An embedded wide-band sensor for PD on-line monitoring of XLPE cable joint

Fangda Fu¹, Xu Yang²,³, Lin Cheng², Luliang Wang¹, Jing Zhang² and Zijun Pan³,⁴

¹Electric Power Research Institute of Hainan Power Grid Limited Liability Company, Haikou 570311, China
²Wuhan Nari Limited Liability Company of State Grid Electric Power Research Institute, Wuhan 430074, China
³School of Electrical Engineering and Automation, Wuhan University, Wuhan 430072, China
⁴E-mail: panzijunw@163.com

Abstract. Monitoring partial discharge (PD) activities in the joint of cross-linked polyethylene (XLPE) cables has attracted much attention due to its extensive application and high fault rate. In this paper, we designed a wide-band sensor with simple configuration, which was embedded in the outer semi-conductive layer of the cable. Based on the analysis of circuit and antenna models, the structural parameters of sensor were determined, and it was found that the effective bandwidth reached up to 500 MHz. In addition, the sensor had a quick response to the pulse with a rising time longer than 2 ns by testing its square response, as well as a linear input-output characteristic and a sensitivity of 3 pC. At last, the sensor was applied to insulation defect type identification in the cable joint. As for three common defects, both the single PD pulse and PD patterns showed distinct. These indicated that the sensor had a potential application prospect in the PD online detection for cable joint.

1. Introduction

Due to the advantages of excellent electrical performance, high heat resistance, superior mechanical performance, convenient installation and environment-friendly characters, the high-voltage (HV) cross-linked polyethylene (XLPE) cables have been extensively applied in power grids [1-4]. In a long period of operation, the cables will suffer from combined effects of electric field, heating, forces and so on, leading to the formation of voids, cracks or electrical trees [5-7]. These defects degrade the insulation of XLPE cables and will further develop into insulation failures, posing a serious threat to power systems. According to a survey, the failures are distributed at the cable joint, termination and body with the proportion of 37%, 32% and 31% [8, 9]. Therefore, as for the XLPE cables, the safety operation of cable joints should attract much more attention.

At the insulation defects, the electric field distribution distorts due to the non-uniform parameters and configuration of dielectrics, and a localized gas breakdown may take place, which is named partial discharge (PD). Because the PD is sensitive to the existence of defects, it is usually considered as an effective method to detect the defects [10, 11]. Moreover, the characters of PDs are relevant to the defects, so it is also used to diagnose the insulation status of XLPE cables, mainly including defect type identification and fault location.
Nowadays, with the development of signal sensing and processing technologies [12-14], the on-line measurement of PDs has become a common practice for assessing the insulation condition of power equipment, e.g. XLPE cables. This measurement is carried out during normal operation equipment, so the electrical service is not interrupted for the testing. In addition, it allows continuously monitoring of utilities, which is very useful for the defect type identification and facilitates the analysis of the defects’ evolution over time. As for XLPE cables, especially cable joints, two types of methods have been proposed to monitor PD activity, including non-electrical and electrical techniques. The former mainly indicates optical and acoustic emission detection methods, while the latter consists of high frequency current transducer (HFCT), ultra-high frequency (UHF) antenna, difference method, directional coupling method and inductor coupler. Compared with the non-electrical method, the latter usually has a higher sensitivity and easily obtains richer information of PD signals.

Owing to the complicated configuration of cable joints, there are no methods to completely meet the demands of PD monitoring on site up to now. Inspired by a capacitive coupler with high sensitivity and very-high frequency (VHF) bandwidth, which was initially designed for the off-line measurement, a novel sensor for PD on-line monitoring was developed in this paper. At first, the sample configuration was proposed, and its structural parameters were determined based on the circuit and antenna models. Then the transient response and input-output characteristics were tested, as well as the sensitivity. At last, its application to insulation defect identification was investigated.

