



## Behavior of Rubber Materials under Exposure to High Electric Fields

**Candela Garolera, Anna; Holbøll, Joachim; Henriksen, M,**

*Published in:*  
Proceedings of the 23rd NORDIC INSULATION SYMPOSIUM

*Publication date:*  
2013

*Document Version*  
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

*Citation (APA):*  
Candela Garolera, A., Holbøll, J., & Henriksen, M. (2013). Behavior of Rubber Materials under Exposure to High Electric Fields. In *Proceedings of the 23rd NORDIC INSULATION SYMPOSIUM* (pp. 175-178)

---

### General rights

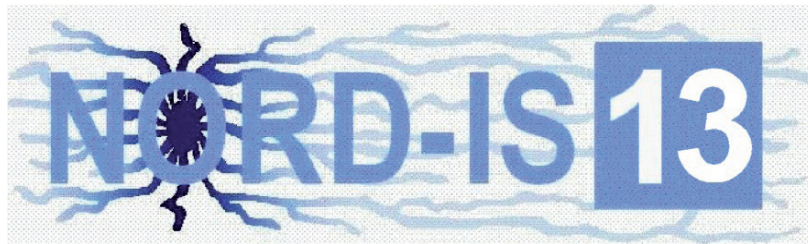
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

**Proceedings of the**

**23<sup>rd</sup> NORDIC INSULATION  
SYMPOSIUM**



**June 9–12, 2013**  
**Trondheim, Norway**

**Department of Electric Power Engineering**  
**NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY**

© *NORD-IS & Akademiika Publishing, 2013*

*ISBN 978-82-321-0274-7*

*This publication may not be reproduced, stored in a retrieval system or transmitted in any form or by any means; electronic, electrostatic, magnetic tape, mechanical, photo-copying, recording or otherwise, without permission.*

*Layout: The authors*

*Cover Layout: Akademiika Publishing*

*Paper: Gprint 90 gr*

*Printed and binded by AiT Oslo AS*

*Photo cover:*

*Pål Keim Olsen*

*palkeim@ntnu.no*

*We only use environmentally certified printing houses.*

*Akademiika Publishing*

*NO-7005 Trondheim,*

*Norway*

*Tel.: + 47 73 59 32 10*

*www.akademikaforlag.no*

*Publishing Editor: Lasse Postmyr (lasse.postmyr@akademika.no)*

# Preface

This publication contains all the papers presented at the 23<sup>rd</sup> Nordic Insulation Symposium (Nord-IS 13) held in Trondheim, Norway, June 9 - 12, 2013. Before acceptance, the abstracts and then the 44 received papers were reviewed by members of the Organizing Committee and the Advisory Council with respect to relevance and quality. *Challenges arising from use of HVDC* is selected as the preferential subject for Nord-IS 13. All subjects dealt with at previous Nord-IS are, however, included. This means for example ageing and breakdown phenomena, condition assessment and measurement techniques.

The Symposium is an interdisciplinary forum for open discussion of ideas, research results and practical experiences related to application of insulating materials and systems in electrical power apparatus. It is addressed to PhD students, researchers and engineers working within academia, research institutes, power industry and power utility companies. Nord-IS is held every second year in one of the Nordic countries; Norway, Denmark, Sweden and Finland. Young researchers are particularly encouraged to contribute. English is the working language of Nord-IS and participants from outside the Nordic area are welcome.

I would like to express my gratitude to all those who have worked hard and contributed in many different ways to make Nord-IS 13 possible. Thanks are due to the members of the Organizing Committee and the Advisory Council for their cooperation in planning of the program and acting as session chairmen during the Symposium. I am particularly indebted to PhD fellow Pål Keim Olsen for his invaluable efforts as secretary, executing all the work associated with Nord-IS 13. – Last but not least I would like to thank all authors and participants for making Nord-IS 13 a success.

Trondheim, May 2013

Erling Ildstad

Chairman, Nord-IS 13

# Organizing Committee

Stanislaw Gubanski	Chalmers	Sweden
Joachim Holbøll	Technical University of Denmark	Denmark
Erling Ildstad	Norwegian University of Science and Technology	Norway
Kari Lahti	Tampere University of Technology	Finland

# Advisory Council

Georg Balog	Subsea Cable Consultants	Norway
Jörgen Blennow	Chalmers	Sweden
Hans Edin	Royal Inst. Of Technology	Sweden
Rolf Hegerberg	Sintef Energy Research	Norway
Henrik Hilborg	ABB Corporate Research	Sweden
Claus Leth Bak	Aalborg University	Denmark
Petri Hyvönen	Aalto University	Finland
Anders Jensen	NKT Cables	Denmark
Harri Suonpää	Alstom Grid	Finland
Bjørn Sanden	StatNett	Norway
Juha Laakko	Terichem Tervakoski	Finland

# Secretary

Pål Keim Olsen

Department of Electric Power Engineering, NTNU

NO-7491 Trondheim

Mail: [palkeim@ntnu.no](mailto:palkeim@ntnu.no)

