The Attenuation and Propagation Law of Ultrasonic Wave in UHV Gas Insulated Line

YE FEI, YUNPENG LIU, (Member, IEEE), JIANGBO CHEN, LIN CHENG, MENGQI LI, YI LIU, AND MINFENG SHAO

1Electrical and Electronic Engineering College, North China Electric Power University, Baoding 071003, China
2China Electric Power Research Institute, Wuhan 430074, China
3State Grid Electric Power Research Institute Wuhan Nari Company Ltd., Wuhan 430074, China

Corresponding author: Yunpeng Liu (liuyunpeng@ncepu.edu.cn)

This work was supported in part by the National Key Researcher and Development Program of China under Grant 2017YFB0902500, and in part by the Science and Technology Project of State Grid Corporation of China under Grant GYW11201801543 and Grant GYW11201605592.

ABSTRACT Gas insulated transmission line (GIL) is widely used for power transmission in special geographical environment such as river crossing, mountain crossing and city tunnel crossing scenarios. Because of its totally enclosed structure, it is difficult to locate the fault position when the internal breakdown discharge occurs. Fault location by using the ultrasonic wave aroused by discharge is an efficient method for GIL maintenance. This paper reports the experimental and theoretical results of attenuation and propagation law of ultrasonic signal in GIL. An ultra-high voltage (UHV) GIL model was set up to simulate the geometry and material conditions of real GIL. The common lead breaking signal was adopted to generate ultrasonic source, and the propagation velocity and attenuation coefficient of ultrasonic wave were obtained. The experimental results show that the attenuation coefficient of ultrasonic wave on GIL linear unit is about 0.234 dB/m, and its propagation velocity is about 3.3 km/s. But the attenuation level of ultrasonic wave is much higher when it passes through the epoxy insulators or expansion joints. The validity of the method is verified by the creeping discharge test on the GIL model. In order to analyze the propagation path of ultrasonic wave, the relationship between the path and time is calculated and the shortest propagation time is obtained. The results of this research provide support for the fault location of GIL by ultrasonic wave.

INDEX TERMS GIL, fault location, breakdown discharge, ultrasonic wave, lead breaking signal, UHV, propagation velocity, attenuation law, linear unit, epoxy insulator, expansion joint.

I. INTRODUCTION

Gas insulated transmission line (GIL) is a kind of high-voltage, high-current and long-distance pipeline electric power transmission equipment [1]–[3]. The conductor and shell are insulated by compressed gas insulation such as SF6 or SF6 mixed gas [4]–[6]. GIL is mainly used in urban centers with tight transmission corridors or areas with extremely bad climate or environment, e.g. the first ultra-high voltage (UHV) GIL project crossing Yangtze River [7], [8]. It is quite important to ensure the safety operation of UHV GIL, which requires that the fault must be located in time once it happens.

Current techniques of fault location for electrical equipment mainly include UHF [9]–[11], short-circuit current [12], ultrasonic method and so on [13]–[15]. The time difference of arrival UHF signals generated by discharge can be used to locate the fault. However, the UHF signals are susceptible to background noise [16]. The short-circuit current method is not suitable for GIL when it is running under the condition of small load current. Ultrasonic method has been widely studied and applied in partial discharge (PD) localization for power transformers [17], [18]. It can locate the fault according to the amplitude of ultrasound, which is less affected by background noise, convenient to operate and easy to realize on-line monitoring. However, there are few reports on the application of ultrasound in GIL fault location.

Moreover, data-driven fault location approaches have been widely studied in previous literatures [19], [20], such as a hierarchical event detection method based on spectral theory of multidimensional matrix for power system [21], zero-sequence current suppression strategy with common mode voltage control [22], [23]. Most of these studies are based on
algorithms. However, due to the lack of basic data, such as ultrasonic propagation velocity, attenuation coefficient, and ultrasonic location data and so on, it is difficult to carry out data-driven algorithm research at this stage. The propagation characteristics and attenuation law of ultrasonic wave in GIL are key factors in fault location. The structure and material of UHV GIL are very different from those of ordinary cables and transformers, it may lead to the difference of ultrasonic propagation characteristics and affect the positioning effect. Based on the above problems, the propagation velocity and attenuation law of ultrasonic wave in UHV GIL are studied in this paper.

This paper is organized as follows. The propagation and attenuation characteristics of ultrasound in GIL are firstly studied theoretically and experimentally. Then the verification test is carried out by creeping discharge on the UHV GIL model. Finally, the relationship between the propagation path and time is calculated and the shortest propagation time is analyzed, which provides support for sensor position setting.