2. Design of the Sensor

2.1. Configuration of the Sensor

A 110 kV XLPE cable (model: YJLW02, 1×500 mm²) was employed, which mainly consisted of six layers. From the outermost to the innermost, these were sheath, metallic shield, outer semi-conductive layer, XLPE, inner semi-conductive layer and conductor. At first, the sheath and metallic shield were stripped off. Then a copper ring was embedded and fixed on the outer semi-conductive layer in the usage of polypropylene film as a supporting component. Meanwhile, two clamp-type semicircular flanges bridged metallic fractures so that the shield was recovered, as Figure 1. With the application of power frequency voltage, the electric potential of outer semi-conductive layer was almost equivalent to that of metallic shield due to the resistance of semi-conductive layer much smaller than the insulation. Both of them could be considered as the earth potential, so the introduction of embedded ring would have no effects on the electric field distribution of the cable, and did not negatively affect the normal operation.

![Figure 1. The embedded wide-band sensor. (a) Configuration of the sensor; (b) Physical map of the sensor.](image-url)
2.2. **Confirmation of sensor parameters**

The PD source induced by an insulation defect within a cable joint was considered as a pulse current source. It propagated along the axial direction of cable, leading to the spatial and temporal evolution of electromagnetic wave. During this process, the sensor obtained PD signals either by capacitive coupling or electromagnetic radiation receiving.

2.2.1. **Capacitive coupling.** Due to the coaxial configuration of cable, the sensor could be considered as a capacitance divider, which obtained PD signals by capacitive coupling when the frequency was below UHF (300 MHz-3 GHz) [15]. The circuit model is shown in Figure 2. \( C_1 \) is the capacitance between the conductor and the ring electrode, while \( C_2 \) is the capacitance between the ring electrode and the metallic shield. They made up the high-voltage and low-voltage arms of divider, respectively. \( Z_0 \) indicates the characteristic impedance of XLPE cable, \( L_s \) is the stray inductance of metallic wire from the ring electrode to the Bayonet Nut Connector (BNC), and \( Z_L \), with the value of 50 Ω, represents the input impedance of measurement system. In order to avoid high frequency oscillation induced by \( L_s \) and \( C_2 \), two identical resistors were introduced between the electrode and the metallic flanges. Their values are indicated by \( R \).

\[
\begin{align*}
\text{Figure 2. Circuit model of capacitive coupling.}
\end{align*}
\]

The capacitance of the cable per unit length, \( C_0 \), is expressed as

\[
C_0 = \frac{2\pi\varepsilon_0 \varepsilon_r}{\ln(D_i/D_c)}
\]

where \( \varepsilon_0 \) indicates the vacuum permittivity, with the value of \( 8.85 \times 10^{-12} \) F/m, and \( \varepsilon_r \) indicates the relative permittivity of 2.3. \( D_i \) is the outer diameter of main insulation layer, and \( D_c \) is the outer diameter of the inner semi-conductive layer. They were 61.1 mm and 26.1 mm, respectively.

The inductance of the cable per unit length, \( L_0 \), is expressed as

\[
L_0 = \frac{\mu_0 \mu_r \ln(D_i/D_c)}{2\pi}
\]

where where \( \mu_0 \) is the vacuum magnetic permeability, equal to \( 4\pi \times 10^{-7} \) H/m, and \( \mu_r \) is the relative permeability of XLPE, with the approximate value of 1. Based on the Equations (1) and (2), \( Z_0 \) is approximately expressed as follows as

\[
Z_0 = \sqrt{\frac{L_0}{C_0}}
\]

As for the circuit model, \( R \), \( C_1/C_2 \) and \( L_s \) would affect the performance of sensor. Based on the transfer function as follows
\[ H(f) = \frac{V_0(f)}{V_i(f)} = \frac{j2\pi fZ_C C_i}{j2\pi fZ_L(C_1 + C_2) - (2\pi f)^2 L_s(C_1 + C_2) + (j2\pi fL_s + Z_L)/R + 1} \]  \hspace{1cm} (4)

where \( f \) is the frequency, the effects of the above parameters on the sensor’s amplitude-frequency response were calculated.

Figure 3 shows the amplitude-frequency under different \( L_s \). It was found that the sensor was equivalent to a high-pass filter, the effective bandwidth at -20 dB of which ranged from 30 MHz-500 MHz. As the frequency increased, the sensor response enhanced. When the frequency was below 100 MHz, the curves of (a) and (b) were both linear and almost superimposed. It meant that the effect of \( L_s \) could be neglected in this frequency range. When the frequency was between 100 MHz and 300 MHz, the gain with \( L_s=8 \) nH was slightly higher. After the frequency further exceeded 300 MHz, \( L_s \) would seriously reduce the gain. In this case, the circuit model is actually non-applicable [15], and an antenna model will be proposed in the later content.