Phone: +47 73594722

Fax: +47 73594279

## History

- 1: 1968 - Nord-PD in Västerås, Sweden
- 2: 1970 - Otnäs, Finland
- 3: 1972 - Trondheim, Norway
- 4: 1974 - Kollekolle, Denmark
- 5: 1976 - Saltsjöbaden, Sweden
- 6: 1978 - Vaasa, Finland
- 7: 1980 - Røros, Norway
- 8: 1982 - Odense, Denmark
- 9: 1984 - Kungälv, Sweden
- 10: 1986 - Hanaholmen, Finland
- 11: 1988 - Trondheim, Norway
- 12: 1990 - Lyngby, Denmark
- 13: 1992 - Västerås, Sweden
- 14: 1994 - Vaasa, Finland
- 15: 1996 - Bergen, Norway
- 16: 1999 - Lyngby, Denmark
- 17: 2001 - Stockholm, Sweden
- 18: 2003 - Tampere, Finland
- 19: 2005 - Trondheim, Norway
- 20: 2007 - Lyngby, Denmark
- 21: 2009 - Gothenburg, Sweden
- 22: 2011 - Tampere, Finland
- 23: 2013 - Trondheim, Norway

# PROGRAM NORD-IS 2013

## Sunday, June 9, 2013

**17:00-19:00 Registration at NTNU. Mounting of Posters**

## Monday, June 10, 2013

**08:00 - 09:00 Registration and mounting of posters**

**09:00 - 09:10 Opening of symposium: Welcome to NTNU by head of department  
prof. Olav Fosso**

**09:10 - 09:40 Opening lecture: "Challenges arising from use of HVDC".....p. XVII**

Erling Ildstad, NTNU, Norway

**09:40 - 10:00 Coffee break and mounting of posters**

**10:00 - 12:00 Session 1 - HVDC Challenges**

Chair: Bjørn Sanden, StatNett (Norway)

**Conduction behavior of polyaniline/elastomer composites and the  
influence of carbon black addition.....p. 3**

Bjørn Sonerud<sup>1</sup>, Knut Magne Furuheim<sup>1</sup>, Staffan Josefsson<sup>1</sup>, Jani Pelto<sup>2</sup>, Marjo  
Ketonen<sup>2</sup>, Outi Härkki<sup>2</sup>

<sup>1</sup> Nexans Norway AS

<sup>2</sup> VTT Technical Research Institute of Finland

**Short and long term behavior of functionally filled polymeric insulating  
materials for HVDC insulators in compact gas-insulated systems.....p. 7**

Michael Tenzer, Maximilian Secklehner, Volker Hinrichsen

*TU Darmstadt, High Voltage Laboratories*

**Comparison of simulated and measured field dependent charge injection  
in mineral oil under dc bias.....p. 11**

Olof Hjortstam, Christian Sonehag, Joachim Schiessling

*ABB Corporate Research*

**Space Charge Accumulation in XLPE versus Temperature and Water  
Content.....p. 15**

Torbjørn Andersen Ve, Frank Mauseth, Erling Ildstad

*NTNU*

**Surface Potential Decay on Silicon Rubber Samples at Reduced Gas Pressure**.....p. 18  
Shahid Alam, Yuriy Serdyuk, Stanislaw Gubanski  
*Chalmers University of Technology*

**Challenges when measuring the DC electric field very close to an insulator surface**.....p. 23  
Birgitta Källstrand<sup>1</sup>, Daniel Borg<sup>1</sup>, Lars Walfridsson<sup>1</sup>, Charles Doiron<sup>2</sup>,  
Kenneth Johansson<sup>1</sup>  
<sup>1</sup> *ABB AB, Corporate Research*  
<sup>2</sup> *ABB Schweiz AG, Corporate Research*

**12:00 - 13:00 Lunch**

**13:00 - 14:15 Poster Session 1 and coffee break**

**14:15 - 15:35 Session 2 - Breakdown and Ageing of Solid Insulation Systems**

Chair: Hans Edin, KTH (Sweden)

**The Effect of DC Electro-thermal Ageing on Electrical Treeing in Polyethylene**.....p. 29  
Adrian Mantsch, Xiangrong Chen, Jörgen Blennow, Stanislaw Gubanski  
*Department of Materials and Manufacturing Technology, Chalmers University of Technology*

**Effect of Film Thickness and Electrode Area on the Dielectric Breakdown Characteristics of Metallized Capacitor Films**.....p. 33  
Ilkka Rytöluoto, Kari Lahti  
*Tampere University of Technology*

**Development of insulation system for variable speed driven motors; performance of a corona resistant magnet wire**.....p. 39  
Tomi Nuorala<sup>1</sup>, Janne Lehtonen<sup>2</sup>, Markus Takala<sup>1</sup>  
<sup>1</sup> *ABB Oy, BU Motors and Generators*  
<sup>2</sup> *ABB Oy, BU Transformers*

**Enhancement of Water Tree Initiation due to Residual and Applied Mechanical Strain on XLPE Cables**.....p. 43  
Erling Ildstad<sup>1</sup>, Simon Årdal Aarseth<sup>1</sup>, Hallvard Faremo<sup>2</sup>  
<sup>1</sup> *NTNU*  
<sup>2</sup> *Sintef Energy Research*

**15:30 - 16:00 Coffee break**



**16:00 - 17:00 Session 3 - Breakdown and Ageing of Solid Insulation Systems**

Chair: Jørgen Blennow, Chalmers (Sweden)

**Thermal Ageing of XLPE Cable Insulation under Operational Temperatures – Does It Exist?**.....p. 49

Rasmus Olsen<sup>1</sup>, Joachim Holboell<sup>2</sup>, Mogens Henriksen<sup>2</sup>, Jens Hansen<sup>3</sup>

