FIBRE-OPTIC SENSORS FOR EARLY DAMAGE DETECTION IN PLASTIC INSULATIONS OF HIGH-VOLTAGE FACILITIES

W. R. Habel[1*], U. Buchholz, G. Heidmann[2], M.Hoehse[1], and C. Lothongkam[1]
[1]BAM Federal Institute for Materials Research and Testing,
Unter den Eichen 87, 12205 Berlin, Germany
[2]IPH Institut „Prüffeld für Elektrische Hochleistungstechnik“ GmbH,
Landsberger Allee 378A, 12681 Berlin, Germany
*Email: wolfgang.habel@bam.de

Abstract: Fibre-optic sensors (FOS) have great potential as online damage detectors when integrated in HV accessories. Among their well-known use as temperature and strain sensors, there are some more opportunities of use, e. g. they can intimately be embedded in polymeric insulations of HV cable terminations and joints to detect and monitor partial discharges right at the location of their origin. Two FOS types for early PD detection were investigated: an embeddable fibre-optic acoustic sensor to measure acoustic waves in polymeric insulations generated by PDs, and a fluorescent optical fibre to detect first optical effects during ionization processes in the insulation material. The paper describes these methods, related monitoring problems and shows first test results.

1 INTRODUCTION

Fibre-optic sensors (FOS) in high voltage facilities are already known because of their advantageous non-electrical functional principles. Their components can exceptionally be made from dielectric material and do not need any electrical power supply. Such components are immune to high voltage and electromagnetic interference. Their tiny size and compactness enable integration into facilities of high voltage substations, into power transformers, generators or power circuit breakers. Some more properties make fibre sensors interesting: capability of taking measurement signals along the optical fibre over up to several kilometres, capability of recording highly accurate digital information with high signal bandwidth and dynamic range. Commonly, fibre-optic sensors can be easily installed and do not require extensive maintenance.

The placement of this young sensing technology is only successful if either its use is more efficient than the use of established ones, or customers get a problem solved that is not solvable in any other way. Not to forget reliability, long-term stability and/or availability aspects that are of paramount importance in the high voltage energy sector.

One outstanding example of commercial use of FOS in the energy sector is the measurement of temperature distribution along very long overhead transmission line conductors. Transmission lines are reaching their designed load limits due to the higher demands on transported power. Providing enough energy, thermal overloading can lead to critical situations. Distributed temperature sensors installed along transmission lines avoid damage. There are numerous examples of such condition monitoring systems both in overhead line and in high-power cables [1], [2]. The secret behind the successful use lies in the lack of competitive methods to measure the temperature or strain distribution along lines or cables. However, FOS are also excellently suitable for measurement or monitoring of other measurands or operational states, such as local temperatures [3], electric field, ac and dc current, voltage, and magnetic field [4]. It must be stated that in these cases the fibre sensor market is still a niche market.

An efficient monitoring solution is the combination of two fibre-optic sensor systems, such as a fibre Bragg grating strain measurement system with a fibre-optic magnetic field sensor based on the Faraday effect. Using this combination, lightning damage can be detected, the impact point can be estimated and temperature or vibration-induced loads in the structure can be analysed. Such monitoring systems installed e. g. in a wind turbine, enable dynamic cost-effective maintenance scheduling and damage prevention [5].

Research activities are focussed on improvement of commonly used methods to detect and locate partial discharges (PDs) inside electrical insulations. Initially, PDs are very small sparks within the insulating materials. They grow gradually more or less fast to severe discharge zones with destructive effects. Especially in polymeric insulations, PDs damage the insulating material sustainably, and - if the faults cannot be recognized in sufficient time - catastrophic failure will occur. It is important to capture charge carriers, electrons and ions that are generated during a PD.

Because established PD detection methods have some restrictions, alternative fibre optic methods are discussed and under development. This contribution will mainly focus on new ways and opportunities to improve the early PD detection.

2 METHODS TO DETECT EARLY ONSET OF PARTIAL DISCHARGES

Occurrence of PDs in electrical insulation is always attended with emission of signals: electrical pulses and acoustic waves as well as chemical reactions. These signals and/or reactions must be detected to locate and quantify PD activities. Several methods to measure PDs are in use. Following, conventional and innovative measurement methods are considered.

