# PD MONITORING OF EXTRA HIGH VOLTAGE CABLE JOINT USING EMBEDDED FIBER OPTIC ACOUSTIC EMISSION-BASED SENSORS

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## ABSTRACT

***Much attention has been paid to monitoring the high voltage (HV) and extra HV (EHV) cable systems. Most of the failures and defects appear in cable accessories like cable joints and terminations. The practical limitations of conventional electrical partial discharge (PD) monitoring systems constrain their use for long-term and long-distance implementations. Fiber optic-based PD solutions could be an effective approach to mitigate the challenges of conventional methods. However, there is an industry gap in the literature about the highly sensitive fiber optic-based PD solution based on the acoustic emission principle. This paper aims to fill such an industry gap. In this paper, the fiber optic-based PD sensing (OptiFender) technology is applied to monitor the PD in 245 kV cable joints. Test results show that the sensitivity of the proposed solution, using the embedded sensor configuration is equivalent to 2-3 pC. The advantages of the proposed solution to have a smart EHV cable joint have been highlighted.***

## Keywords

Acoustic emission (AE)-based sensing technology, Cable accessories, Cable joints, Extra high voltage (EHV) systems, Fiber optic, partial discharge (PD).

## 1. INTRODUCTION

There are several practical benefits of high voltage (HV) and extra HV (EHV) cable systems. Hence, the deployment of HV and EHV cable systems in power systems and transmission networks is steadily growing [1], [2]. Fig. 1 shows the world history of EHV (220-800kV) power cables according to the E-Highway 2050 report [3], [4].

The cable accessories, including the cable joints and terminations, are the weak points of cable systems [5], [6]. Their insulation conditions based on the manufacturing and installation quality would affect the power system's reliability and stability [7]. For instance, an EHV cable joint of the Shanghai Power Grid was broken in 2013. Due to this failure in the power cable joint, two 500 kV and 220 kV main transformers were interrupted, and 13,000 customers experienced a power outage [8].

The statistics infer that around 85% of HV failures correspond to insulation defects and problems [9]. Accordingly, the insulation management of HV cable systems, like other HV assets, is essential to prevent unnecessary urgent repairs/replacements, and unplanned outages and downtimes. The partial discharge (PD) monitoring of cable accessories, focusing on insulation management, could be an effective solution to guarantee the safe and reliable operation of HV and EHV cable systems [10], [11].

Different conventional and non-conventional methods/sensors have been reported for PD monitoring of HV cable accessories, i.e., high-frequency current transformer (HFCT), ultra-high frequency (UHF), piezoelectric-based acoustic emission (PZT-AE), flexible magnetic coupler (FMC), and transient earth voltage (TEV) sensors. The HFCT, UHF, and piezoelectric-based sensing technologies would be vulnerable to electromagnetic interference (EMI) [12]. In addition, the installation of these sensors for HV cables is not easy and convenient [13].

Fiber optic-based sensing technology is one of the effective solutions to monitor the PD of HV cable systems [14], [15].

The fiber optic-based PD sensors are immune to EMI. They are passive and do not need any power at the sensing location. Therefore, they can be utilized for monitoring cable joints in remote locations. The transmission of data across fiber optics can travel long distances >40km without attenuation of the signal. Fiber optic sensing technology's small size and long-distance coverage are other advantages.

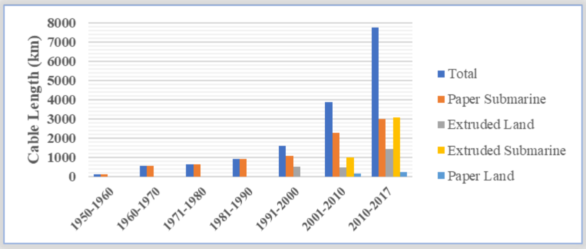


**Fig 1. World history of EHV (220kV-800kV) power cables** [3], [4]**.**

In [16], the PD of cable joints has been measured by distributed acoustic sensing (DAS), using fiber optic sensors. The introduced solution by Zhu et al. [16] was useful to mitigate the challenges of monitoring several cable joints at different sensing points. However, the introduced solution was based on Fiber Bragg grating (FBG) sensors. Accordingly, the manufacturing and implementation of these FBG sensors would not be easy. The sensitivity of available approaches, such as [16], would be of essential concern. The distributed PD detection of cable joints, using the single mode fiber (SMF), has been reported in [17]. The problem with this reported distributed solution is its sensitivity. Hence, this low sensitivity might adversely affect the introduced solution in realistic cases.

The low intensity of observed PD signals by fiber optic-based sensors is one of the important challenges. Reference [5] introduced a fiber optic interferometer-based sensor to measure the PD of cable accessories. In [5], the 10 kV XLPE terminals have been studied. Hence, there are no studies regarding the HV and EHV cable accessories in [5]. Also, that solution is a single point. A single-point solution is not effective for HV and EHV cable accessories because there are several joints in such systems.

Mitigating challenges regarding the low sensitivity of the fiber optic-based AE (FO-AE) technology for PD measurement have been responded to by OptiFender [18], [19]. The OptiFender technology has been developed based on interferometric concepts to measure and monitor the PD in MV, HV, and EHV assets [20], [21]. The PD monitoring and localization of power transformers, cable accessories, gas-insulated substations (GISs), and other HV assets are applications for the novel commercially off-the-shelf system called OptiFender. This proposed sensing technology mitigates the challenges regarding the low intensity of fiber optic-based sensors. For instance, 196 pC has been recognized in [5], while the OptiFender is able to detect PDs less than 5 pC. Indeed, the OptiFender sensors could be 10 times more sensitive to the PD compared to other fiber-optic sensors, like [5]. Moreover, most of the existing approaches have been applied to MV cable accessories. Less attention has been paid to PD detection of HV and EHV cable joints by fiber optic-based solutions. Since the structure of the EHV cable accessories is more complicated than the MV ones, such studies are needed. Furthermore, the ability to daisy-chain multiple sensors in series facilitates the deployment of the OptiFender for EHV cable systems, including several cable joints and sensing nodes.