**Figure 3.** Effect of \( L_s \) on the sensor’s amplitude-frequency with \( C_1=9 \) pF, \( C_2=21 \) pF and \( R=2 \) kΩ: (a) \( L_s=8 \) nH; (b) \( L_s=0 \) nH.

In addition, the effects of \( C_1/C_2 \) and \( R \) on the amplitude-frequency were investigated, as Figures 4 and 5. It was found that the high frequency response characteristics of sensor were greatly improved as \( C_1/C_2 \) increased. If \( R \) was larger than 2 kΩ, its effect could be neglected. Therefore, \( R \) was chosen to be 2.5 kΩ.

**Figure 4.** Effect of \( C_1/C_2 \) on the sensor’s amplitude-frequency with \( R=2 \) kΩ and \( L_s=8 \) nH: (a) \( C_1/C_2=5/9 \); (b) \( C_1/C_2=21/9 \); (c) \( C_1/C_2=50/9 \); (d) \( C_1/C_2=100/9 \).
Figure 5. Effect of $R$ on the sensor’s amplitude-frequency with $C_1=9\,\text{pF}$, $C_2=21\,\text{pF}$ and $L_s=8\,\text{nH}$: (a) $R=50\,\Omega$; (b) $R=100\,\Omega$; (c) $R=500\,\Omega$; (d) $R=5\,\text{k}\Omega$.

Look back Figures 1 and 2, it was found that $C_1$ was relevant to $C_0$ and the ring width, and $C_2$ mainly depended on the distance between the ring and the flanges. Based on the above analysis, we arrived at conclusions that the ring width or the distance should be increased to improve the response characteristics of sensor. And $L_s$ should be restricted by reducing the wire length from the ring electrode to the BNC.

2.2.2. Antenna coupling. If the signal frequency exceeded the VHF band, the circuit model was not applicable [15]. When it was in the UHF band, the sensor received the signal by electromagnetic coupling. In this case, an antenna model should be used to analyze the response characteristics [15]. Figure 6 shows the equivalent circuit of sensor in the UHF band. The sensor acted as a receiving antenna with the open circuit voltage of $V_i$. $\dot{Z}_a$ indicates the antenna impedance, which is made of $C_a$ in series with $R_a$. Therefore, $\dot{Z}_a$ is expressed as

$$\dot{Z}_a = R_a + jX_a = R_a + \frac{1}{j2\pi fC_a}$$

(5)

And $\dot{Z}_L$ is the input impedance of the measurement system, $\dot{Z}_L = R_L + jX_L$.

![Figure 6. The equivalent circuit of sensor in the UHF band.](image)

After the sensor was mounted on the cable, the shape of metallic flanges should be considered. Figure 7 shows the equivalent circuit of sensor mounted on the cable. 22’ indicates the uniform
transmission line starting from the middle between the sensor lead wire and the flanges to the signal output termination (33'). Its length was \( L_d \), and the impedance was \( Z_d \). \( Z \) indicates the output impedance of sensor.

![Figure 7. The equivalent circuit of sensor mounted on the cable in the UHF band.](image)

Take the terminal of lead wire 33' as the reference, the input impedance \( \hat{Z}_i \) is expressed as follows

\[
\hat{Z}_i = Z_d \times \frac{\hat{Z}_a + jZ_d \tan(\frac{2\pi L_d f}{c})}{Z_d + j\hat{Z}_a \tan(\frac{2\pi L_d f}{c})}
\]  

(6)

where \( c \) is the light velocity, equal to \( 3\times10^8 \) m/s. Moreover, the transfer function is

\[
\hat{Z}_i = Z_d \left| \frac{\hat{V}_a}{\hat{V}_i} \right| = \frac{Z}{|Z + \hat{Z}_i|}
\]  

(7)

Because the configuration of sensor was similar to the microstrip patch antenna, \( R_a \) and \( C_a \) can be expressed as [16].

\[
R_a = \frac{90(c/f)^2}{w^2}
\]  

(8)

\[
C_a = \frac{wr}{f}
\]  

(9)

where \( w \) is the width of the ring, and \( r \) indicates its radius. Based on the Equation (6), \( \hat{Z}_i \) could be calculated if \( L_d \), \( w \) and \( r \) were pre-set. Moreover, the frequency-amplitude response was obtained by the Equation (7) with \( Z=50 \) \( \Omega \).