<sup>1</sup> *Energinet.dk*

<sup>2</sup> *Technical University of Denmark*

<sup>3</sup> *Danish Energy Association*

**Influence of DC Stress Superimposed with High Frequency AC on Water Tree Growth in XLPE Insulation**.....p. 53

Frank Mauseth<sup>1</sup>, Sverre Hvidsten<sup>2</sup>, Hans-Helmer Sæternes<sup>2</sup>, Jørund Aakervik<sup>2</sup>

<sup>1</sup> *NTNU*

<sup>2</sup> *SINTEF Energy Research*

**Influence of antioxidants in epoxy-anhydride resin used for HV applications**.....p. 57

Chau Hon Ho, Emmanuel Logakis, Andrej Krivda

*ABB Switzerland Ltd. - Corporate Research*

**19:00 - 21:30 Symposium opening banquet at Banksalen, Trondheim city centre**

## **Tuesday, June 11, 2013**

**08:00 – 09:00 Mounting of Poster Session 2**

**09:00 - 10:50 Session 4 - Condition Assessment and Test Procedures**

Chair: Petri Hyvönen, Aalto University (Finland)

**On-line condition monitoring importance and evolution.....p. 63**

Nicolaie Fantana  
*ABB DECRC*

**Study of the dielectric response of ester impregnated cellulose for moisture content evaluation.....p. 67**

Andrzej Graczkowski, Jarosław Gielniak, Piotr Przybyłek, Krzysztof Walczak, Hubert Morańda  
*Poznan University of Technology*

**Correction of Geometric Influence in Permittivity Determination.....p. 71**

Xiangdong Xu<sup>1</sup>, Tord Bengtsson<sup>2</sup>, Jörgen Blennow<sup>1</sup>, Stanislaw Gubanski<sup>1</sup>  
<sup>1</sup> *Chalmers University of Technology*  
<sup>2</sup> *Chalmers University of Technology and ABB Corporate Research*

**System for detection and analysis of partial discharges under transient voltage application.....p. 75**

Søren Valdemar Kjær<sup>1</sup>, Joachim Holbøll<sup>2</sup>  
<sup>1</sup> *DONG Energy*  
<sup>2</sup> *Technical University of Denmark*

**VLF testing for High Voltage Cables, state of the art.....p. 79**

Peter Mohaupt, Kurt Misteli, Harald Geyer  
*Mohaupt High Voltage*

**10:50 - 11:00 Coffee break**

**11:00 - 12:00 Poster Session 2**

**12:00 - 13:00 Lunch**

**13:00 – 16:00 Technical visits – NTNU/SINTEF laboratories and Leirfossen Hydro Power Station**

**18:30 - 19:30 Greetings from the Mayor’s Office and Concert in Nidarosdomen**

**19:30 - 20:30 Tour Nidarosdomen**

## **Wednesday, June 12, 2013**

### **09:00 - 10:30 Session 5 Breakdown and Ageing of Liquid Insulation Systems**

Chair: Henrik Hillborg, ABB Corporate Research (Sweden)

**Oil Aging due to Partial Discharge Activity**.....p. 85

Mohamad Ghaffarian Niasar, Respicius Cemence Kizza, Hans Edin

*KTH Royal Institute of Technology, Stockholm*

**Streamer Propagation in a Long Gap in Model Liquids**.....p. 89

Van Dung Nguyen<sup>1</sup>, Hans Kristian Høidalen<sup>1</sup>, Dag Linhjell<sup>2</sup>, Lars E

Lundgaard<sup>2</sup>, Mikael Unge<sup>3</sup>

<sup>1</sup> *Norwegian University of Science and Technology*

<sup>2</sup> *SINTEF Energy Research*

<sup>3</sup> *ABB Corporate Research*

**Investigation of the Static Breakdown Voltage of the Lubricating Film in a Mechanical Ball Bearing**.....p. 94

Abhishek Joshi, Jörgen Blennow

*Chalmers University of Technology, Gothenburg*

**Measurement techniques for identifying polarity dependence of ion injection in transformer oil**.....p. 98

Joachim Schiessling<sup>1</sup>, Deepthi Kubevoor-Ramesh<sup>1</sup>, Yuriy Serdyuk<sup>2</sup>, Olof

Hjortstam<sup>1</sup>

<sup>1</sup> *ABB Corporate Research*

<sup>2</sup> *Chalmers University Gothenborg*

### **10:30 - 10:45 Coffee break**

### **10:45 - 12:05 Session 6 Gaseous and Impregnated Insulation Systems**

Chair: Rolf Hegerberg, Sintef Energy (Norway)

**Mechanical Simulations Regarding the Influence of Paper Insulation Degradation on the Radial Mechanical Strength of Continuously Transposed Conductors for Power Transformers**.....p. 103

Daniel Geißler, Thomas Leibfried

*Institute of Electric Energy Systems and High Voltage Technology at Karlsruhe Institute of Technology (KIT)*

**Effect of High Voltage Impulses on Surface Discharge at the Oil-Paper Interface**.....p. 108

Respicius Clemence Kiiza, Mohamad Ghaffarian Niasar, Roya Nikjoo, Xiaolei

Wang, Hans Edin

*KTH*

**Radial Flow Paths for Oil in Mass Impregnated HVDC Subsea Cables** .....p.112  
Bendik Støa<sup>1</sup>, Erling Ildstad<sup>1</sup>, Magne Runde<sup>2</sup>  
<sup>1</sup> *Norwegian University of Science and Technology*  
<sup>2</sup> *SINTEF Energy Research/Norwegian University of Science and Technology*