2.1 Electrical or electromagnetic PD detection

The measurement of partial discharges by electrical methods according to IEC 60270 is a well approved diagnostic tool to detect PD activities in insulations of HV devices. There are also electromagnetic and acoustic detection methods, for which the new IEC 62478 Ed. 1.0 standard is being developed. In general, there are two detecting strategies: the direct probing where measurement devices are directly connected to the HV accessory and the RF emission testing strategy where antennas are used. Although the electrical PD detection is widely established, there are some limitations. The primary limitation is its susceptibility to noise. Just PD measurements in high-voltage substations are complicated by a high level of electric noise, both narrowband and broadband. In cases, where it is hardly possible to distinguish between noise and PD pulses, non-electrical methods should be preferred [6].

2.2 Detection of acoustic signals

PDs also generate extremely small materials oscillations from which mechanical waves propagate through the insulation material. Such acoustic events can be detected by dynamically sensitive sensors, e. g. piezo-electric transducers which convert the acoustic energy into an electrical signal. Acoustic detection is widely used in HV transformers or gas insulated substations. Though this detection method uses sensors with electrical output signal externally or internally placed, non-electrical signals are recorded. The primary advantage of using acoustic detection methods over electrical methods is that it provides information about the location and severity of insulation problems. The disadvantage when using this method in non-homogeneous devices or insulations could be that the wave propagation is quite complex and not easy to analyse [7], [8].

2.3 Non-electrical detection methods

Among electrical or electromagnetic effects and the generation of acoustic waves during PDs, different optical effects generated by ionization, excitation and recombination processes in insulating materials can be exploited. Subsequently, two basic methodologies are considered whereby priority is placed on the fibre-optic detection technology.

2.3.1 Free-space optical detection

In order to save expenses for the continuous inspection of HV transmission lines and substation equipment usually carried out by ground patrol or even by helicopter, an apparently traditional optical detection method is used: detection of hot spots or electrical discharges by cameras. There are different camera technologies: infrared cameras for location of hot spots and ultraviolet cameras for location of corona problem areas, e. g. on insulators. They enable to detect unwanted changes on either visible or even non-visible components. Simple visible inspection cameras support remote inspection. Presently, the different cameras appear as stand-alone instruments. New developments show the combination of all three inspection techniques into one instrument to a multi-spectral imaging camera. Such combined camera techniques enable simultaneous UV and IR inspection recordings and reports and thus provide better informed decisions about the integrity of the electrical equipment or necessary maintenance [9].

2.3.2 Optical waveguide sensors

Completely different from camera techniques are optical detection methods based on optical fibres. There is a massive difference between camera techniques and waveguide-based optical detection methods: optical fibres and fibre-optic sensing elements can be embedded into the hardware of HV substation equipment, even into zones of high electrical field strength. Basically, they do not interfere with the electromagnetic field and they provide complete galvanic separation from any devices operating on earth potential. Because of the major advantages of fibre-optic sensors, this technology offers some possibilities to monitor and indicate the integrity or to detect deteriorating effects in insulations by fibre-optic sensor elements directly embedded into the insulating material [10].

In chapter 3, selected examples of new approaches to detect partial discharges by integrated acoustic and fluorescent fibre-optic sensors are presented. It is focussed on HV termination and cable joints with polymeric or elastomeric insulations.

3 PD MONITORING USING INTEGRATED OPTICAL FIBRE SENSORS FOR PREVENTION OF INSULATION BREAKDOWN

3.1 Embedded fibre-optic acoustic sensors

Research activities on embedded fibre-optic acoustic sensors for detection of PD-induced acoustic signals are described by several authors

[11], [12]. They focussed mainly on signal detection in insulations of transformers. Acoustic wave detection inside of insulation media, e. g. oil, or even in polymeric materials implies some specific requirements. Among the complex nature of the spark sound's propagation that depends on the geometry and the physical behaviour of the edge areas (e. g. interface between different insulation materials), the attenuation behaviour of the stress cone has a significant influence on the detectability of acoustic waves with increasing distance from the PD source. Another issue concerns the acoustic signature of the waves possibly influenced by ageing effects or temperature changes. These issues have to be clarified when fibre-optic acoustic sensor are to be embedded in polymeric HV insulations.