Different solutions, utilizing OptiFender technology, have been proposed for PD monitoring of MV, HV, and EHV assets. A. Zadeh and N. [21] reported the PD detection in HV and MV terminations, using fiber optic sensing technology. The recorded signals were measured at 8 kV and PD levels lower than 100 pC. Also, the signal-to-noise ratio (SNR) was satisfactory in the measurements. In [22], PD detection in HV GIS, using FO-AE, has been introduced. The OptiFender could measure PDs even at the inception voltage. It has been concluded that the measurements were not affected due to EMI around the under-study GIS. Reference [18] studied the monitoring of smart HV cable joints with embedded FO-AE sensors. The OptiFender sensitivity was reported around 10 pC. This sensitivity level is desired. However, to follow the IEC requirements for routine and type tests, higher sensitivity is needed. Another issue that is needed to complete this evaluation is studying the behaviors of EHV cable joints compared to HV ones. A preliminary investigation has been given in [23] for PD measurement in inverter-based machines. The PD detection of MV joint, using OptiFender, has been reported by A. Zadeh et al. [19]. The sensitivity level was better than 70 pC. This paper is one of the article series published to share the latest updates and innovations in the field of fiber optic-based PD monitoring of HV assets, using OptiFender technology.

This paper proposes the PD monitoring of 245 kV cable Joint, using embedded FO-AE sensing technology (OptiFender). The 245 kV cable joint is used to artificially simulate the PD, measuring the AE-based PD, and sensitivity evaluation of the OptiFender according to electrical PD measurements. Tests have been done in the HV laboratory and using electrical and FO-AE PD measurement systems in Halol, India.

Test results show that the OptiFender sensitivity for PD monitoring of the EHV cable joint in the embedded configuration of sensors is around 2-3 pC. The obtained results highlight the advantages of the proposed FO-AE-based sensing technology to design and manufacture a smart joint.

The rest of this paper is structured as follows. The OptiFender (FO-AE PD sensing) technology is given in Section 2. Section 3 presents the test results and test procedures. Finally, the conclusion is drawn in Section 4.

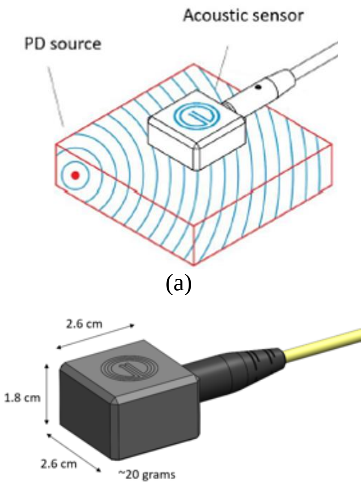
## 2. OPTIFENDER (FO-AE PD SENSING) TECHNOLOGY

The proposed FO-AE PD sensing technology (OtiFender) has been designed based on interferometry. Two identical fibers (the same type and length) are configured according to Michelson interferometry configuration. One of these fibers is used as the sensing point, and another one would be the reference. The sensing and reference fibers are set up inside the designed AE-based PD sensor. A damper has been designed and installed to isolate the reference fiber from mechanical vibrations and disturbances. The sensing fiber is wound around a mandrel with a flat bottom [24].

The OptiFender sensor is installed on the body of the equipment under test (EUT), as depicted in Fig. 2a. Since the OptiFender sensor is non-metallic, it can be installed in both embedded and retrofitted configurations. The physical contact of the OptiFender sensor and the surface of the EUT should be appropriate. The loose contact between the sensor and the surface of the EUT dramatically affects the sensitivity of the PD measurements. To install the PD sensors can be done by the following approaches:

- Rubber clamps
- Brackets and straps
- Magnetic clamps (For external installations, e.g., PD monitoring of power transformers)
- Adhesive materials

The dimensions and weight of the OptiFender sensor are presented in Fig. 2b. It should be noted that the used sensor in this research has been upgraded compared to the previous version. The new sensor is significantly more sensitive than previous versions.



(a)

(b)

**Fig. 2. OptiFender principle and sensor specifications; (a) Sensor installation on the surface of the EUT and (b) Sensor dimension and weight [25].**

If there is a PD, an AE signal passes through the sensor. Hence, the vibration due to this AE signal would be transferred to the sensing mandrel, attaching the sensing fiber wound around it. The interferometric signal is transmitted to the OptiFender interrogator. The AE signal acquisition and demodulation are done. Afterward, the edge software communicates with the interrogator for PD detection and further activities. The performance in terms of sensitivity of the OptiFender AE-based sensors is like state-of-the-art PZT-AE ones. Therefore, the advantages of the OptiFender sensor compared to PZT-AE sensors, e.g., being lightweight, passive, non-metallic, and robust against the EMI, emphasize its applications [20].

The PD and defect in the insulation material of HV cable accessories result in an AE event. The AE waves transmit through insulation and semiconductive layers to reach the OptiFender sensor. Accordingly, if the sensor could be installed close to the PD source, the PD measurement sensitivity would be improved. The OptiFender sensor is non-metallic, and it can be installed in the embedded configuration of HV cable joints and terminations easily. In the embedded configuration, a satisfactory sensitivity could be achieved.

The AE signals due to the PDs are usually from 20 kHz to 150 kHz [26]. An OptiFender interrogator can support up to 32 sensing points with simultaneous measurement of PD across all 32 sensors. The number of supported sensing points could be increased using the daisy chaining and multi-core sensors. In Fig. 3, the PD monitoring of HV and EHV cable accessories based on Daisy Chaining is shown.