Figure 8 shows the effects of \( L_d \), \( r \) and \( w \) on the response. For each curve in sub-figures, it was found that the gain linearly increased with the frequency from 300 MHz to 1 GHz. If it exceeded 1 GHz, the gain reached saturated or even became lower. In detail, increasing the length of lead wire could improve the amplitude-frequency response, but when it increased to 30 mm, the gain would decrease after the frequency was higher than 2 GHz, as Figure 8(a). The increase of ring radius was also helpful to improve the response. When it reached 50 mm, the gain was in saturation when the frequency exceeded 2 GHz, as Figure 8(b). In addition, the effect of ring width on the response was similar to that of lead wire length, as Figure 8(c).
In terms of the circuit and antenna models, it was found that increasing ring width could improve the amplitude-frequency response of sensor in both cases. The increase of sensor radius would have a negative effect on the response for the circuit model, but positively affect it for the antenna model. Therefore, designing sensor configuration should take the two models into account, as well as the cable configuration. Here, we chosen \( L_d = 20 \text{ mm}, w = 30 \text{ mm}, r = 40 \text{ mm} \) to manufacture the sensor.

![Graph](image)

**Figure 8.** The effects of sensor configuration on its frequency-amplitude response: (a) \( L_d \) varied, \( w = 30 \text{ mm}, r = 40 \text{ mm} \); (b) \( r \) varied, \( w = 30 \text{ mm}, L_d = 20 \text{ mm} \); (c) \( w \) varied, \( r = 40 \text{ mm}, L_d = 20 \text{ mm} \).

### 2.3. Test of Sensor performance

#### 2.3.1. Transient response characteristic

In order to test the detection ability of the sensor for transient pulse signals, the square wave response method was used. In the test, a 50 \( \Omega \) matched resistor was connected to the cable terminal, as Figure 9. After a square pulse with the rise part of 2 ns and amplitude of 512mV was injected into the cable conductor in the usage of arbitrary signal generator (AFG3252), the output signal was observed by the oscilloscope (LeCroy 7100). It was reasonable to represent a PD signal with the fast rising part, i.e. several nanoseconds. Figure 10 shows the waveform of input and output signals. It was found that the sensor could restore the rise part of square correctly, and there was a slight oscillation for the output signal. However, the falling part appeared distinct. It was because that the coupling capacitance of sensor was much lower than the cable capacitance, which led to a large difference between initial voltage ratio and steady one.
2.3.2. Input-output characteristic. The input-output characteristic of sensor was tested according to Figure 9. The amplitude of input square waveform ranged from 50 mV to 2000 mV, and the output signal was recorded, as Figure 11. Obviously, there was a linear relationship between the input and output signals. It indicated that the sensor could reflect PD magnitude proportionally, which would facilitate the PD measurement.

2.3.3. Sensitivity. In Figure 9, the signal generator was replaced by a correction pulse generator (KJF96-1), and the charges with 1 pC, 3 pC, 5 pC, and 10 pC were injected, respectively. It is found that if the input signal was larger than 3 pC, the output one could be distinguished in the usage of the sensor. Therefore, the sensitivity was about 3 pC.
3. PD characteristics obtained by the sensor under different defects

Based on the design of wideband sensor, a PD measurement system for the prefabricated cable joint was established, as Figure 12. The maximum output voltage of transformer was 100 kV, and it was free of PD. The ratio of capacitance divider was 1000:1, and the protective resistor was 10 kΩ. Two cables, each in the length of 4.2 m, were connected by a joint, and a termination was mounted on each terminal of cable body. Apart from the wideband sensor, a HFCT was used to monitor PD current for comparison, which was installed on the wire from the metallic shield to the earth.

