

EUROSENSORS 2015

Optical-only detection of partial discharge with fluorescent polymer optical fiber sensors

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Abstract

This paper reflects recent progress in the field of fluorescent polymer optical fiber sensors (F-POF) for partial discharge (PD) detection in high voltage (HV) cable accessories using optical-only PD detection by coincidence single photon counting. In experiments with artificial PD sources these sensors show the ability to detect optical emissions from picocoulomb-level PDs in a real-scale model of a translucent high voltage cable accessory. False positives (caused by detector noise) are efficiently suppressed while maintaining sufficient sensitivity, even when the sensor is located in an unfavorable position.

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Peer-review under responsibility of the organizing committee of EUROSENSORS 2015

Keywords: Partial discharge; silicone rubber; high voltage cable accessories; polymer optical fiber POF; fluorescence; coincidence

1. Introduction

Partial discharge (PD) measurement is a common method to test high voltage (HV) cable accessories under real-life conditions for defects that would otherwise limit the estimated lifetime of the devices. As conventional electric and electromagnetic methods suffer from electromagnetic interference (EMI), EMI-resistant-PD measurement methods would be beneficial, especially for on-site and on-line testing. In this context fiber optic [1] and fiber acoustic [2] PD detection have been discussed recently, but until now only electrical PD measurement systems for HV applications and acoustic systems for medium voltage applications are accepted. We have shown elsewhere [3] that fiber-optic PD detection can suppress external electromagnetic noise of the conventional electric PD

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measurement in an electrically polluted environment. In that context fiber-optic PD detection is an add-on to the conventional techniques to gain EMI resistance. Hence it is necessary to elucidate if the fiber-optic method can act as reliable stand-alone method for PD detection in translucent HV cable accessories.

2. Materials, Methods and Test Setup

2.1. Specimen, reference, artificial PD sources and test setup

Experiments were conducted in a shielded HV laboratory under AC voltage with a real scale HV connector model. The connector consists of a translucent silicone rubber stress cone with opaque field control which was placed into a non-transparent connector jack (Fig. 1. (a)). Two different artificial PD sources were used to simulate common defects in HV components. PD source #A simulates inner PD activity occurring at the interface of cable core and stress cone and consists of a HV electrode embedded in transparent silicone rubber in a tip-to-plate geometry. PD source #B consists of aluminum foil in a tip-to-plane geometry embedded in silicone rubber gel which simulates PDs between stress cone and connector jack.

A modular commercially available electrical PD measurement system from Omicron GmbH, Austria (MPD 600) was used as reference, calibrated according to IEC standard 60270.

2.2. Sensing fiber and optical PMT detector units

The suitability of different fluorescent polymer optical fibers (F-POF) as sensing fiber was evaluated based on measurements of light absorption performance in the relevant spectral range (PD emission) and optical attenuation of each fiber. The embedment of the fibers in silicone rubber was necessary to surface-attach the fiber on top of the silicone stress cone. Thus fibers made of polystyrene core and poly(methyl methacrylate) cladding were chosen to guarantee highest light absorption probability due to the matching refractive index gradient between silicone rubber material, fiber cladding and fiber core material. Best suited for this purpose was a green fluorescent F-POF from Industrial Fiberoptics Inc., USA (P/N 81 0082). This F-POF can absorb light over the whole fiber volume in the wavelength range of $380 \text{ nm} \leq \lambda_{\text{abs}} \leq 500 \text{ nm}$ and emits this fraction of absorbed light wavelength shifted to lower energies between $500 \text{ nm} \leq \lambda_{\text{em}} \leq 650 \text{ nm}$ without pre-dominant direction (Fig. 1. (b)). The optical attenuation was determined using the side-illumination method [4] at distances between 0.15 m and 1 m with a cold white LED and an avalanche photodetector (Thorlabs APD120A2). The data points of the measurement were fitted by a mono-exponential regression function leading to an attenuation of $\alpha_{\text{tot}} \approx (1.7 \pm 0.2) \text{ dB m}^{-1}$.

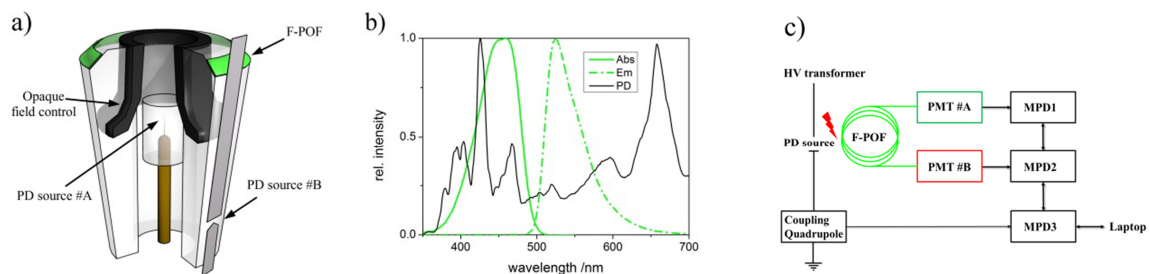


Fig. 1. (a) PD emission spectrum in silicone rubber (solid black) and F-POF absorption and emission spectrum (solid and dash-dotted green). (b) Schematic cutaway of a real-scale translucent silicone stress cone with artificial low-level PD sources (PD source #A and #B) and surface attached thermoplastic F-POF. (c) Schematic drawing of the test setup of F-POF assisted optical coincidence PD measurement.

