

Technische Universität München
Fachgebiet Verteilte Messsysteme

Ferrimagnetic Fiber-Optic Sensor System for Lightning Detection on Wind Turbines

Sebastian Gerhard Maxim Krämer

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: Univ.-Prof. Dr.-Ing. Rolf Witzmann

Prüfer der Dissertation: 1. Univ.-Prof. Dr.-Ing. Fernando Puente León
 2. Univ.-Prof. Dr.-Ing. Norbert Schwesinger

Die Dissertation wurde am 02.06.2008 bei der
Technischen Universität München eingereicht und durch die Fakultät
für
Elektrotechnik und Informationstechnik am 17.09.2008 angenommen.

Berichte über Verteilte Messsysteme

Band 4

Sebastian G. M. Krämer

**Ferrimagnetic Fiber-Optic Sensor System
for Lightning Detection on Wind Turbines**

Shaker Verlag
Aachen 2008

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., 2008

Copyright Shaker Verlag 2008

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 978-3-8322-7711-6

ISSN 1864-6379

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

Contents

Preface	5
1 Introduction	7
2 Wind energy generation	11
2.1 Global wind energy development	11
2.2 Wind turbine technology	13
2.3 Damage statistics	17
3 Lightning—physics and effects	23
3.1 Physics of lightning	23
3.2 Lightning current characteristics	25
3.3 Lightning effects on wind turbines	30
3.4 Lightning protection for wind turbine blades	34
3.5 State-of-the-art lightning measurement systems	36
3.5.1 Lightning current measuring sensors	37
3.5.2 Lightning measurement setups for research	38
3.5.3 Commercial lightning detection system for wind turbines	39
4 Fiber-optic sensors—materials, their properties and applications	43
4.1 Classification of fiber-optic sensors	43
4.2 Foundations of optical fiber technology	44
4.2.1 Optical guidance	44
4.2.2 Polarization in optical fibers	51
4.2.3 Birefringence	54
4.2.4 Loss mechanisms in optical fibers	54
4.2.5 Commercially available optical fibers	58
4.2.6 Nonlinear optics	60
4.3 Fiber-optic magnetic field sensors	60
4.3.1 Faraday effect	62

4.3.2	Verdet constant	63
4.3.3	Ferro- and ferrimagnetic materials	65
4.3.4	Magnetic garnets	67
5	Lightning detection system	71
5.1	System architecture	72
5.2	Components	75
5.2.1	Light source	75
5.2.2	Fiber-optic sensing device	80
5.2.3	Optical-to-electrical converter	83
5.2.4	Fiber-optic components	84
5.2.5	Data acquisition and data processing	86
5.3	Software structure	89
5.4	Data fusion	90
5.4.1	Processing architectures	93
5.4.2	Data fusion methods	94
5.4.3	Parameter estimation	98
6	System validation and limitations	107
6.1	System calibration	107
6.2	Temperature sensitivity	111
6.3	Mechanical shock resistance	113
7	Advanced combined fiber-optic sensor systems	117
7.1	Fused fiber-optic lightning and health monitoring system for wind turbines	118
7.1.1	Fiber-Bragg gratings for wind turbine monitoring .	118
7.1.2	Combined fiber-optic sensor setup	119
7.1.3	Backscattering spectrum on part of the LDS . .	120
7.1.4	Optimal wavelength area for FBG integration .	120
7.2	Combined distributed temperature sensing and current monitoring	120
7.2.1	Raman light scattering and distributed temperature sensing	122
7.2.2	Proposed combined fiber-optic sensor system . .	125
7.2.3	Experimental setup and discussion	125
8	Conclusion and outlook	133

A List of abbreviations	135
Bibliography	138