In the following first results achieved on the road to a future use of fibre-optic acoustic PD sensors embedded in polymeric/elastomeric insulating materials are shown.

3.1.1 Characterization of sound propagation in polymeric/elastomeric insulation materials

In order to design embeddable fibre-optic acoustic sensors with regard to their discrimination threshold (sensitivity) and frequency behaviour (band-pass filter function), investigation of the sound propagation behaviour in elastomeric electrical insulations has to be carried out. Usable information on velocity of propagation and attenuation behaviour of elastic waves in polymeric electrical insulations was not found in literature. Therefore, material-specific “acoustic” data (wave velocity and wave attenuation) were investigated first.

Figure 1 shows a test device for evaluation of velocity and attenuation of longitudinal waves in elastomeric test samples. Using ultrasonic excitation, a direct measurement of the velocity and the acoustic attenuation index is possible. The attenuation of the elastomeric materials can then be calculated from measurement results. The PD pulse was simulated by different technologies: laser pulses, piezo fuses, and acoustic emission from pencil lead fracture to avoid time-consuming tests in HV laboratories during the first investigation period.

Results achieved for cured liquid silicone rubber (LSR) Elastosil 7665 AB, 3003/30 AB and M 4642 as well as for cross-linked polyethylene (XLPE) are very promising. The most essential result is that the measured loss factors are surprisingly small: <0.01 for LSR, and <0.03 for XLPE. This means that ultrasonic elastic waves can propagate in elastomeric materials over distances in the range of several decimetres [13]. Considering both material attenuation and structure attenuation of typical HV terminations or cable joints (conductor/plastic insulation of the slipped stress cone/oil insulation), it could be shown that more than 50 % of the wave intensity pass the insulating zone for frequencies <150 kHz.

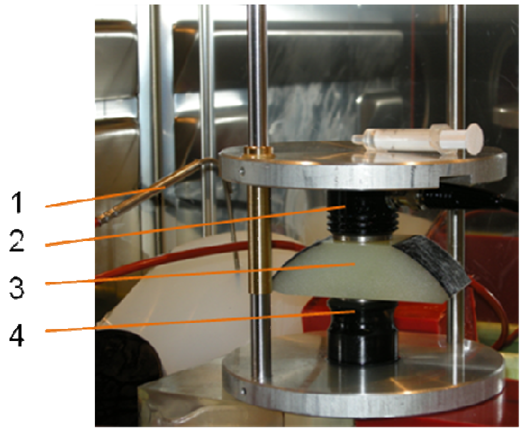

Figure 1: Test equipment for measurement of acoustic characteristics located in a temperature chamber (-20 °C till +50 °C) for a frequency range from 200 kHz till 600 kHz.
(1 - temperature sensor, 2 - ultrasound receiver, 3 - test sample, 4 - ultrasound transmitter).

It was also found that the longitudinal wave velocity drops linearly with increasing temperature for the investigated materials but the values are different for XLPE and LSR. This behaviour is caused by a decreasing storage modulus over temperature and was verified by DMTA (Dynamic Mechanical Thermal Analysis) in the temperature range from -100 °C till +100 °C [14], [15].

3.1.2 Acoustic signal recording using embedded fibre-optic sensors

The materials investigation (see section 3.1.1) revealed that fibre-optic acoustic sensors for embedment into elastomeric insulations should have their maximum sensitivity in the range from 20 kHz until 150 kHz. According to the calculated sound field distribution in a cylindrical part of a HV termination or cable joint, several sensors must be located radially over the circumference of the insulating assembly.

Extrinsic Fabry-Perot interferometer sensors (EFPI) were chosen as dynamically sufficiently sensitive sensor type. There are many designs to maximize the EFPI sensitivity. The principle and basic configuration is shown in Figure 2.