**Corona at Large Coated Electrodes**.....p. 116  
Mats Larsson<sup>1</sup>, Olof Hjortstam<sup>1</sup>, Håkan Faleke<sup>1</sup>, Ming Li<sup>1</sup>, Liliana Arevalo<sup>2</sup>, Dong Wu<sup>2</sup>  
<sup>1</sup> *ABB Corporate Research*  
<sup>2</sup> *ABB HVDC*

**12:05 - 13:05 Lunch**

**13:05 - 14:45 Session 7 – Design and Modeling of Electric Components**

Chair: Anders Jensen, NKT Cables (Denmark)

**Strategies for Inclusion of Structural Mass Estimates in the Direct-Drive Generator Optimization Process**.....p. 123  
Matthew Henriksen, Bogi Jensen  
*Technical University of Denmark*

**Estimating Transmission Line Parameters of Three-core Power Cables with Common Earth Screen**.....p. 127  
Yan LI<sup>1</sup>, Peter A. A. F. Wouters<sup>1</sup>, Paul Wagenaars<sup>2</sup>, Peter C. J. M. van der Wielen<sup>2</sup>, E. Fred Steennis<sup>2</sup>  
<sup>1</sup> *Eindhoven University of Technology*  
<sup>2</sup> *DNV KEMA Energy & Sustainability*

**Effects of Ambient Conditions on the Dielectric Properties of Thermally Sprayed Ceramic Coating**.....p. 131  
Minna Niittymäki<sup>1</sup>, Tomi Suhonen<sup>2</sup>, Jarkko Metsäjoki<sup>2</sup>, Kari Lahti<sup>3</sup>  
<sup>1</sup> *Department of Electrical Engineering, Tampere University of Technology*  
<sup>2</sup> *Advanced Materials, VTT Technical Research Centre of Finland*  
<sup>3</sup> *Department of Electrical Engineering, Tampere University of Technology*

**Water Diffusion Barrier – A Novel Design for High Voltage Subsea Cables**.....p. 136  
Knut Magne Furuheim<sup>1</sup>, Susanne Nilsson<sup>1</sup>, Svein Magne Hellesø<sup>2</sup>, Sverre Hvidsten<sup>2</sup>  
<sup>1</sup> *Nexans Norway AS*  
<sup>2</sup> *Sintef Energy Research*

**Robustness Analysis of Classical High Voltage Joint Design Under High Voltage DC Stress**.....p. 140  
Fredrik Fälth<sup>1</sup>, Santhosh Kumar BVMP<sup>2</sup>, Hossein Ghorbani<sup>1</sup>  
<sup>1</sup> *ABB High Voltage Cables*  
<sup>2</sup> *ABB GISL*

**14:45 - 15:00 Closing of the symposium**

**Poster Session 1**

- Charge Decay Measurements on Polymeric Insulation Material under Controlled Humidity Conditions**.....p. 149  
Yvonne Späck, Sarath Kumara, Stanislaw M. Gubanski  
*Chalmers University of Technology*
- Dielectric Breakdown Strength of Polymer Nanocomposites-The Effect of Nanofiller Content**.....p. 153  
Markus Takala  
*ABB Oy, BU Motors and Generators*
- Sensitivity Improvement of Acoustic Partial Discharge Detection Measurements through Wavelet Analysis**.....p. 157  
Demetres Evagorou, Patrick Janus, Mohamad Ghaffarian Niasar, Hans Edin  
*KTH Royal Institute of Technology*
- Comparison of Test Setups for High Field Conductivity of HVDC Insulation Materials**.....p. 161  
Johan Andersson<sup>1</sup>, Villgot Englund<sup>1</sup>, Per-Ola Hagstrand<sup>1</sup>, Carl-Olof Olsson<sup>2</sup>,  
Andreas Friberg<sup>2</sup>  
<sup>1</sup> *Borealis AB*  
<sup>2</sup> *ABB AB, Corporate Research*
- Influence of Applied Voltage and Temperature on the Current through the Alumina-filled poly(ethylene-co-butyl acrylate) Nanocomposites Under Constant Stress**.....p. 165  
Nadja Jaeverberg, Bandapalle Venkatesulu, Lars Jonsson, Hans Edin  
*KTH*
- Mechanical Stress Distribution inside Dry Capacitor Elements**.....p. 169  
Linnea Petersson, Kun Wei, Göran Paulsson, David Stromsten, Johan Ekh  
*ABB AB, Corporate Research*

## Poster Session 2

- Behavior of Rubber Materials under Exposure to High Electric Fields**.....p. 175  
Anna Candela Garolera, Joachim Holböll, Mogens Henriksen  
*Technical University of Denmark*
- Thickness Dependency in Dielectric Breakdown Strength of Biaxially Oriented Polypropylene-Silica Nanocomposite Films**.....p. 179  
Hannes Ranta, Ilkka Rytöluoto, Kari Lahti  
*Tampere University of Technology, Department of Electrical Engineering*
- Lumped-circuit Modeling of Surface Charge Decay in a Needle-plane geometry**.....p. 183  
Xiaolei Wang, Nathaniel Taylor, Mohamad Ghaffarian Niasar, Respicus Clemence Kiiza, Hans Edin  
*KTH*
- Capacitor performance limitations in high power converter applications**.....p. 187  
Walid Ziad El-Khatib, Joachim Holböll, Tonny W. Rasmussen  
*Denmark Technical University*
- Positive Breakdown Streamers and Acceleration in a Small Point-Plane Liquid Gap and Their Variation with Liquid Properties**.....p. 191  
Dag Linhjell<sup>1</sup>, Stian Ingebrigtsen<sup>1</sup>, Lars Lundgaard<sup>1</sup>, Mikael Unge<sup>2</sup>  
<sup>1</sup> *SINTEF Energy Research*  
<sup>2</sup> *ABB Corporate Research*
- Axial Water Ingress MV XLPE Cable Designs with Watertight Barrier**.....p. 197  
Knut Brede Liland<sup>1</sup>, Svein Magne Hellesø<sup>1</sup>, Sverre Hvidsten<sup>1</sup>, Karl Magnus Bengtsson<sup>2</sup>, Arve Ryen<sup>2</sup>  
<sup>1</sup> *SINTEF Energy*  
<sup>2</sup> *NEXANS Norway*
- Modelling of Partial Discharges in Polymeric Insulation Exposed to Combined DC and AC Voltage**.....p. 202  
Pål Keim Olsen, Frank Mauseth, Erling Ildstad  
*Norwegian university of science and technology*