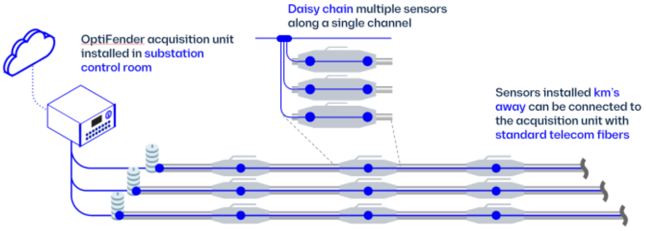


**Fig. 3. PD monitoring of HV and EHV cable accessories based on Daisy Chaining.**

The sensing points of the OptiFender can be centralized in one HV substation, like the power transformers. Also, the distributed sensing points, such as the HV and EHV cable joints, could be supported by the proposed fiber optic-based technology.

The phase-resolved PDs (PRPDs) are suitable results for interpreting the PD source, PD classification, and noise cancelation. Although the PRPD for electrical PD measurement is ordinary, less attention has been paid to the PRPD for AE-based PD measurement in available industrial solutions. The OptiFender technology's capability to generate PRPDs is another advantage of this solution.

## 3. TEST SET-UP AND TEST PROCEDURE

### 3.1. Equipment under test (EUT)

The tests have been conducted on the 245 kV cable joint. It should be noted that the main body of the cable joint, semi-conductive tapes, and copper mesh for both types of cable joints (heat shrink and heavy-duty) are identical. In Fig. 4, the structure of this type of cable joint, including internal layers, is shown. The internal layers of the cable joints are as follows:

- Layer 1: Mechanical connector
- Layer 2: Silicone rubber body
- Layer 3: Inner electrode/Faraday cage
- Layer 4: Deflector
- Layer 5: Outer screen
- Layer 6: Copper mesh
- Layer 7: Solderless shield connection
- Layer 8: Sealant mastic

- Layer 9: Insulating tubes
- Layer 10: Outer protection with integrated moisture barrier

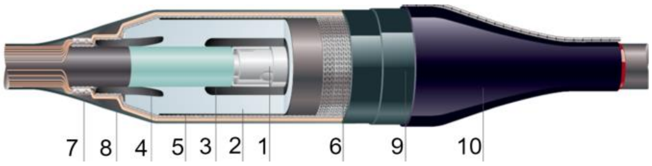


**Fig. 4. Structure of the under-test 245 kV heat shrink One Piece Joints (EHVS-S).**

Fig. 5 depicts the different steps of 245 kV joint installation. It should be noted that the structure of the heavy-duty cable joint, except its copper casing and coffin box, is the same as heat shrink ones.

The maximum operating voltage, standard, and other specifications of the equipment under test are demonstrated in Table 1. Also, the detailed descriptions and dimensions of the under-test 245 kV cable joint are demonstrated in Table 1.

### 3.2. Test Set-up and Test Circuit

In Fig. 6, the test set-up and test circuit for PD measurement of the 245 kV cable joint by the OptiFender have been shown. In addition, the configuration of sensors and their location have been shown in Fig. 6.

According to the IEC 62067 standard [27], the test voltages shown in Table 2 should be applied to the EUT of this study. According to sub-clause 9.4 of IEC 62067 for routine tests, the sensitivity of the PD measurement should be better than 5 pC. No detectable PD exceeding the declared sensitivity shall be observed during the routine tests.

**Table 1. Technical details and specifications of the 245 kV heat-shrink rejacketing cable joint**

| Specification | Value |
|---|---|
| Product model | EHVS-245SW |
| Max. operating voltage Um (kV) | 245 |
| Standard | IEC 62067 |
| Rated voltage U (kV) | 220-230 |
| Rated lightning impulse withstand voltage (BIL) (kV) | 1050 |
| Range of conductor cross-section (mm2) | 300-2500 |
| Under test conductor cross-section (mm2) | 1200 |
| Range of diameter over cable insulation (prepared) (mm) | 71-119 |
| Max. diameter over outer cable sheath (mm) | 150 |
| Length (mm) | 2500 |
| Diameter (mm) | 310 |
| Screen treatment | Inline/shield break/grounded |

## 4. TEST RESULTS AND DISCUSSIONS

### 4.1. Test Results and Discussions on Clean Cable Joint

Firstly, the clean cable joint has been tested. The PD measurement by non-conventional methods, e, g., electromagnetic and AE ones, has been discussed in IEC TS 62478. According to IEC TS 62478 [28], the sensitivity evaluation of non-conventional PD measurement should be done.

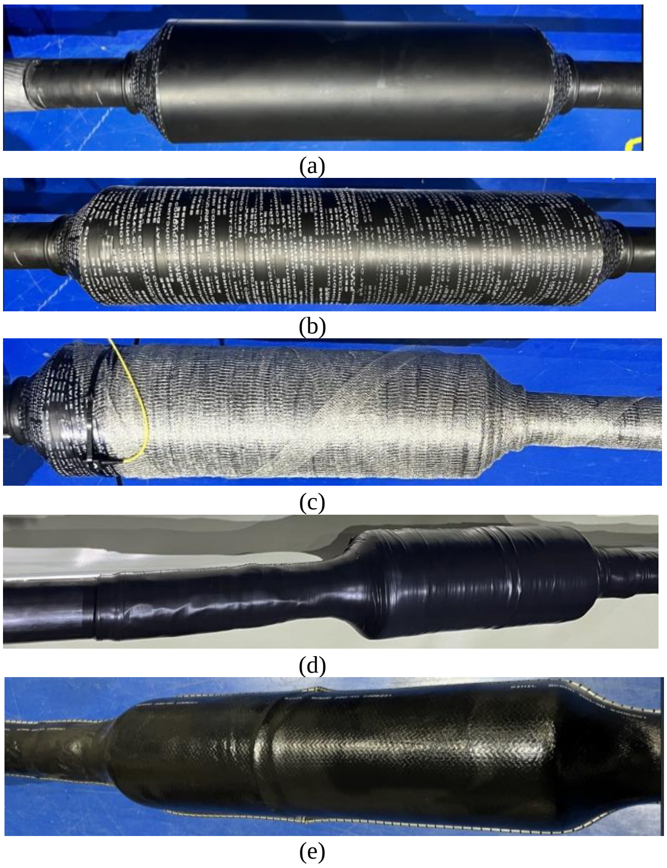

(a)
(b)
(c)
(d)
(e)