Materials oscillations or travelling waves in the medium where the sensor is embedded lead to deformation or oscillation of the two moving fibre ends inside a capillary (inner diameter about 130 µm). Parts of the light reflected at the fibre ends, interfere and the sensor represents any mechanical deformation with frequencies up to the kilohertz range. A huge number of samples were tested to optimise the design (Figure 3).

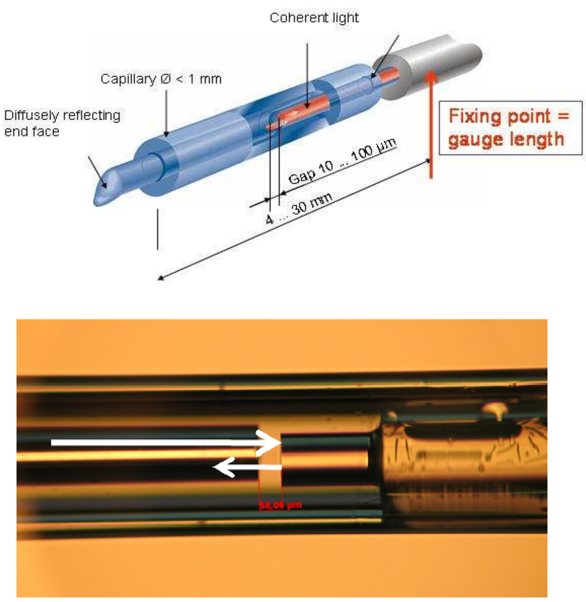

Figure 2: Above: Scheme of the used fibre Fabry-Perot acoustic sensor; below: designed sensor sample for experimental investigation in HV environment.

The face-to-face design had to be modified to achieve the response threshold. There was found a cantilever-type design which measures very low-energy material deformations in the nanometre range. In this case, there is only one fibre with angled polished endface (similarly to APC connectors), and the inner capillary wall forms the second mirror. Tests under simulated PD signals provided promising results shown in Figure 4 [13]. Further tests are carried out together with Beuth-Hochschule für Technik Berlin to investigate the sensor behaviour under real PD events occurring in the range of about 30 kV (Figure 5).

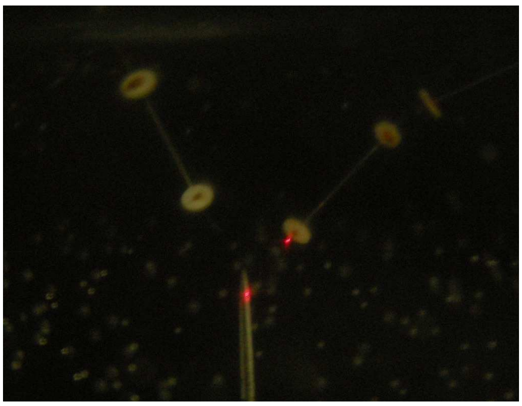

Figure 3: EFPI sensor samples embedded in transparent silicone elastomer, radially aligned to the needle under high voltage. (The illuminated points come from the laser beam.)

One problem to be solved yet is the detection of PD signal under the influence of accompanying oscillations typically in the environment of HV substations or plants.

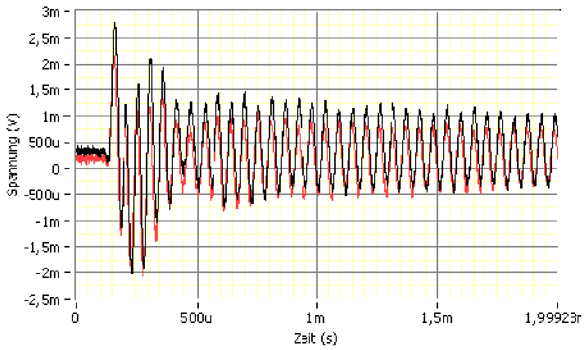

Figure 4: Sensor signal responses from two different excitations to prove the sensor reproducibility.

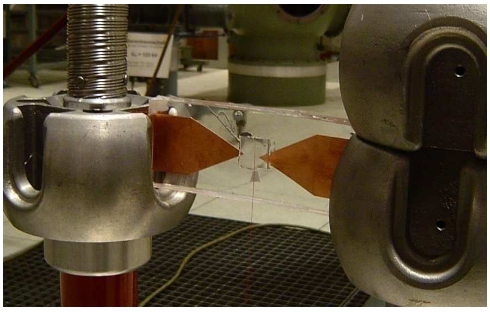

Figure 5: Silicone sample with embedded sensor prepared for measurement of PD signals.