II. THEORETICAL STUDY

A. GENERATING MECHANISM OF ULTRASONIC

When discharge fault happens, strong current pulse will be generated. The current heats the discharge channel, making the discharge area expand instantaneously. With the development of discharge, the expansion area returns to the original volume. Because of the volume change of the partial gas, the density of the gas changes instantaneously, thus forming the ultrasonic pulse, including longitudinal wave (LW), transverse wave (TW) and surface wave (SW) [24]. A long GIL is spliced by standard units. A typical UHV GIL usually consists of several 18 m units, such as linear unit, compensation unit, etc., [25], which are shown in Fig. 1. The compensation unit is to eliminate the influence of thermal expansion and cold contraction on the pipeline. In case of discharge fault in GIL, only longitudinal wave could propagate in SF₆ gas, and it will propagate forward in the form of spherical wave. When it reaches the metal shell, the sound wave will collide with the shell and cause mechanical vibration of the shell. The vibration frequency ranges from tens of kHz to hundreds of kHz. The vibration signal can be detected by ultrasonic sensors arranged on the shell. According to the characteristics of phase and amplitude of multiple ultrasonic signals, the discharge fault can be located.

B. THEORETICAL ATTENUATION LAW OF ACOUSTIC

The amplitude of acoustic signal always decreases with the increase of propagation distance. The attenuation of sound wave is expressed by the attenuation coefficient $\alpha$ when it propagates in a certain medium. The expression of attenuation coefficient is shown in (1).

$$\alpha = 20 \log(\frac{p_0}{p})$$

$x$ is the distance between the measurement point and the sound source, $p$ is the sound pressure at the measurement point, and $p_0$ is the sound pressure at the sound source. It can be seen that the attenuation coefficient is the attenuation of sound wave per unit length in the propagation path. According to (1), the sound pressure at the measuring point can be expressed by (2).

$$p = p_0 10^{-\alpha x/20}$$

III. EXPERIMENTAL STUDY

A. EXPERIMENTAL PLATFORM

In order to obtain the attenuation characteristics of ultrasound on real GIL, a 1000 kV GIL model is firstly set up. The experimental platform is shown in Fig. 2. On the linear UHV GIL model, an ultrasonic source point inside the GIL and four ultrasonic sensors on the metal shell are set. These sensors are connected to different channels on the same oscilloscope. The ‘channel’ in Fig. 2 represents the corresponding sensor. The distance between sensors 3 and 4 is 4.3 m, and that between 2 and 3, 1 and 2 are both 3 m. They are not evenly distributed because sensors 1, 2 and 3 are used to measure the propagation velocity but sensors 4 and 3 are used for verification. The sensitivity of the sensor is higher than 75 dB. The sensor used in the experiment is shown in Fig. 3.

The sensors are triggered synchronously through channel 4. The sampling rate of the oscilloscope is 2.5 GS/s and
FIGURE 3. The ultrasonic sensor used in the experiment model (Center frequency 150 kHz, detection frequency 20 kHz–180 kHz).

FIGURE 4. Ultrasonic signals detected by four sensors at different positions on the GIL metal shell.

FIGURE 5. Relative amplitude of the ultrasonic signal on GIL shell at different distances.

The bandwidth is 500 MHz. The ultrasonic source is generated by pencil lead breaking signal, which is a common way to produce ultrasound [26]–[28]. A 60 dB preamplifier is used in the measurement.

B. EXPERIMENTAL RESULTS

1) THE PROPAGATION VELOCITY

Firstly, we measured the propagation velocity of ultrasound passing through UHV GIL pipeline using several ultrasonic sensors in a given spacing interval. The propagation velocity equals to the distance between adjacent sensors divided by the time the ultrasound passes. The ultrasonic signals detected in the experiment are shown in Fig. 4. It can be seen that the ultrasonic signal has time delay at different measuring points. The time delay between No. 3∼No. 2 and No. 2∼No. 1 is equal and less than that between No. 4∼No. 3. This is because the distance between No. 3 and No.4 is about 4.3 m, more than 3 m, which is set to verify the accuracy of measurement. According to the distance and time delay between the measuring points, it can be calculated that the propagation speed of ultrasound on the UHV GIL metal shell is about 3333 m/s. This data provides a basis for ultrasonic fault location in UHV GIL equipment.

2) THE ATTENUATION CHARACTERISTICS

The relationship between the measured signal amplitude and the distance from the sound source is obtained by moving the measuring point No.4 repeatedly. So as to evaluate the attenuation amplitude of ultrasonic signal on GIL shell. Fig. 5 shows the experimental results of attenuation characteristics of ultrasonic amplitude with distance on GIL shell.