**Fig. 5. Under-test 245 kV heat-shrink cable joint according to different installation steps and layers.**

**Table 2. Test voltages based on IEC 62067 standard’s requirements for 245 kV (220-230 kV rated voltage) cable joints**

| Voltages | Value |
|---|---|
| Rated voltage (kV) | 220-230 |
| Highest voltage (kV) | 245 |
| Value of the phase-to-ground voltage (U0) for determination of test voltages (kV) | 127 |
| Voltage test (kV) | 318 |
| Duration of voltage tests (min) | 30 |
| Voltage of the PD test in Routine and Type tests (1.5 U0) | 190 |

The electrical PD measurement has been used to evaluate the sensitivity of the proposed AE-based PD measurement, using the embedded configuration of sensors.

Fig. 7 shows the electrical PD measurement (QIEC(t)-VRMS(t)) results for the clean reference cable joint. As seen in Fig. 7, the PD inception voltage (PDIV) is 247 kV. It means there is no detectable PD at 1.5 U0. Moreover, the PD at the maximum voltage level is less than 3.5 pC. It is concluded that the clean cable joint quality is high, and it will be PD-free at the U0 and 1.5 U0.

Table 3 demonstrates the results of PD measurement under the copper mesh for the clean reference cable joint.

**Table 3. Measurement results of the clean reference cable joint**

| Results | 247 kV | 280 kV | 300 kV | 318 kV |
|---|---|---|---|---|
| PD at Sensor 1 (nm) | 0.2 | 0.25 | 0.25 | 0.2-0.3 |
| PD at Sensor 5 (nm) | --- | 0.1-0.15 | 0.1-0.15 | 0.1-0.2 |
| PD at Sensor 6 (nm) | --- | 0.1-0.15 | 0.1-0.2 | 0.3-0.4 |
| Electrical PD (pC) | 2.3 | 2.6 | 2.9 | 3.3 |
| PDIV (kV) | 247 | | | |
| PDEV (kV) | 230 | | | |
| Temperature (°C) | 31.5 | | | |
| Humidity (%) | 61 | | | |

Three sensors could detect the PD at different voltage levels. Test results infer that the OptiFender sensitivity is better than 2.3 pC if the PD sensor is installed close to the PD source. The obtained results highlight the advantages of the proposed PD monitoring solution, using the embedded configuration of sensors.

The time-domain AE signals measured by Sensor 1 corresponding to 2.3 pC, 2.6 pC, and 2.9 pC at 247 kV, 280 kV, and 300 kV are shown in Fig. 7. Fig. 8 also shows the electrical PD measurement of clean cable joint.

## 4.2. Test Results and Discussions on Simulated PD/Defect

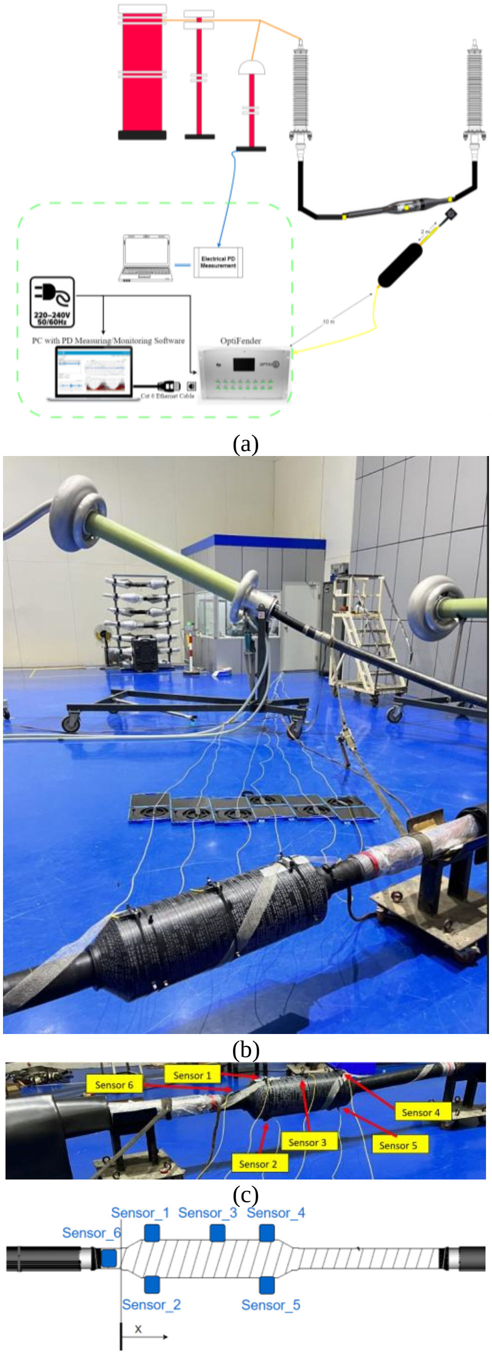
After measuring the PD of the clean reference cable joint, a PD has been simulated. To simulate the PD, a metallic needle has been inserted into the cable joint. Fig. 9 shows the approach to creating the PD in the cable joint. Table 4 presents the results.