![Figure 12. Schematic of the PD measurement system for the cable joint.](image)

In order to verify the sensor’s ability to detect PD signals, three common types of insulation defects were introduced into the prefabricated cable joint, as Figure 13. Semi-conductive particles may be not cleaned up during the installation process, and some remained on the surface of main insulation layer. These particles would induce the distortion of localized electric field, leading to the occurrence of PDs. Because the effect of semiconductor on electric field was similar to that of metal in this case, a rectangular aluminum foil (2 mm × 3 mm) was embedded on the surface of XLPE, as Figure 13(a). As for the needle defect, it came from the nonuniform crosslinking of semi-conductive layer, burrs on the metallic shield or the deformation of connection tube. Here, we placed a needle with the length of 3
mm and tip radius of 0.2 mm to the surface of connection tube, as Figure 13(b). In addition, the void defect resulted from cavities within insulation or surface scratch. In order to simulate it, a cylindrical cavity with the diameter of 2 mm and height of 0.02 mm was introduced on the surface of XLPE, as Figure 13(c).

Before tests, an increasing AC voltage with the frequency of 50 Hz was applied to a healthy cable joint (as Figure 12). After it increased to 80 kV, there was no PD signal obtained either by the wide-band sensor or HFCT. This indicated that the partial discharge inception voltage (PDIV) for the measurement system without insulation defects was higher than 80 kV. As for each defect, the PDIV was measured at first, and then the test voltage was set to be 1.1 times the PDIV, which should not exceed 80 kV.

3.1. Characteristics of Single PD Pulse

Figure 14 shows the waveform of PD pulse obtained by the wide-band sensor under three kinds of insulation defects, as well as the frequency spectrum. The PD pulse induced by metallic contamination appeared as several peaks, followed by oscillations. The duration of pulse was about 330 ns, and the frequency was below 150 MHz. As for the needle defect, a pulse with one peak, followed by oscillations, was observed. The pulse duration was about 280 ns, and the frequency was below 200 MHz. The PD pulse resulting from the void defect had a single peak and weak oscillations, the duration time of which was about 150 ns. Therefore, the characteristics of single PD pulse obtained by the sensor showed distinct for different insulation defects, which was helpful to defect type identification. Table 1 lists the parameters related to PD pulse characteristics under three types of defects so that the differences could be quantitatively addressed.

![Figure 14](image)

**Figure 14.** Waveform of PD pulse and the corresponding frequency spectrum under various defects. (a) Metallic contamination, (b) Needle, (c) Void.
### Table 1. Parameters of PD pulse resulting from different insulation defects.

| Defect type       | PDIV (kV) | Peak value (mv) | Rising part (ns) | Duration time (ns) | Frequency (MHz) |
|-------------------|-----------|-----------------|------------------|-------------------|-----------------|
| Metallic contamination | 21        | 40              | 4.5              | 330               | <150            |
| Needle            | 13        | 15              | 1.6              | 280               | <200            |
| Void              | 32        | 18              | 2.3              | 150               | <250            |

#### 3.2. PD Pattern

PD signals during 400 cycles were obtained by the sensor, and $\varphi$-$q$-$n$ ($\varphi$: discharge phase, $q$: discharge magnitude, $n$: discharge number) patterns for different defects were depicted, as Figure 15. For the metallic particle defect, the induced PDs were mainly distributed at $50^\circ$-$150^\circ$ and $220^\circ$-$320^\circ$, and the discharges with higher amplitude located at $100^\circ$ and $270^\circ$. The polarity effect was observed for the needle defect. In detail, no discharges appeared under the positive half-cycle, while they took place under the negative one, i.e. $240^\circ$-$320^\circ$. PDs from the void defect had phase distributions at $40^\circ$-$100^\circ$ and $200^\circ$-$280^\circ$, slightly narrower than that from the metallic particle defect. And the discharges with higher amplitude were observed at $70^\circ$ and $240^\circ$. These differences of PD patterns further indicated that it was capable of distinguishing insulation defects in the usage of the wide-band sensor.

![Figure 15. $\varphi$-$q$-$n$ patterns for different insulation defects. (a) Metallic contamination, (b) Needle, (c) Void.](image)

#### 4. Conclusions

In this paper, an embedded wide-band sensor was designed with the aim to monitor PD activities in the XLPE cable joint on-line. After its performances were tested and the application to defect type identification was carried out, the conclusions were summarized as follows:

The wide-band sensor mainly consisted of an embedded ring electrode, two flanges and two resistors. On one hand, based on the circuit model, it was found that the ring width should be increased, but the radius should be reduced to improve the response characteristics of sensor. On the other hand, increasing ring width and radius could improve the amplitude-frequency response of sensor for the antenna model. Considering these and the configuration of cable (YJLW02, $1 \times 500 \text{ mm}^2$), the width and radius were set to be 30 mm and 40 mm, respectively.

