigen, spannenden und herausfordernden Aufgaben, an denen ich während der letzten Jahre arbeiten und wachsen durfte.

Herrn Professor Armin Schnettler danke ich für die bereitwillige Übernahme des Korreferats und das der Arbeit entgegengebrachte Interesse.

Die Arbeit ist im Rahmen eines Projektes mit der AixControl GmbH und der Maschinenfabrik Reinhäusen (MR) entstanden. Ein großer Dank geht an das AixControl-Team, das entscheidend zum Gelingen der Arbeit beigetragen hat, allen voran Jochen von Bloh und Stephan Thomas. Stephan danke ich außerdem für die wertvollen Anmerkungen beim Korrekturlesen. Weiterhin möchte ich mich bei Herrn Dr. Karsten Viereck und Andrey Gavrilov von MR für die ausgezeichnete Zusammenarbeit bedanken.

Allen ISEAnern gilt mein Dank für die ausgesprochen angenehme Arbeitsatmosphäre am Institut. Ein besonderer Dank geht an Nils Soltau für die gemeinsamen Arbeiten an unseren Veröffentlichungen, und an meine langjährigen Bürokollegen Thomas Butschen, Marco Stieneker und Hauke van Hoek für die fachlichen Diskussionen, die gute Gemeinschaft und so manchen erheiternden Moment.

Ganz besonders danke ich meinen Eltern, die mich immer unterstützt und gefördert haben, und die dadurch den entscheidenden Grundstein für diese Arbeit gelegt haben. Zu guter Letzt möchte ich von Herzen meiner lieben Frau Agnethe für ihre Liebe und ihre uneingeschränkte Unterstützung danken.

Aachen, im Dezember 2016

Stefan Engel

Abstract

Photo-voltaic installations and wind farms are erected faster than network extension can be realized. Furthermore, the volatile nature of these renewable power sources leads to increased voltage fluctuations in the connected medium-voltage and low-voltage ac grids. Mechanical on-load tap changers are widely used to keep the voltage in these grids within prescribed limits. However, mechanical on-load tap changers are not designed for the high number of switching cycles that are required in grids that have high capacity on volatile sources. Their contacts can only handle a limited number of switching actions during their lifetime.

This thesis investigates fully electronic on-load tap changers that are capable of switching extremely fast and that exhibit virtually no wear due to switching actions.

In the first part of the thesis, topologies of classical mechanical and modern solid-state on-load tap changers are reviewed and their operation principles are outlined. Different types of switching cells and configurations of solid-state on-load tap changers are compared. It is shown that modularized topologies tend to have a lower number of solid state switches and taps and that the required blocking voltage of the switches is lower compared to less modular topologies.

Different semiconductor switching devices are briefly discussed and the choice for the thyristor, which features a high current capability and low losses at a reasonable cost, is motivated. An anti-parallel connection of two thyristors is used to obtain a bidirectional ac switch.

A generalized approach for the control of the commutation process is elaborated in the second part of the thesis. The complex switching process is outlined for different load cases with ideal voltage and current waveforms and a simplified model of the transformer winding. A generalized control approach is developed that reduces all possible commutations to two basic commutation processes.

In the third part, disturbances of load current and grid voltage are investigated. The disturbances that can be expected during operation are derived based on relevant standards and application-specific conditions. Furthermore, the influence of the transfer characteristics of the transformer with focus on the cross coupling of the windings is studied. Successively, a robust control is developed. The new control scheme uses separate gate trigger signals for each thyristor of a bidirectional thyristor pair. Thereby, safe commutation at highly disturbed load currents is achieved. Robustness against voltage disturbances is accomplished by a new zero crossing predictor for the grid voltage. Undesired short-circuits from tap to tap during commutation are avoided effectively. Consequently, the stress on the switching elements is reduced significantly.

Based on the previous investigations, design rules for thyristor-based tap changers and the corresponding transformers are derived.

A detailed simulation model of transformer and tap changer is synthesized in the last part of the thesis. The model is exemplary verified using a low-power experimental setup of a 9-step prototype tap changer. The simulation is used to comprehensively test the developed control under highly disturbed load conditions. Basic switching tests are performed on a 27-step prototype with a nominal regulating range of ± 7600 V and a current capability of 950 A.