**Table 4. Measurement results of the cable joint with a simulated PD**

| Results | 75.5 kV | 69.7 kV | 69 kV | 67.7 kV |
|---|---|---|---|---|
| PD at Sensor 1 (nm) | 0.8 | 0.5 | 0.25 | 0.25 |
| PD at Sensor 3 (nm) | 0.12 | 0.1 | --- | --- |
| PD at Sensor 4 (nm) | 0.14 | 0.12 | --- | --- |
| PD at Sensor 5 (nm) | 0.12 | 0.1 | --- | --- |
| PD at Sensor 6 (nm) | 0.1 | 0.08 | 0.08 | --- |
| Electrical PD (pC) | 20-25 | 14-15 | 7-8 | 5-7 |
| PDIV (kV) | 68 | | | |
| PDEV (kV) | 62.5 | | | |
| Temperature (°C) | 30.8 | | | |
| Humidity (%) | 60 | | | |

Figs. 10 and 11 show the electrical and AE-based PD measurement results for the cable joint after creating the virtual defect. The PRPDs of Sensor 1 (near the simulated PD source) and electrical PRPDs at different voltage and PD levels are depicted in Figs. 12 and 13. The phase shift between the electrical PRPDs and AE-based ones might appear due to different power supply phases of the OptiFender (trigger signal) and HV system.

According to the sensitivity evaluation of the AE-based PD measurement of the cable joint with the simulated PD, it can be concluded that the equivalent sensitivity of the OptiFender is around 5 pC. The lower PD levels could not be simulated virtually. It is expected to detect 2-3 pC defects with the OptiFender according to the results obtained from the clean reference cable joint tests.



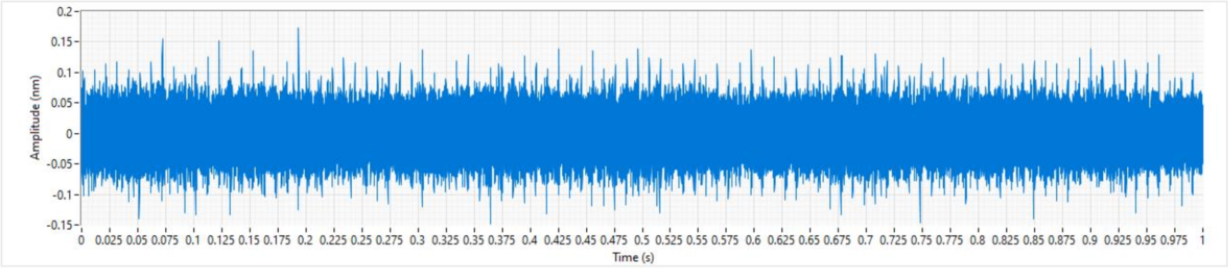
(a)

(b)

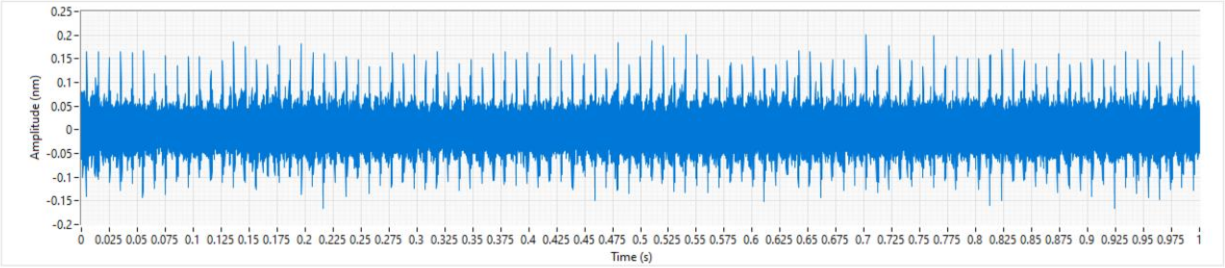
(c)

(d)

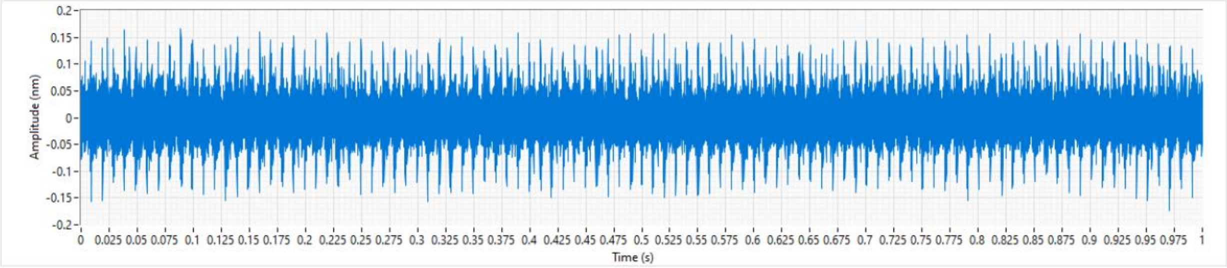
**Fig. 6. Test circuit and test set-up of the PD measurement of 245 kV cable joint with embedded sensor configuration; (a) Test circuit, (b) Test set-up, and (c) Sensor configuration, (d) Sensor locations.**