## POSTER SESSION 2

# Behavior of Rubber Materials under Exposure to High Electric Fields

A. Candela, J. Holboell, M. Henriksen

*Technical University of Denmark, Department of Electrical Engineering  
Kgs. Lyngby, Denmark*

## Abstract

The effect of high electrical stress on rubber materials is investigated by performing breakdown tests and tracking resistance tests on selected samples. The study is focused on the relationship between the dielectric strength and the thickness of the samples, as well as the influence of the interfaces between different layers of material. Tracking resistance tests are also performed on the rubber material. The purpose is to provide a complete study of the applicability of the rubber material in thunderstorm environments.

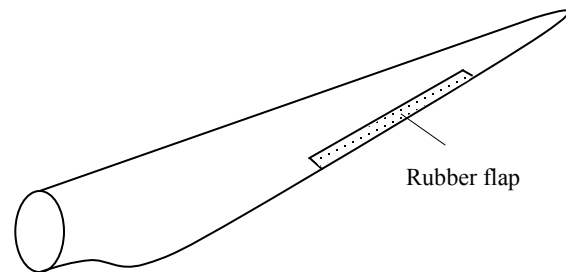
## 1. Introduction

In the recent years, new technologies have been developed to increase the efficiency of wind turbine blades, some of which involve the use of rubber materials in the blade structure. Amongst these technologies, the deformable flaps aim at reducing the load on the blade, thus alleviating the fatigue strain on the whole wind turbine [1]. This is achieved by installing a rubber flap in the trailing edge of the blade (Fig. 1), and controlling its deflection using a compressed-air system. Once installed in the blade, the rubber flap will be subjected to severe ambient conditions. This paper is focused on the effect of high electric fields on the electrical performance of rubber materials.

During their lifetime wind turbines are repeatedly exposed to high electric fields from thunderstorms, which degrade progressively the insulating properties of the blade materials [2]. The interaction between the thunderstorm electric field and the fiberglass material usually used in wind turbines has been widely studied, [3]. However, the behavior of the rubber material in a thunderstorm environment is not fully known and therefore needs to be assessed.

The IEC standard on lightning protection of wind turbines [2] defines the tests to be performed in wind turbines to reproduce the effects of direct lightning strike. However, there is a need for tests aimed at assessing the effects of repeated high electric field and discharge exposure on the insulating materials of the blade. In this study, the rubber behavior under high electric fields is investigated by performing breakdown and tracking resistance tests. These methods have been used previously to evaluate the performance of blade insulating materials against lightning [3], [4]. The criterion used to evaluate the tests results on fiberglass was to affect the material as it was seen in blades in service.

Samples of four different rubber materials have been subjected to breakdown and tracking tests. The samples and setups used in the tests are described in section 2. Section 3 summarizes the test results, comparing the different rubber materials. The relationship between the breakdown strength and the thickness of the samples and the influence of the interfaces between the layers of material are also investigated and described in this section. Finally, the outcome of the tests is discussed in section 5, where the suitability of rubber materials in wind turbine blades is discussed.



**Fig.1** – Wind turbine blade equipped with a rubber flap system, installed on the blade trailing edge.

## 2. Materials and tests description

Four different rubber materials are used for both the breakdown and the tracking resistance tests. These materials are a representative selection of different types of rubber:

- Santoprene 121-73W175 (Polyolefin elastomer)
- Silicone rubber 5060-5
- PUR 8070-3 (Polyurethane)
- EPDM 2165-1 (Ethylene Propylene Diene monomer (M-class))

### 2.1. Breakdown strength tests

The specimens used for this test are square shaped, with a side length of 100 mm. Each material has been tested with a thickness of 1, 2, 3 and 4 mm.

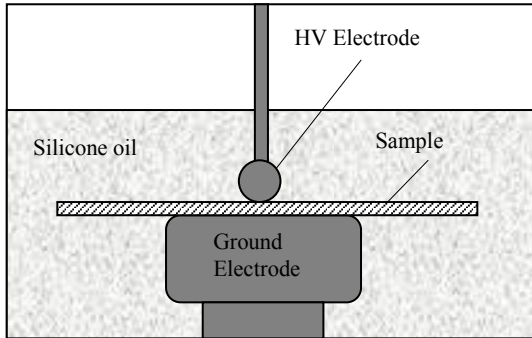
The sample is placed between two electrodes inside a container filled with silicone oil (Fig. 2). The upper electrode is spherical, with a diameter of 12.5 mm, and it is connected to the high impulse voltage generator. The lower electrode is cylindrical with rounded edges, with a diameter of 70 mm, and is connected to ground. The purpose of the silicone oil is to increase the electrical breakdown of the media around the specimen, in order to prevent side flashovers.