3.2 Embedded fluorescent optical fibres

3.2.1 Optical properties of transparent silicon insulation materials during PD event

The optical detection of PD events requires optically transparent or translucent insulation materials. Exemplarily, a transmission spectrum of the transparent silicone Elastosil LR 7665 is shown in Figure 6A. The transmission is about 90 % over a broad spectral range (ca. 300 nm till 900 nm), being more or less similar for all investigated silicones. Thus, the detection of PDs in silicone insulators is promising, assuming that the PDs emit either directly in this optically transparent range of silicones or the emission can be shifted towards it. Figure 6B displays a spectrum of a PD in the silicone Elastosil 7665.

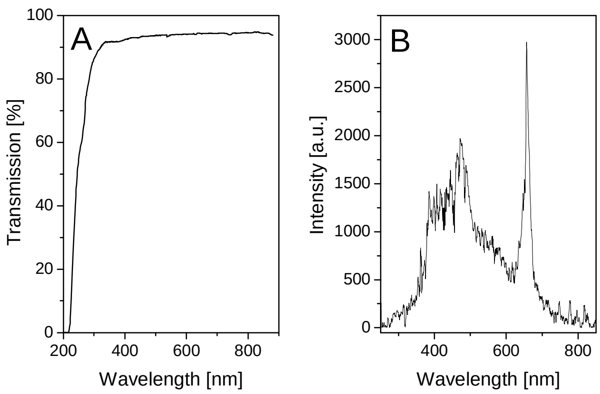

Figure 6: Wavelength depending transmission of a 10 mm layer of silicone (A), and spectrum of PD in silicone (B), both Elastosil 7665.

Besides the strong emission of Hydrogen at 655.279 nm, the broad continuum (approx. 400 nm till 750 nm) can be exploited for PD detection. The low-loss transport of light through the silicone insulation is ensured as the emission occurs in the optical transparent range of the investigated silicone materials.

3.2.2 Optical properties of fluorescent optical fibres in HV environment

In order to achieve optimal detection of PDs, the design of optical fibres has to match various aspects: In praxis, the precise spot of PDs is not known, thus, PD emission cannot be detected by the front surface of a single fibre. One alternative is the coupling of light via the fibre surface which requires the avoidance of light absorption by the fibre coating and/or cladding. For this purpose, the refractive index of the fibre coating and cladding has to be lower than or similar to the refractive index of the insulation material. In this case, the effect of total reflection does not impede the light transfer into the fibre. Due to the little differences in the refractive index of core and cladding (max. 0.1), the critical angle for light coupling into the fibre is very low. Thus, most parts of the light will pass the undoped optical fibre without being transported via total reflection. Fluorescent fibres improve the light coupling efficiency. The fluorescent dye absorbs light independently of the angle of incidence and emits fluorescence into all directions in space. Therefore, a higher percentage of light fulfils the requirements relating to total reflection, and is guided to the detector. The coupling efficiency is improved with increasing amount of fluorescent dye although the attenuation characteristics of the fibre deteriorate. For some fluorescent fibres, the guided light decreases by 50 % every 20 cm of fibre length. In summary, the fluorescent fibres are beneficial for effective coupling of light into the fibre; however, undoped fibres are the better option for light transport.

Embedment of optical (fluorescent) fibres into insulation material for PD detection requires investigation of the fibre material with regard to the HV environment. Figure 7 shows two types of optical fibres being hit by PDs and the associated microscope pictures of the fibres after being exposed to PDs. In contrast to silicone fibre samples (Figure 7A), PMMA fibres are damaged after being hit by tree channels (Figure 7B). The damage is clearly visible by the red laser light shining through the broken cladding.

Silicone fibres offer great potential for PD detection as the electrical properties are similar to the silicone insulation material. However, silicone fibres are not commercially available yet.