(a) 247 kV-2.3 pC



(b) 280 kV- 2.6 pC



(c) 300 kV- 2.9 pC

**Fig. 7. Time-domain results of Sensor 1 for the clean reference cable joint at different voltage levels.**

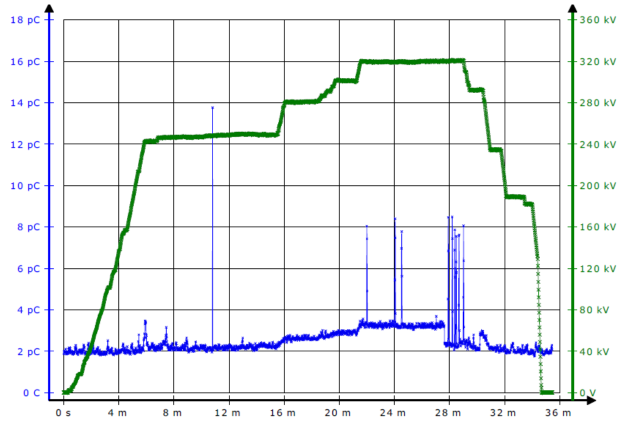
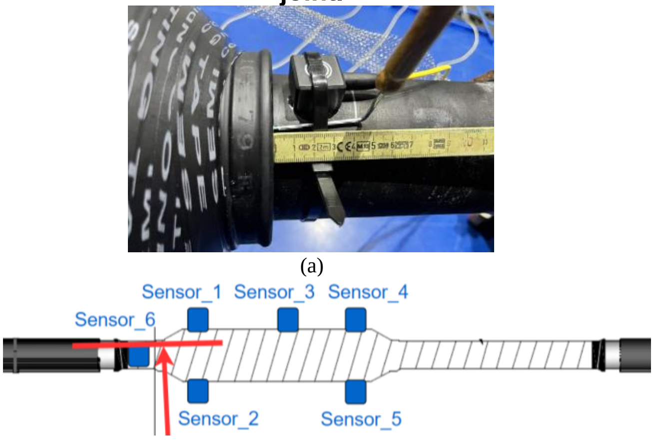


**Fig. 8. Electrical PD measurement (QIEC(t)-VRMS(t)) results for the clean reference cable joint.**



(a)

(b)

**Fig. 9. Simulated PD in the cable joint.**

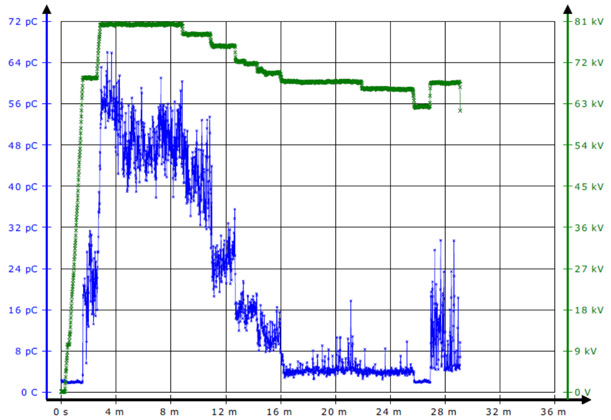
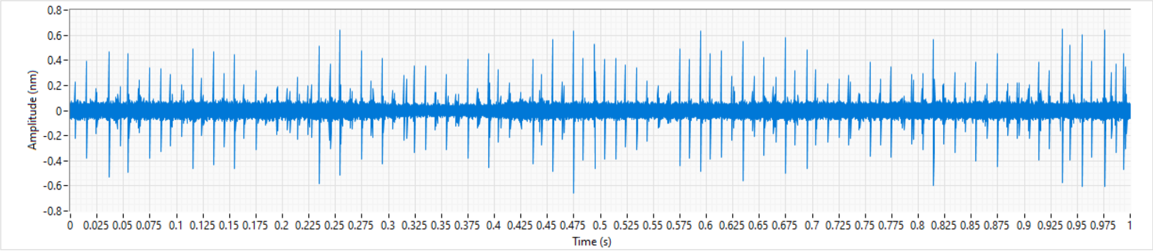


**Fig. 10. Electrical PD measurement (QIEC(t)-VRMS(t)) results for the cable joint with the simulated PD.**

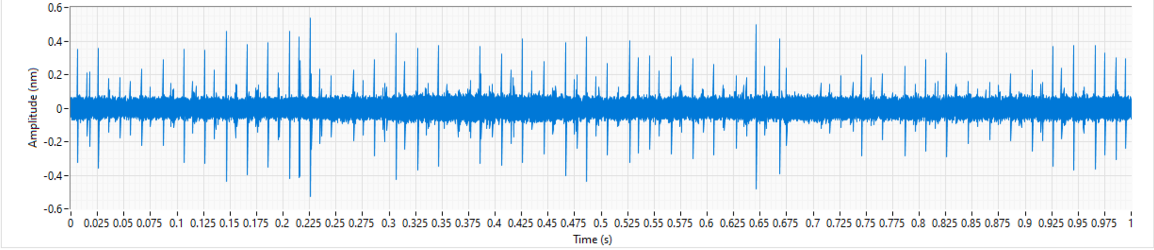
It is concluded that the embedded PD monitoring of the EHV cable joint by the OptiFender is an effective solution. The sensitivity of the PD monitoring is satisfactory, and all PDs and defects could be detected early with the proposed solution. The AE-based PRPDs could be useful for classifying the PD types in further projects and establishing an appropriate database of results and interpretations.

## 5. CONCLUSION

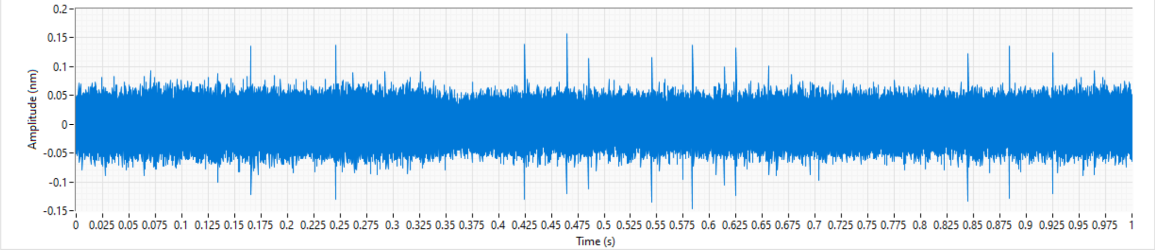
The monitoring of HV and EHV cable systems has received a great deal of attention in recent years. In the cable systems, the cable accessories, e.g., cable joints and cable terminations, are probable sources of defects and failures.



