Fluorescence lidar imaging of fungal growth on high-voltage outdoor composite insulators

Bengtsson, Magnus; Grönlund, Rasmus; Sjöholm, Mikael; Abrahamsson, Christoffer; Dernfalk, AD; Wallstrom, S; Larsson, A; Weibring, P; Karlsson, S; Gubanski, SM; Kröll, Stefan; Svanberg, Sune

Published in:
Optics and Lasers in Engineering

DOI:
10.1016/j.optlaseng.2004.09.019

2005

Citation for published version (APA):

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.

Take down policy
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.
Fluorescence lidar imaging of fungal growth on high-voltage outdoor composite insulators

M. Bengtsson\textsuperscript{a,*}, R. Grönlund\textsuperscript{a}, M. Sjöholm\textsuperscript{a}, Ch. Abrahamsson\textsuperscript{a}, A.D. Dernfalk\textsuperscript{b}, S. Wallström\textsuperscript{c}, A. Larsson\textsuperscript{d}, P. Weibring\textsuperscript{e}, S. Karlsson\textsuperscript{c}, S.M. Gubanski\textsuperscript{b}, S. Kröll\textsuperscript{a}, S. Svanberg\textsuperscript{a}

\textsuperscript{a}Department of Atomic Physics, Lund Institute of Technology, P.O. Box 118, SE-221 00 Lund, Sweden
\textsuperscript{b}Department of Electric Power Engineering, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden
\textsuperscript{c}Department of Fibre and Polymer Technology, The Royal Institute of Technology, SE-100 44 Stockholm, Sweden
\textsuperscript{d}Weapons and Protection Division, FOI – Swedish Defence Research Agency, SE-147 25 TUMBA, Sweden
\textsuperscript{e}The National Center for Atmospheric Research, Atmospheric Technology Division, 3450 Mitchell Lane, Boulder, Colorado 80301, USA

Received 4 June 2004; accepted 17 September 2004
Available online 8 December 2004

Abstract

Remote fluorescence imaging of fungal growth on polymeric high-voltage insulators was performed using a mobile lidar system with a laser wavelength of 355 nm. Insulator areas contaminated by fungal growth could be distinguished from clean surfaces and readily be imaged. The experiments were supported by detailed spectral studies performed in laboratory using a fibre-optic fluorosensor incorporating an optical multi-channel analyser system (OMA) and a nitrogen laser emitting radiation at 337 nm.

© 2004 Elsevier Ltd. All rights reserved.

Keywords: Lidar; Fungal growth; Polymeric insulators; Fluorescence; Remote sensing

*Corresponding author. Tel.: +46 46 222 4595; fax: +46 46 222 4250. E-mail address: magnus.bengtsson@fysik.lth.se (M. Bengtsson).
1. Introduction

Modern society is increasingly dependent upon electric power and a reliable electric power transmission is of paramount importance. Thus, when developing new high-voltage outdoor insulators, for instance for support of power lines, these must be proven to withstand the impact from the surrounding environment and have a sufficient lifetime. Over the years, the use of polymeric materials in outdoor insulation has increased steadily [1]. One of the advantages of the polymeric, or composite, insulators over traditional ceramic ones is their light weight, making them easier and cheaper to store, transport, handle and install [2]. Another major advantage of these composite insulators is their low surface-free energy, making their surface hydrophobic and thereby, suppresses the development of a continuous layer of water on their surfaces. Such water layers can trigger a process leading to a surface flashover, which will lead to disconnection and possibly a power outage. As a consequence, a composite insulator has superior electric withstand performance compared to ceramic ones in polluted environments [2].

However, composite insulator performance can possibly be affected by biological growth, such as algae, fungi or lichen, which have been found to colonize insulators all over the world [3]. The presence of algae and fungi have, for instance, been found to decrease wet flashover withstand voltage [4]. Chlorophyll fluorescence from algae on insulators has been investigated remotely in earlier studies [5]. Algal growth, exhibiting a characteristic fluorescence peak due to chlorophyll \(a\) at about 685 nm, could readily be detected from a surface by a frequency-tripled Nd:YAG laser generating radiation at 355 nm. The imaging of algae on insulators [5] followed similar previous investigations, such as fluorescence imaging of vegetation status [6] and the monitoring of vegetation on historical monuments [7,8]. In the present paper, we report on remote fluorescence studies of the fungal growth on insulator surfaces.