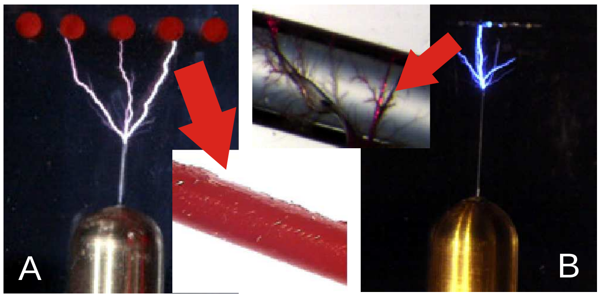

Figure 7: PDs on fluorescent silicone fibre-like samples (A), PMMA fibres (B); microscopic pictures (central) of the fibres after being exposed to trees.

3.2.3 Experimental verification of optical PD detection results

Experimental set-up and the implementation of electrical/optical PD measurements are described in another conference paper [16]. Typically, the measurement system records and visualizes the optical and electrical pulses as phase resolved partial discharge (PRPD) pattern (Figure 8). A comparison of electrical (above) and optical (below) patterns for a small channel on a metallic tip shows a nearly identical visualization. Note that only the electrical channel (above) is calibrated.

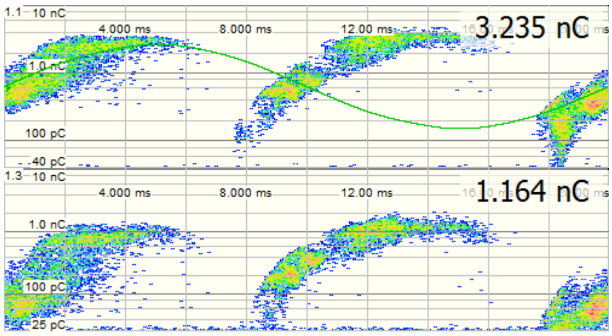

Figure 8: PRPD pattern (electrical channel above, optical channel below), cable and tip in air on high AC voltage of 19 kV.

4 FUNDAMENTAL COMPATIBILITY CONSIDERATIONS FOR EMBEDDED FIBRE-OPTIC SENSORS

The influence of embedded optical fibres on electrical properties of the insulation material has to be considered to avoid damage in the insulating system. In order to investigate this influence, two sample sets were produced and related PD-inception voltage (U_{PD}) and breakdown voltage (U_B) were measured. One sample set consisted of 5 samples with embedded fluorescent PMMA fibre as shown in Figure 9, the other one consisted of 10 similar samples without embedded fibre. The results are presented in Table 1.

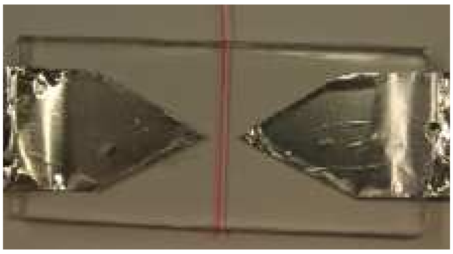

Figure 9: Sample with fluorescent optical fibre (PMMA) embedded between two Aluminium electrodes (Silicone: Elastosil RT 604).

It can be seen that no significant difference occurred either in PD inception voltage or in breakdown voltage between samples with or without embedded fibre. This demonstrates the ability of safe operation of optical fibres for PD detection.

Table 1: PD inception voltage U_{PD} and breakdown voltage U_B for samples with and without embedded fluorescent fibre

Sample	U_{PD} [kV]	U_B [kV]
Without fibre	9.3 ± 0.5	40.5 ± 1.3
With fibre	9.7 ± 0.9	38.8 ± 2.6

5 CONCLUSION AND OUTLOOK

Early detection of PDs in polymeric insulations of HV cable terminations and joints is increasingly important. For this purpose, two different fibre-optic sensor types were embedded in transparent silicone and XLPE insulations to detect optical effects accompanying the development of PDs as well as acoustic waves generated by PDs. Embedded fluorescent optical fibres are able to recognize PDs clearly before acoustic or electrical detection methods are successful. Using a combination of these non-electrical methods, intelligent accessories can be designed to avoid serious damage.

6 ACKNOWLEDGMENTS

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