The test follows the procedure described in [5]. It consists of applying a high voltage impulse with a rise



time and decay to half value of 1.2 and 50  $\mu$ s respectively, according to [6]. The test starts at relatively low voltage, where there is no risk of breakdown, and it is increased progressively until the breakdown of the material is reached.

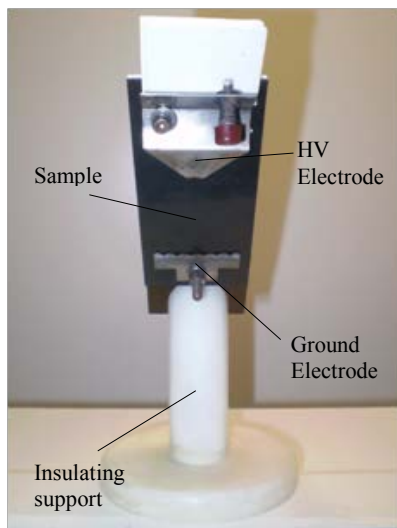
This procedure is repeated 6 times. Each time, the peak value of the voltage impulse that produces breakdown and the peak value of the withstand voltage previous to breakdown are measured. The breakdown and withstand voltages of each material found in section 3 correspond to the average value of the measurements.



**Fig.2** – Breakdown test setup: rubber sample placed between the high voltage and ground electrodes, inside a container filled with silicone oil.

## 2.2. Tracking resistance tests

The setup arrangement and the test procedure follow the standard setup described in [7]. The specimens are mounted on an insulating support, which stands at an angle of 45 degrees from the horizontal. Two electrodes are placed on the top and the bottom of the sample, connected to high voltage and ground respectively (Fig. 3). The specimens are arranged in sets of 5 samples. Each sample is 50 x 120 mm, with a thickness of 2 mm (Fig. 4).



**Fig.3** – Tracking resistance test setup. Sample of rubber material mounted on the insulating support with the electrodes.



**Fig.4** – Tracking resistance test setup. Set of 5 samples mounted on the supports.

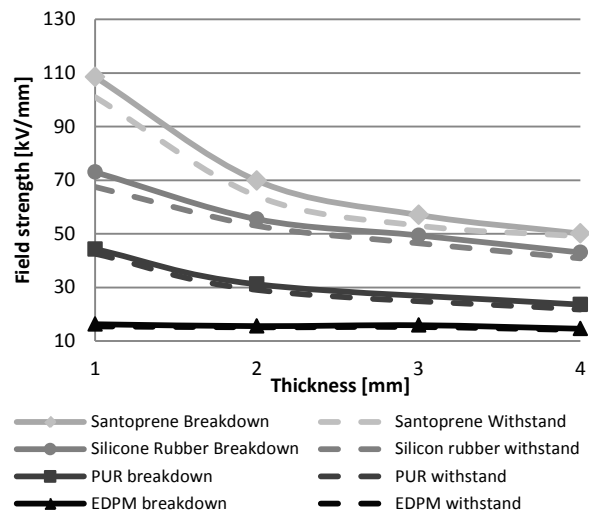
The procedure follows the Method 2, according to [7]: stepwise tracking voltage. It mainly consists of applying a sequence of AC voltage levels across the sample while a contaminant solution based on  $NH_4Cl$  is flowing over the sample lower surface. The initial voltage is chosen in such a way that no sample will fail during the three first steps, and is increased by 250 V every hour. The end-point criterion used in this test is “End-point criterion A: the value of current through the specimen exceeds 60 mA”. In order to determine when the current is over the maximum value allowed, a fuse is installed in the HV circuit of each sample.

## 3. Tests results

This section summarizes the results of the breakdown strength and the tracking resistance tests on the rubber materials.

### 3.1. Breakdown strength tests

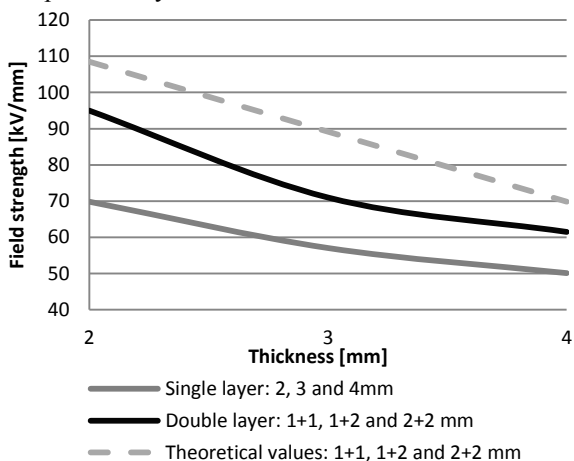
The breakdown strength tests were performed on 6 samples of each thickness, for the four different rubber materials. The average breakdown and withstand voltages for each material and thickness are displayed in Fig 5.



**Fig.5** – Breakdown and withstand field strength of the tested materials, for thicknesses from 1 to 4 mm.

According to the test results, the Santoprene material presents the highest breakdown field strength of 110 kV/mm, followed by silicone rubber showing 72 kV/mm. It is also observed that the breakdown strength decreases when increasing the thickness of the sample. This can be explained by the so-called volume effect, where an increase of the material thickness involves a higher probability of impurities or microscopic defects. These inhomogeneities, normally small particles and air bubbles, enhance the electric field around or inside them, and lead to an earlier breakdown of the material. The volume effect can be found in all the tested materials except the EPDM. Considering that this material shows a very low breakdown strength, the negative influence of possible impurities is less dominant.