2. Instrumentation

A mobile and self-contained light detection and ranging (lidar) system [9], based on all solid-state laser technology and housed in Volvo F610 truck was used. Although the system has multi-wavelength excitation capabilities [10], the present fluorescence experiments were conducted at a single wavelength. The light source used was a frequency-tripled Nd:YAG laser operating at 355 nm with a pulse energy of about 12 mJ. The laser light pulses had a duration of about 4–5 ns and were delivered at a 20 Hz repetition rate.

The light was sent out from the lidar truck, by a roof-top transmission and receiving an optical dome that could be horizontally rotated at 360° using a computer-controlled stepper motor with a resolution of 0.0035°. Similarly, a folding mirror could handle the vertical directionality of the light in the range of \(-10°\) to \(+55°\) with a resolution of 0.011 deg. That corresponds to a resolution of 3.7 and 12 mm, respectively, at the target insulators which were mounted at a 60 m distance.
from the lidar system. The beam diameter at the target was 3 cm as adjusted with a Galilean transmitting telescope and the separation between adjacent measurement points was 3 cm. The change in position of the laser beam at the target due to mechanical instability of the whole truck was estimated to be about 1 cm. The transmitter, dome and light receiving unit are illustrated in Fig. 1.

Part of the laser-induced fluorescence light was captured by a 40-cm-diameter Newtonian telescope via the roof-top transmission and receiving an optical dome and focused into an optical fibre. A BG 385 coloured-glass cut-off filter was inserted in the optical path to block the elastically scattered laser light while passing most of the fluorescence light for wavelengths longer than 385 nm. An optical fibre with a 600 \( \mu \)m core diameter and a numerical aperture of 0.22 guided the fluorescence light to an optical multi-channel analyser system (OMA), consisting of a crossed Czerny–Turner spectrometer, a time-gated image intensifier, and a charge-coupled device (CCD) camera. The Peltier-cooled detector had a CCD array of 1024 \( \times \) 128 pixels where the 128 vertical pixels were binned. The resolution of the OMA system, set by the 100 \( \mu \)m slit width, was 2.2 nm, and the spectrum could be recorded up to 805 nm. A time gate of 40–50 ns was utilized during the experiments.

Fig. 1. Transmitter, dome and light receiving unit.
to suppress ambient light. The time gate was delayed with respect to the transmission of the laser pulse, to match the arrival of the fluorescence burst, some 400 ns later. Spectra from the OMA system were gathered by a data collection computer that stored the spectrum together with information about the measurement coordinates.

The OMA system could also be used separately, without the lidar system, and in that case a nitrogen laser, generating radiation at 337 nm was used as an excitation source. An optical fibre led the light to the target and also guided the fluorescence light back to the OMA system. This set-up has enabled the detailed laboratory studies of fungal growth on the small pieces of silicone rubber insulator material.

The extent of fungal growth on the material samples were estimated using a Jeol JSM-5400 scanning electron microscope (SEM) at an acceleration of 10 kV. Samples were dried in vacuum over night and sputtered with palladium/gold (60%/40%) for 30 s under an argon pressure of 0.5 kp/cm² (49 kPa) and a loading of 45 mA before the analysis.

3. Measurements, analysis and results

Several measurements have been performed, both remotely outdoors using the Nd:YAG laser-equipped lidar system combined with the OMA system and locally using the nitrogen laser-equipped OMA system in the laboratory. First small material samples (diameter ~5 cm) of silicone rubber, where one side of the samples was heavily colonized by fungal growth, were studied in the laboratory. It was observed that the intensity of the fluorescence light was substantially higher from clean surfaces compared to surfaces covered by fungal growth. This observation was previously noticed in an attempt to estimate fungal coverage [5]. However, the absolute intensity recorded in remote measurements is dependent on several factors such as laser pulse energy, laser spot size compared to the area of the sample studied and angle between the studied surface and incident laser beam. Thus, absolute intensity can be difficult to utilize for retrieving an unambiguous information. A more promising approach is to use the spectral shape of the fluorescence spectrum.

An example from the laboratory measurements is displayed in Fig. 2, where it can be seen that the fluorescence spectrum from a fungus-covered sample surface is much wider than the spectrum from a clean sample surface. Only a small variation in the spectral shapes between more or less fungus-covered areas (determined by the naked eye) was observed, indicating that the fluorescence imaging can reveal additional information compared to photographic imaging. Some parts of the rubber surface looked clean, but still showed the response of a fungus-covered area. When these parts were studied under SEM it was found that the studied areas were still infected. This shows that a fungus-covered surface can be partly cleaned but still show the same spectrum, even if it looks clean to the naked eye.