(a) 75.5 kV (20-25 pC)

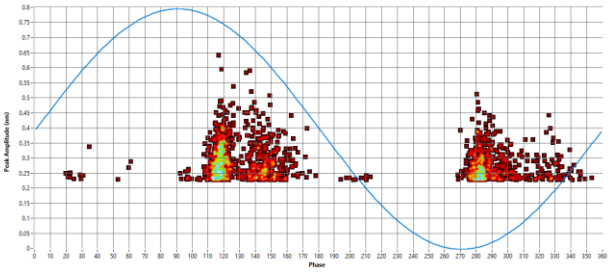


(b) 69.7 kV (14-15 pC)

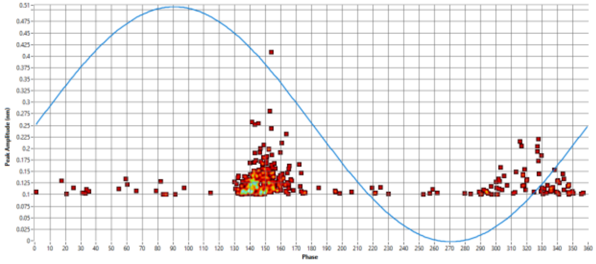


(c) 67.7 kV (5-7 pC)

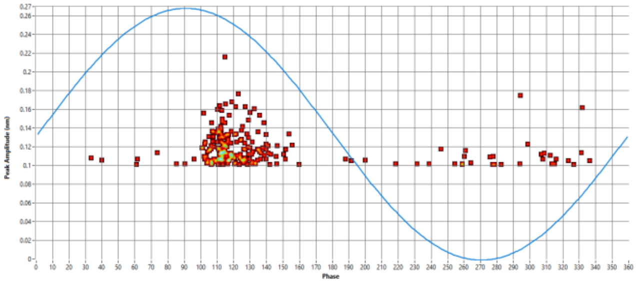
**Fig. 11. Time-domain results of Sensor 1 for the cable joint with the simulated PD at different voltage levels.**



(a) 75.5 kV

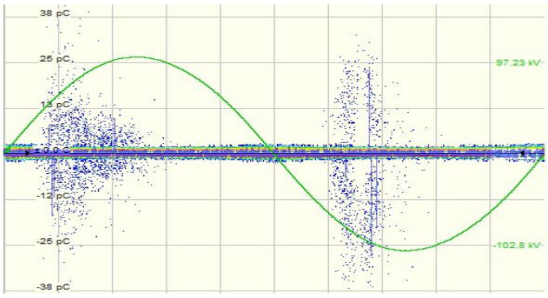


(b) 69.7 kV

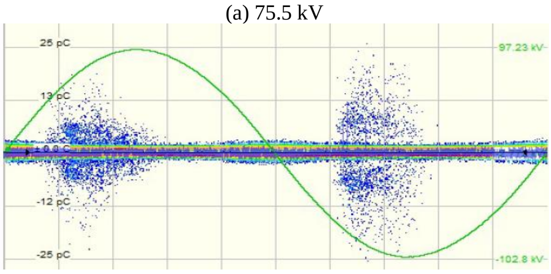


(c) 67.7 kV

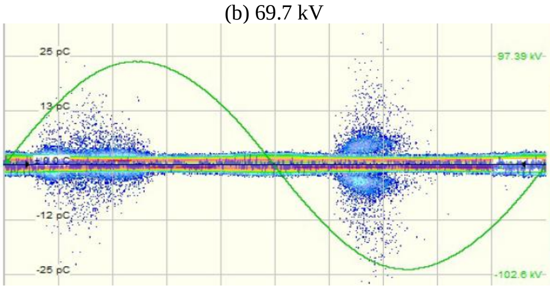
**Fig. 12. AE-based PRPDs of Sensor 1 for the cable joint with the simulated PD at different voltage and PD levels.**



(a) 75.5 kV



(b) 69.7 kV



(c) 67.7 kV

**Fig. 13. Electrical PRPDs for the cable joint with the simulated PD at different voltage and PD levels.**

Different technical issues limit the deployment of conventional PD monitoring methods for HV and EHV cable accessories. In this paper, the FO-AE sensing (OptiFender) technology based on embedded sensor configurations has been examined. The proposed technology has been applied to 245 kV cable joints. The AE-based and electrical PD measurements have been done in the HV lab in India. Test results imply that the proposed solution is highly sensitive, and all PD activities in the EHV cable joints could be detected early by the proposed solution. Indeed, the reliability of the power system and EHV cable networks could be improved, using the smart joints equipped with OptiFender sensors.

In addition to embedded OptiFender sensors to monitor the PD of EHV cable joints, some supplementary evaluations have been done for the retrofitted configuration of sensors. In applications where embedding sensors is not feasible, retrofitted sensor configuration could be an option with some compromise on the sensitivity level. The sensitivity of the retrofitted PD monitoring solution for rejacket heat shrink cable joint is 20-30 pC. This sensitivity level is satisfactory, while the retrofitted sensor installation could be feasible for different projects. In further future industrial publications, results, and discussions on PD monitoring of EHV cable joints, using the retrofitted sensors, would be studied.

## ACKNOWLEDGMENT

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## REFERENCES

[1] Y. Xie *et al.*, “Investigation on cable rejuvenation by simulating cable operation,” *IEEE Access*, vol. 8, pp. 6295–6303, 2020, doi: 10.1109/ACCESS.2019.2963423.

[2] Z. Wu *et al.*, “Analysis of influencing factors on buffer layer discharge for high-voltage XLPE cable,” *IET Generation, Transmission & Distribution*, vol. 16, no. 20, pp. 4142–4157, Oct. 2022, doi: https://doi.org/10.1049/gtd2.12585.

[3] E. Zaccone, “High voltage underground and subsea cable technology options for future transmission in Europe,” in *Europacable High Voltage Systems Group, E-Highway 2050, WP3 workshop proceedings, April 15th, Brussels 2014*, Brussels, May 2014.

[4] P. Cichecki, “Testing and diagnosis of high voltage and extra high voltage power cables with damped AC voltages.,” TUDelft, Delft, 2018.