In order to study further the volume effect and the influence of interfaces, additional tests were performed to Santoprene, the material showing the highest breakdown strength. These tests consisted of testing two layers of material together. The results were compared to the breakdown strength of a single layer with the same total thickness and with the theoretical calculation of the breakdown strength obtained from the independent layers.



**Fig.6** – Comparison of breakdown field strength between single-layer setup, double-layer setup and theoretical values for the double layer setup calculated from the breakdown strength of the independent layers.

The test reveals that the double-layer setup has higher breakdown strength than the single-layer setup. At a first glance, this may be surprising, since we have an additional interface in the material. On the other hand each layer of the double-layer setup presents fewer impurities per volume than the thicker single-layer, which makes the result more plausible. It is also found that the breakdown strength of the double-layer setup is lower than the value calculated from each independent layer. This fact indicates that in the double-layer setup, the breakdown occurs first in the weakest layer, directly followed by the other layer. Therefore, the weakest layer determines the breakdown of both layers. This phenomenon is more evident in the case of mixed thickness (1+2 mm), where the difference between the

calculated and the actual breakdown strength of the double-layer is greater.

### 3.2. Tracking resistance tests

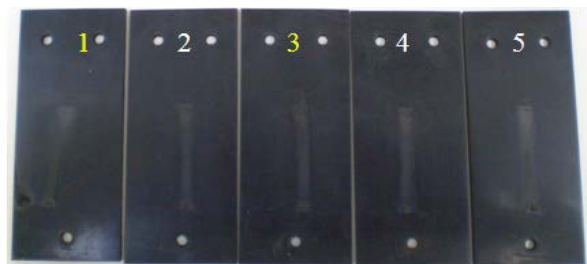
The tracking resistance tests were performed on sets of five samples of the four different materials. Table 1 summarizes the results. The initial and the final voltages are the voltage level applied to the samples at the beginning of the test and the voltage level where the first sample failed, respectively. The classification of the material according to [7] corresponds to IEC Class – Method used to apply the voltage/end-point criterion/maximum level of voltage withstood.

**Table.1** – Tracking resistance tests: classification of the material according to the test results.

Material	Initial voltage [kV]	Final Voltage [kV]	IEC Class
Santoprene	3.5	4.5	2A 4.25 kV
Silicone rubber	3	4.5	2A 4.25 kV
PUR 8070-3	3	4.75	2A 4.5kV
EPDM 2165-1	1	1	Failed

The PUR material reached the highest voltage level before failure, followed by the Santoprene and silicone rubber, which show similar results. The EPDM material failed at the lowest level of voltage, and it is therefore out of the range of the IEC classification.

The end-point criterion chosen for the tracking tests depends only on the level of current flowing through the sample. Still, it is relevant for this investigation to look at the erosion of the samples after the tests, since it varies considerably in materials that withstand a similar level of voltage. Figs. 7 to 10 show the surface erosion of the samples after the tests.



**Fig.7** – Surface erosion in Santoprene rubber material after the tracking resistance tests. Samples 1 and 3 failed.



**Fig.8** – Surface erosion in Silicone rubber material after the tracking resistance tests. Sample 1 failed.



**Fig.9** – Surface erosion in PUR rubber material after the tracking resistance tests. Sample 1 failed.



**Fig.10** – Surface erosion in EPDM rubber material after the tracking resistance tests. All samples failed.

It is seen in the pictures (Figs. 7-10) that all the samples show a matt appearance between the electrodes. However, this band is different in each material, and only some materials present a deep track. The Santoprene and EPDM materials have a narrow track. The Santoprene samples present erosion only next to the bottom electrode, while the EPDM samples have severe erosion in the whole path between the electrodes. The silicone and PUR materials have a wider dry band and no significant erosion. A failed sample of each material is shown in Fig. 11.



**Fig.11** –The surface erosion (marked in yellow) and dry band can be compared in failed samples of each material. From left to right: Santoprene, Silicone rubber, PUR, EPDM.

#### 4. Discussion

In this paper, the assessment of materials is done by comparison of the tests results regarding break down and tracking. Though being relevant for wind turbine flap application, the tests themselves do not directly provide information to determine if the material is suitable for the flap application with respect to interaction with lightning discharges. The breakdown strength tests show that the Santoprene material performs better than the other rubber materials, and its performance is comparable to the fiberglass materials used in wind turbine blades [3]. It is also observed that

the thickness of the sample has a significant impact on the breakdown strength of the material due to the volume effect. Regarding the tracking resistance tests, all rubber materials reach similar levels of voltage, except the EPDM material, which failed at the beginning of the tests. Furthermore, significant differences in erosion are observed in the materials that withstand the same level of voltage. Finally, it has to be considered that a rubber flap installed in a blade in service will be subjected to mechanical fatigue. Therefore mechanical tests should be done with the tested samples in order to evaluate how the erosion due to tracking affects the performance of the material in general.

#### 5. Conclusions

Breakdown and tracking tests were performed on a selection of rubber materials following the same procedure as in GFRP materials for wind turbine blades. The tests results show that the Santoprene material performs better than the other materials, and has comparable properties to the fiberglass material used in blades with respect to tracking resistance and breakdown strength. Therefore, it can be considered as a suitable candidate for wind turbine blade flaps application, regarding its performance in interaction with lightning discharges.