The F-POF sensor consists of a total fiber length of 9 m. 6 m of the bare fiber were used as sensing element and embedded in transparent silicone elastomer whereas the non-embedded part of the fiber acted as transport fiber to guide absorbed light to the detector units. The F-POF sensor was interrogated using two single-photon detectors (photon multiplier tubes, PMT #A and PMT #B, Hamamatsu H10682-210), having a quantum efficiency of

$QE(\lambda_{\max} \approx 525 \text{ nm}) \approx 11 \%$. Both detectors showed dark count rates of $8\text{--}10 \text{ s}^{-1}$. The scheme of the test setup is shown in Fig 1. (c). All PD data of all channels were recorded simultaneously with three separate MPD boxes.

3. Results and discussion

We have shown elsewhere [3] that already one single optical measurement channel can enhance the noise immunity of the conventional PD measurement. Especially under low-transmittance conditions, optical PD detection alone suffers from detector noise. In a monitoring scenario, this would make it difficult to decide whether PD is actually present or not. In consequence this may mean to risk a failure caused by too high threshold, or to risk unnecessary and costly shutdowns in the case of too low threshold. The proposed method to reduce this uncertainty makes use of coincidence counting with two independent detectors.

Depicted in Fig. 2. (a) is the AC-phase resolved PD measurement (PRPD) conducted with the setup shown in Fig. 1. (a) and (c). The dataset of the original electrical measurement is shown as grayscale contours. The dataset of the electrical measurement, coincidence filtered with each single PMT independently, is shown as red and green histograms. The dataset of the coincidence filtered photon detectors is represented by yellow data points.

Although only a tiny fraction of PD events is detected in both optical channels, coincidence filtering is beneficial due to three facts: Firstly, the probability to coincidentally detect two fluorescence photons at two opposite ends of the sensing fiber that have been caused by one single PD event is small but finite. Secondly, the probability of detecting coincident events caused by dark counts is considerably smaller. Thirdly, low dark count rate of photodetectors may be achieved even at room temperature; this way, specificity can be improved at lower cost of instrumentation; however, low dark count rates have to be traded against reduced quantum efficiency, reducing sensitivity.

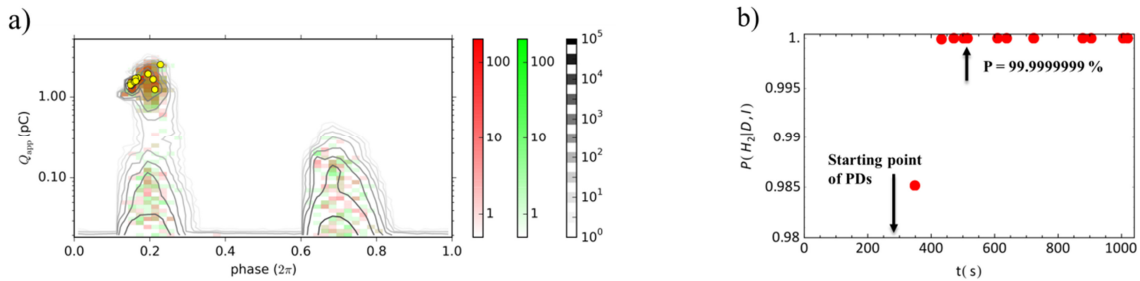


Fig. 2. (a) PRPD-histogram of a model PD source inside a HV field control device. The dataset of the original electrical measurement is shown as grayscale contours. The dataset of the electrical measurement coincidence filtered with each single PMT independently is shown as red and green histograms. The dataset of the coincidence filtered photon detectors is represented by yellow data points. (b) Results of the probabilistic evaluation of coincidence-based purely optical PD detection. After $t = 500$, PD detection probability exceeds 99.999999 %.

We denote the count of optically registered events that are correctly identified as caused by PD (“true positives”) as n_{TP} , the number of false alarms (“false positives”) as n_{FP} , and use corresponding definitions for events identified as noise, n_{TN} and n_{FN} . Then the usual definitions of *specificity* and *sensitivity* of the detection procedure,

$$\text{specificity} = \frac{n_{TN}}{n_{TN} + n_{FP}} \quad \text{sensitivity} = \frac{n_{TP}}{n_{TP} + n_{FN}} \quad , \quad (1)$$

suggest that the goal should be to increase the *specificity* of detection to virtually 1 (that is, exclude false alarms), however maintaining sufficient *sensitivity*.