[5] Y. Hao, Y. Chen, Y. Chen, T. Huang, J. Xiao, and L. Yang, “A partial discharge detection system for XLPE cable terminals and acoustic wave sensing characteristics based on fiber optic Mach-Zehnder interferometer,” *IEEE Sens J*, vol. 21, no. 19, pp. 21782–21790, 2021, doi: 10.1109/JSEN.2021.3101835.

[6] A. Ghaderi, A. Mingotti, L. Peretto, and R. Tinarelli, “Effects of mechanical pressure on the tangent delta of MV cable joints,” *IEEE Trans Instrum Meas*, vol. 68, no. 7, pp. 2656–2658, 2019, doi: 10.1109/TIM.2019.2910001.

[7] W. Qin *et al.*, “Distributed detection and acoustic emission waveform retrieval of cable joint partial discharge,” *IEEE Transactions on Power Delivery*, vol. 38, no. 4, pp. 2977–2980, 2023, doi: 10.1109/TPWRD.2023.3276197.

[8] “National Energy Administration, ‘“6.5” failure blackout situation of Shanghai power grid,’ 2013. Accessed: Dec. 15, 2022. [Online]. Available: http://www.nea.gov.cn/2013-06/06/c_132436249.htm.”

[9] A. Ragusa, H. Sasse, and A. Duffy, “Towards modeling partial discharge phenomena and propagation in power networks using the transmission-line matrix method,” *Energies (Basel)*, vol. 14, no. 3, Feb. 2021, doi: 10.3390/en14030689.

[10] C.-K. Chang and H.-H. Chang, “Learning entirely unknown classes in time-series data using convolutional neural networks for insulation status assessment of partial discharges in power cable joints,” *IEEE Transactions on Dielectrics and Electrical Insulation*, p. 1, 2023, doi: 10.1109/TDEI.2023.3280441.

[11] X. Hu, S. Yang, Q. Du, X. Chen, and F. Tang, “Radio-frequency detection of partial discharge in power cable joints,” *IEEE Transactions on Power Delivery*, pp. 1–7, 2023, doi: 10.1109/TPWRD.2023.3334310.

[12] W. Qin, G. Ma, S. Wang, J. Hu, T. Guo, and R.-B. Shi, “Distributed discharge detection based on improved COTDR method with dual frequency pulses,” *IEEE Trans Instrum Meas*, vol. 72, pp. 1–8, 2023, doi: 10.1109/TIM.2023.3246483.

[13] H. D. Ilkhechi and M. H. Samimi, “Applications of the acoustic method in partial discharge measurement: A review,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 28, no. 1, pp. 42–51, 2021, doi: 10.1109/TDEI.2020.008985.

[14] S. Liu, F. Yu, R. Hong, W. Xu, L. Shao, and F. Wang, “Advances in phase-sensitive optical

time-domain reflectometry," *Opto-Electronic Advances*, vol. 5, no. 3, 2022, doi: 10.29026/oea.2022.200078.

[15] H. Zhou *et al.*, "Optical sensing in condition monitoring of gas insulated apparatus: a review," *High Voltage*, vol. 4, no. 4, pp. 259–270, Dec. 2019, doi: https://doi.org/10.1049/hve.2019.0128.

[16] P. Zhu, H. Wen, Q. Che, X. Li, and X. Liu, "Disturbed PD detection system based on improved φ-OTDR assisted by wFBG array," in *2019 18th International Conference on Optical Communications and Networks (ICOCN)*, 2019, pp. 1–3. doi: 10.1109/ICOCN.2019.8934677.

[17] P. Rohwetter, R. Eisermann, and K. Krebber, "Distributed acoustic sensing: towards partial discharge monitoring," in *Proc.SPIE*, Sep. 2015, p. 96341C. doi: 10.1117/12.2194850.

[18] A. R. Zadeh, "Monitoring of smart HV cable joints with embedded fiber optic-based acoustic partial discharge sensors." *Jicable Conference*, Lyon, France, 2023.

[19] A. R. Zadeh, N. Piva, and L. Castro Heredia, "Partial discharge detection and characterization with optical acoustic emission sensors", Optics11 white paper, 2021.

[20] M. Sorgente, A. R. Zadeh, and A. Saidoun, "Performance comparison between fiber-optic and piezoelectric acoustic emission sensors." Optics11, 2020.

[21] A. R. Zadeh and N. Lebedev, "Partial discharge detection in HV and MV terminations with fiber optic sensors." Proceedings of the SPIE, Volume 12643, id. 126430R 4 pp. (2023).

[22] A. R. Zadeh and L. C. Heredia, "Partial discharge detection in high-voltage gas insulated switchgear using fiber optic based acoustic sensors", Optics11 white paper, 2021.

[23] A. R. Zadeh *et al.*, "PD detection in inverter-fed machines using acoustic emission sensors.A preliminary investigation," in *2022 IEEE Electrical Insulation Conference, EIC 2022*, Institute of Electrical and Electronics Engineers Inc., 2022, pp. 280–283. doi: 10.1109/EIC51169.2022.9833214.

[24] A. R. Zadeh *et al.*, "PD detection in inverter-fed machines using acoustic emission sensors. A preliminary investigation," in *2022 IEEE Electrical Insulation Conference (EIC)*, 2022, pp. 280–283. doi: 10.1109/EIC51169.2022.9833214.

[25] "Design basis document for PD acoustic sensors." [Online]. Available: www.optics11.com

[26] A. Hekmati, "Proposed method of partial discharge allocation with acoustic emission sensors within power transformers," *Applied Acoustics*, vol. 100, pp. 26–33, 2015, doi: https://doi.org/10.1016/j.apacoust.2015.07.011.

[27] IEC standard, "Power cables with extruded insulation and their accessories for rated voltages above 150 kV (Um = 170 kV) up to 500 kV (Um = 550 kV) - Test methods and requirements", IEC 62067 standard, 2022.

[28] IEC standard, "High voltage test techniques - Measurement of partial discharges by electromagnetic and acoustic methods", IEC TS 62478, 2016.