The difference between the fluorescence spectrum of a fungus-covered surface and a clean sample surface is smaller in the remote measurements made by the frequency-tripled Nd:YAG laser-equipped lidar system than in the case of the laboratory measurements, as can be seen when comparing Fig. 3 with Fig. 2. This is probably
Fig. 2. Spectra from a clean; (a) and fungus-covered; (b) sample surface, respectively. The mixed culture originated from an insulator installed in Gothenburg, Sweden, and consisted of Epicoccum nigrum (34%), Cladosporium cladosporides (26%) and Microsphaeriopsis 1 (20%) [11]. The spectra are normalized to have the same intensity around 430 nm. The experiment has been performed by using the nitrogen laser-equipped OMA system.

Fig. 3. Spectra from a clean sample surface and a fungus-covered sample surface can easily be distinguished due to the difference in fluorescence fall-off for longer wavelengths. The wider spectrum originated from the fungal growth. The experiment has been performed by using the lidar system together with the OMA system. Data was obtained by averaging over 200 laser pulses for each sample.
due to the relatively large beam spot size (~3 cm) from the lidar system, which will capture the fluorescence from both clean and fungus-contaminated areas simultaneously. Moreover, the intensities of fluorescence light from the colonized areas are lower than the corresponding intensities from the clean areas, which means that the clean areas are given a higher weight in the surface average. It should also be noted that there was a difference in the excitation wavelength between the laboratory and the remote measurements, which also might have an influence on the spectral shape. To focus on the interesting spectral features of the fluorescence spectra, these have to be intensity normalized in an appropriate way. The fluorescence spectra shown in Figs. 2 and 3 are normalized to have the same intensity in a 10 nm broad interval around 430 nm. However, this is a somewhat arbitrary choice and to more objectively study the spectral shape, a principal component analysis (PCA) [12,13] was performed.

To imitate a real-field measurement, naturally aged insulators were placed at a 60 m distance from the lidar system and fluorescence spectral recordings and imaging were performed remotely. The insulators that were covered by fungal growth were made of silicone rubber (SIR) and ethylene–propylene–diene monomer (EPDM) rubber.

In the PCA, one of the principal components could be used to distinguish a clean surface from a fungus-covered surface. That principal component mainly captures the difference in the fluorescence fall-off towards longer wavelengths between areas with and without fungal growth. However, this fall-off is different for different materials. This means that an obtained spectrum has to be compared to reference spectra from a clean surface and a fungus-covered surface of the same material in order to make it possible to discriminate between fungal growth and clean surface.

Results from imaging fluorescence measurements are presented in Figs. 4 and 5. Fig. 4 shows a fluorescence image of the insulators where the fungus-covered
insulators made of SIR and EPDM are located as the third and the fourth from the top-left. Here, only the average intensity is displayed outlining the insulators. Mean normalized fluorescence spectra obtained from three insulators utilizing the lidar system remotely (light-grey graphs) and compared to spectra collected from clean surfaces in the laboratory (dark-grey graphs) using the same excitation wavelength (355 nm).

To calculate the change in the spectra, PCA data from the fungus-covered SIR insulator and clean surfaces was mean normalized and mean centered. Each spectrum can then be expressed as a sum of the average spectrum, shown in Fig. 6, and the contribution of a principal component, corresponding to the deviation in the spectral shape, shown in Fig. 7. A spectrum from a fungus-covered surface is expressed by a negative contribution of the principal component, but a spectrum from a clean surface adds a positive contribution.
4. Discussion and conclusions

The main goal with this experiment has been to extract information about a potential method for remotely assessing the fungal coverage of insulators. It was found that a fungus-covered surface could be readily detected, imaged and distinguished from a clean surface. Future experiments will include both
algae- and fungus-covered insulator surfaces in the investigations aiming at finding the excitation wavelength giving the best demarcation between algae and fungal growth. The final goal is to perform remote fluorescence imaging in order to get a full status of the insulators and possibly identify the signs of future insulator failure.

Acknowledgements

This work has been partially supported by the Swedish Research Council, FORMAS, Elforsk AB and the Knut and Alice Wallenberg Foundation.

References