The degree of belief that PD is present can be quantified as follows, comparing probabilities of two hypotheses:

- H_1 : “Coincident counts occur with the expected average rate $r_{\text{coinc, nom}}$, that results from assuming that only dark counts are detected in both channels.”
- H_2 : “Coincident counts occur with an average rate $r_{\text{coinc, obs}} > r_{\text{coinc, nom}}$. There are additional coincident counts that have to be attributed to PD activity”. The information entering the evaluation consists of

- data D : “ n_{coinc} coincident counts were observed during t_{obs} seconds”
- prior information I : Dark count rates d_1 and d_2 of both detectors; a coincidence time interval w is fixed based on our knowledge about the timing precision of the individual channels. Dark counts of both detectors are known to be statistically independent. Finally, neither of the hypotheses is preferred a priori.

Denoting the conditional probabilities of hypotheses given data D and prior information I as $P_i | D, I$, the relative probability of both hypotheses is quantified by the odds [5]

$$O_{21} = \frac{P(H_2 | D, I)}{P(H_1 | D, I)} = \frac{P(H_2 | I)}{P(H_1 | I)} \times \frac{P(D | H_2, I)}{P(D | H_1, I)} = \frac{P(D | H_2, I)}{P(D | H_1, I)}, \quad (2)$$

using $P(H_2 | I) = P(H_1 | I)$, as none of the hypotheses is preferred a priori.

Dividing the observation time t_{obs} into $N = t_{\text{obs}}/\Delta t$ time bins of (sufficiently short) duration Δt , and expressing the probability $p_{k, \Delta t}$ (given hypothesis H_k holds) of measuring one pair of coincident counts during an interval of duration Δt , as $p_{k, \Delta t} = \Delta t r_{\text{coinc, nom}}$, the probability of observing exactly n_{coinc} pairs of coincident counts during observation time t_{obs} can be expressed by the binomial distribution:

$$P(D | H_k, I) = P(n_{\text{coinc, obs}}(t_{\text{obs}}) | H_k, I) = \binom{N}{n_{\text{coinc, obs}}} p_{k, \Delta t}^{n_{\text{coinc, obs}}} (1 - p_{k, \Delta t})^{N - n_{\text{coinc, obs}}}, \quad (3)$$

and therefore the odds in favor of hypothesis H_2 , given observational data, are

$$O_{21} = \frac{P(D | H_2, I)}{P(D | H_1, I)} = \left(\frac{r_{\text{coinc, obs}}}{r_{\text{coinc, nom}}} \right)^{n_{\text{coinc, obs}}} \times \left(\frac{1 - \Delta t r_{\text{coinc, obs}}}{1 - \Delta t r_{\text{coinc, nom}}} \right)^{\frac{t_{\text{obs}}}{\Delta t} - n_{\text{coinc, obs}}}, \quad (4)$$

with $r_{\text{coinc, nom}} = 2 d_1 d_2 w$, $r_{\text{coinc, obs}} = n_{\text{coinc, obs}}(t_{\text{obs}}) / t_{\text{obs}}$. In the present experimental setup the measured values of dark count rates of the detectors PMT #A and #B are $d_1 \approx 8 \text{ s}^{-1}$ and $d_2 \approx 10 \text{ s}^{-1}$, respectively, and $w = 100 \text{ ns}$. Because H_1 and H_2 imply $P(H_2 | D, I) + P(H_1 | D, I) = 1$, it follows that $P(H_2 | D, I) = O_{21} / (1 + O_{21})$.

This analysis applied to the data shown in Fig. 2. (a) leads to the result shown in Fig. 2. (b). After $t = 500 \text{ s}$ there is practically no more doubt that Hypothesis H_2 must be favored over H_1 (probability of 99.999999 %). Already the first coincident count at $t \approx 370 \text{ s}$ leads to 98.5 % probability that PD is taking place. It would be up to the operator to decide if the remaining risk justifies to shut down prematurely or to wait for evidence of H_2 to grow further.

4. Conclusion

We have shown that low picocoulomb-level optical-only detection of partial discharge in translucent cable accessories is feasible using F-POF sensors in combination with PMT detectors and coincidence filtering technique.

Acknowledgements

This work is funded by IBB Investitionsbank Berlin and is co-financed by the European Regional Development Fund. The authors acknowledge contributions in terms of F-POF sensor embedment by Polymeric GmbH (Berlin, Germany) and for providing a HV a real scale connector model by IPH GmbH (CESI Group).

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