The effective bandwidth of sensor could reach up to 500 MHz, covering VHF and part of UHF bands. It had a great transit response characteristic with respect to the pulse with the rising rate of 2 ns. This indicated that the sensor was capable of obtaining the PD pulse in cable joint, almost without losing frequency domain information. In addition, the amplitude of input signal was proportional to the output one for the sensor, and its sensitivity was about 3 pC.

The single PD pulse, as well as PD patterns, showed distinct for three types of insulation defects, which indicated that it was capable of identifying insulation defects in the usage of the wide-band sensor.
References

[1] Zhou K, Huang M, Tao W, He M and Yang M 2016 A possible water tree initiation mechanism for service-aged XLPE cables: conversion of electrical tree to water tree IEEE Trans. Dielectr. Electr. Insul. 23 1854-61

[2] Tzimas A, Rowland S, Dissado L, Fu M and Nilsson U 2009 Effect of long-time electrical and thermal stresses upon the endurance capability of cable insulation material IEEE Trans. Dielectr. Electr. Insul. 16 1436-43

[3] Chen X, Wang X, Wu K, Peng Z, Cheng Y and Tu D 2010 Space charge measurement in ldpe films under temperature gradient and dc stress IEEE Trans. Dielectr. Electr. Insul. 17 1796-1805

[4] Chen G, Hao M, Xu Z, Vaughan A, Cao J and Wang H 2015 Review of high voltage direct current cables CSEE. JPES. 1 9-21

[5] Densley J 2001 Ageing mechanisms and diagnostics for power cables - An overview IEEE Electr. Insul. Mag. 17 14-22

[6] Pan C, Chen, G, Tang J and Wu K Numerical modeling of partial discharges in a solid dielectric-bounded cavity: a review IEEE Trans. Dielectr. Electr. Insul.(in press)

[7] Gutierrez S, Sancho I, Fontan L, De No J 2012 Effect of protrusions in HVDC cables IEEE Trans. Dielectr. Electr. Insul. 19 1774-81

[8] Maanen B, Van Plet C and Van Der Wielen P2015 Failures in underground power cables – return of experience, in JICABLE’15 9th Int. Conf. Insulated Power Cables Versailles, France 21–25

[9] Zhou C, Yi H and Dong X 2017 Review of recent research towards power cable life cycle management. High Voltage 2 179-187

[10] Li J, Li X, Du L, Cao M and Qian G 2016 An Intelligent Sensor for the Ultra-High-Frequency Partial Discharge Online Monitoring of Power Transformers. Energies 9

[11] Li T, Li X, Rong M, Wang X and Pan J 2017 Experimental Investigation on Propagation Characteristics of PD Radiated UHF Signal in Actual 252 kV GIS. Energies 10

[12] Rahman M, Naghshvarian Jahromi M, Mirjafari S S and Hamouda A M 2019 Compact UWB Band-Notched Antenna with Integrated Bluetooth for Personal Wireless Communication and UWB Applications. Electronics 8 158

[13] Rahman M, Naghshvarian Jahromi M, Mirjafari S S and Hamouda A M. 2018 Resonator Based Switching Technique between Ultra Wide Band (UWB) and Single/Dual Continuously Tunable-Notch Behaviors in UWB Radar for Wireless Vital Signs Monitoring. Sensors 18 3330

[14] Rahman M, Naghshvarian Jahromi M, Mirjafari S S and Hamouda A M 2018 Bandwidth Enhancement and Frequency Scanning Array Antenna Using Novel UWB Filter Integration Technique for OFDM UWB Radar Applications in Wireless Vital Signs Monitoring. Sensors. 18 3155

[15] Kurrer R, Feser K and Kraub T 1995 Antenna theory of flat sensors for partial discharge detection at ultra-high-frequency in GIS; in The 9th international symposium on high voltage engineering, Austria, Europe, August 28-September 1

[16] Bansal R 2005 Antenna Theory—Analysis and Design John Wiley & Sons Inc Hoboken, America