Contents

Abstract	vii
1 Introduction	1
1.1 Objective of the Work	4
1.2 Outline	4
2 Topologies of On-Load Tap Changers	7
2.1 Mechanical On-Load Tap Changers	7
2.2 Semiconductor-Assisted Tap Changers	9
2.3 Solid-State Tap Changers	10
2.3.1 Reference Criteria	10
2.3.2 Solid-State Switching Cells	11
2.3.3 Comparison of Solid-State Tap Changer Topologies	15
2.3.4 Commutation Cells	18
2.4 Summary	20
3 Bidirectional Solid-State Switches	21
3.1 Overview	22
3.1.1 Devices with Turn-Off Capability	22
3.1.2 Non-Turn-Off Thyristor Devices	22
3.1.3 Conclusions and Component Selection	23
3.2 Thyristors	24
3.3 Snubbers and Surge Protection	25
3.4 Summary	26
4 Commutation under Ideal Conditions	27
4.1 Definitions	27
4.2 Requirements of the Commutation Control	29
4.3 Fundamental Commutation Logic	29
4.3.1 Commutation of a Single Commutation Cell	30
4.3.2 Simultaneous Commutation of Both Commutation Cells	32
4.4 Commutation Type I: Normal Commutation	34
4.4.1 Inductive Phase Shift	38
4.4.2 Distinctly Capacitive Phase Shift	38
4.5 Commutation Type II: Short-Circuit Commutation	48
4.5.1 Slightly Capacitive Phase Shift	48
4.5.2 Very Small Capacitive Phase Shift	53
4.6 Summary	54

5 Control under Distorted and Unbalanced Conditions	55
5.1 Distorted Phase Current	55
5.2 Distorted Grid Voltage	57
5.2.1 Rapid voltage changes	57
5.2.2 Load Fluctuations at the Point of Common Coupling	58
5.3 Transfer Characteristics of the Transformer	59
5.3.1 Admittance Matrix	60
5.3.2 Voltage Measurement and Load Estimation	61
5.3.3 Effective Leakage Inductance and Induced Voltage	63
5.4 Non-Ideal Behavior of Semiconductor Switches	67
5.5 Voltage Zero Crossing Prediction	68
5.5.1 New SOGI-QSG-based Zero Crossing Predictor	69
5.5.2 Voltage Estimation during Commutation	72
5.5.3 Estimation of the Grid Voltage	74
5.6 Robust Commutation Control	78
5.6.1 Strategy 1: Normal Commutation	78
5.6.2 Strategy 2: Short-Circuit Commutation via Short-Term Short Circuit	80
5.6.3 Decision Mechanism	86
5.6.4 Block Diagram	86
5.7 Summary	87
6 Verification	89
6.1 Specification of the Prototypes	89
6.1.1 Small-Scale Prototype	89
6.1.2 High-Voltage High-Power Prototype	92
6.1.3 Control Hardware	95
6.2 Simulation Model	96
6.2.1 Control	96
6.2.2 Transformer Model	96
6.2.3 Thyristor Model	96
6.3 Measurements and Simulation	97
6.3.1 Small-Scale Prototype: Experiment and Simulation	97
6.3.2 High-Power Prototype: Experiment	107
6.4 Summary	113
7 Conclusions and Outlook	115
A Appendix	119
A.1 Mathematical Formulas	119
A.2 Firing Angle α for Commutation at Capacitive Load while S_3 is conducting .	121
A.3 Simulation of Simultaneous Commutation	121
A.4 Sample Transformer	123
A.5 Smooth Noise-Robust Differentiator	124
A.6 Derivation of the Thyristor Currents during Simultaneous Commutation .	124

A.7 Transient Simulation of Multi-Winding Transformers	125
A.7.1 Derivation of a Transient Simulation Model from the Impedance Matrix of a Transformer	126
A.7.2 Stability of the Transient Simulation Model	127
A.8 Commutation Considering Resistance and Threshold Voltage	129
List of Abbreviations	133
List of Symbols	135
List of Figures	141
List of Tables	145
Bibliography	147
Index	155
Curriculum Vitae	157