#### 6. References

- [1] Andersen, P.B. “Advanced load alleviation for wind turbines using adaptative trailing edge flaps: sensing and control” Risø – DTU, National Laboratory for Sustainable Energy, Technical University of Denmark, PhD thesis 2010
- [2] “IEC 61400-24 Ed.1.0: Wind turbines – Part 24: Lightning protection”, IEC, June 2010
- [3] Madsen, S.F. “Interaction between electrical discharges and materials for wind turbine blades – particularly related to lightning protection” Ørsted – DTU, Electric Power Engineering, Technical University of Denmark, PhD thesis 2006
- [4] Candela, A. Holboell, J. Henriksen, M. “Breakdown and tracking properties of rubber materials for wind turbine blades”, IEEE International Symposium on Electrical Insulators, June 2012
- [5] “IEC 60060-1 Ed.3.0: High voltage test techniques – Part 1: General definitions and test requirements”, IEC, September 2010
- [6] “IEC 60243-3 Ed.2.0: Electric strength of insulating materials – Test methods – Part 3: Additional requirements for 1,2/50 impulse tests”, July 2001
- [7] “IEC 60587 Ed.3.0: Electrical insulating materials used under severe ambient conditions – Test methods for evaluating resistance to tracking and erosion”, IEC, May 2007

# Author index

Aakervik, Jørund	53	Ildstad, Erling	15, 43, 112, 202
Aarseth, Simon Årdal	43	Ingebrigtsen, Stian	191
Alam, Shahid	18	Jaeverberg, Nadja	165
Andersson, Johan	161	Janus, Patrick	157
Arevalo, Liliana	116	Jensen, Bogi	123
Bengtsson, Karl Magnus	197	Johansson, Kenneth	23
Bengtsson, Tord	71	Jonsson, Lars	165
Blennow, Jörgen	29, 71, 94	Josefsson, Staffan	3
Borg, Daniel	23	Joshi, Abhishek	94
Chen, Xiangrong	29	Ketonen, Marjo	3
Doiron, Charles	23	Kiiza, Respicius Clemence	85, 108, 183
Edin, Hans	85, 108, 157, 165, 183	Kjær, Søren Valdemar	75
Ekh, Johan	169	Krivda, Andrej	57
El-Khatib, Walid Ziad	187	Kubevoor-Ramesh, Deepthi	98
Englund, Villgot	161	Kumar, BVMP Santhosh	140
Evagorou, Demetres	157	Kumara, Sarath	149
Faleke, Håkan	116	Källstrand, Birgitta	23
Fantana, Nicolaie	63	Lahti, Kari	33, 131, 179
Faremo, Hallvard	43	Larsson, Mats	116
Friberg, Andreas	161	Lehtonen, Janne	39
Furuheim, Knut Magne	3, 136	Leibfried, Thomas	103
Fälth, Fredrik	140	Li, Ming	116
Garolera, Anna Candela	175	Li, Yan	127
Geißler, Daniel	103	Liland, Knut Brede	197
Geyer, Harald	79	Linhjell, Dag	89, 191
Ghorbani, Hossein	140	Logakis, Emmanuel	57
Gielniak, Jarosław	67	Lundgaard, Lars	89, 191
Graczkowski, Andrzej	67	Mantsch, Adrian	29
Gubanski, Stanislaw	18, 29, 71, 149	Mauseth, Frank	15, 53, 202
Hagstrand, Per-Ola	161	Metsäjoki, Jarkko	131
Hansen, Jens	49	Misteli, Kurt	79
Hellesø, Svein Magne	136, 197	Mohaupt, Peter	79
Henriksen, Matthew	123	Moraña, Hubert	67
Henriksen, Mogens	49, 175	Nguyen, Dung Van	89
Hinrichsen, Volker	7	Niasar, Mohamad Ghaffarian	85, 108, 157, 183
Hjortstam, Olof	11, 98, 116	Niittymäki, Minna	131
Ho, Chau Hon	57	Nikjoo, Roya	108
Holbøll, Joachim	49, 75, 175, 187	Nilsson, Susanne	136
Hvidsten, Sverre	53, 136, 197	Nuorala, Tomi	39
Härkki, Outi	3	Olsen, Pål Keim	202
Høidalen, Hans Kristian	89	Olsen, Rasmus	49
		Olsson, Carl-Olof	161

Paulsson, Göran	169
Pelto, Jani	3
Petersson, Linnea	169
Przybyłek, Piotr	67
Ranta, Hannes	179
Rasmussen, Tonny W.	187
Runde, Magne	112
Ryen, Arve	197
Rytöluoto, Ilkka	33, 179
Schiessling, Joachim	11, 98
Secklehner, Maximilian	7
Serdyuk, Yuriy	18, 98
Sonehag, Christian	11
Sonerud, Björn	3
Späck, Yvonne	149
Steennis, E. Fred	127
Stromsten, David	169
Støa, Bendik	112
Suhonen, Tomi	131
Sæternes, Hans-Helmer	53
Takala, Markus	39, 153
Taylor, Nathaniel	183
Tenzer, Michael	7
Unge, Mikael	89, 191
Ve, Torbjørn Andersen	15
Venkatesulu, Bandapalle	165
Wagenaars, Paul	127
Walczak, Krzysztof	67
Walfridsson, Lars	23
Wang, Xiaolei	108, 183
Wei, Kun	169
Wielen, Peter C. J. M. van der	127
Wouters, Peter A. A. F.	127
Wu, Dong	116
Xu, Xiangdong	71