The measured data points are exponentially fitted, which is convenient to obtain the attenuation coefficient from equation (2). The fitting curve is shown as the solid line in Fig. 5, and the fitting expression is shown in (3). According to the definition of attenuation coefficient in (2), the attenuation coefficient of ultrasonic signal propagating in GIL shell is about 0.234 dB/m. This means that the amplitude of the signal attenuates to 97.3% of the current amplitude every 1 m forward. In other words, the amplitude of the signal decreases by 50% every 26 m. These characteristics are helpful for the development of UHV GIL discharge fault positioning scheme using ultrasonic signal.

\[
\frac{p}{p_0} = 1.01 \times 10^{-0.0117x} \quad (3)
\]

\[
\alpha = 0.234 \text{ dB/m} \quad (4)
\]

The above ultrasonic attenuation characteristics only involve the GIL shell. However, when the ultrasonic passes through the GIL section with insulator and expansion joint, its attenuation characteristics may be very different, thus affecting the positioning results. In order to obtain the attenuation characteristics of ultrasonic passing through insulator, expansion joint, etc., we changed the position of measuring point No.4, and measured the ultrasonic amplitude before and after passing through these structures respectively. Fig. 6 (a) and Fig. 6 (b) are the measurement results. Fig. 6 (c) shows the attenuation of ultrasound across the two structures. It can be seen that when ultrasonic passes through GIL unit with insulator or expansion joint, the amplitude of ultrasonic attenuates obviously. Especially when passing through the expansion joint, the amplitude of ultrasonic signal attenuates nearly 90%. It is estimated that the attenuation degree of passing through the insulator and expansion joint is equivalent to the attenuation when they propagate about 45 m and 86 m in the linear GIL shell respectively.

It is known from the above experimental results that when setting up the ultrasonic sensor, if the insulator or expansion joint is encountered, the sensors should be set up on both sides respectively.

IV. VERIFICATION TEST STUDY

In order to verify the effectiveness of the ultrasonic positioning method, the UHV GIL unit is selected to generate
the internal breakdown fault and detect whether the fault positioning device reacts timely and accurately.

A. FAULT DISCHARGE UNIT AND SENSORS SETTING
The fault discharge unit is a section of GIL isolation unit specially developed to simulate the real GIL internal breakdown discharge. The unit can simulate the breakdown discharge fault of GIL conductor to the shell without current. The structure of discharge unit is shown in Fig. 8, which is composed of conductor, shell, insulator, and discharge point electrode. The overall dimension is consistent with that of UHV GIL. The length of point electrode can be adjusted to control breakdown discharge of GIL under different voltage levels. The fault discharge unit is installed on the upper part of GIL straight section, as shown in Fig. 7.

The fault location ultrasonic sensors are SRI 150 with center frequency of 150 kHz. They are fixed on the GIL shell with stainless steel hoop and 3D printing fixture, and the sensor arrangement is shown in Fig. 9. There are 5 sensors in total, the first one is arranged near the fault discharge unit, and the last one is arranged at the end of the line section of GIL. There is only one expansion joint between the 1st and 5th sensors, which is located between the 2nd and 3rd sensors, and the basin insulator is located inside the right corner unit of the 5th sensor.

B. ANALYSIS OF THE VERIFICATION TEST STUDY
When high voltage is applied to the GIL model, the fault discharge unit is controlled to conduct internal breakdown discharge at 100 kV with lower energy. Test the signal received by each sensor, and the fifth sensor (about 40m away) with the farthest measurement can receive the signal, as shown in Fig.10 and Fig.11.

From Fig.11, it is seen that the first sensor has the maximum signal. The signal attenuation of the second to third sensors is about 70%, and the signal is basically not detected in the right compartment of the fifth sensor. It shows that the maximum distance of ultrasonic that can be measured in engineering is about 30 m when the breakdown discharge with lower energy occurs in GIL.

The breakdown point can be located by the attenuation characteristics of ultrasound. According to the ultrasonic attenuation law expressed in (3), the ultrasonic pressures...
detected by sensor 2 and sensor 3 meet (5). \( L \) is the distance between sensor 2 and sensor 3, \( L = 10 \) m. Thus, the ratio of \( p_2 \) to \( p_1 \) is about 76\%, which is consistent with the experimental results. It also proves the correctness of the attenuation coefficient \( \alpha \) measured in this study. The attenuation characteristics of ultrasonic determine the number and arrangement of sensors in engineering.

\[
\log \frac{p_2}{p_3} = 0.0117L 
\]  

(5)

**C. POSITIONING ERROR ANALYSIS**

It is relatively easy to locate the strong discharge such as breakdown discharge. Fig.12 shows the schematic diagram of ultrasonic positioning principle for GIL breakdown fault. Suppose that the breakdown point \( D \) is between sensor \( A \) and sensor \( B \), the distance between discharge point \( D \) and sensor \( A \), sensor \( B \) can be expressed by (6) and equation (7). \( \Delta t \) means the time difference of arrival of ultrasonic signal between sensors \( A \) and \( B \). If \( \Delta t \) is greater than 0, the signal will arrive at sensor \( B \) first, meaning that \( L_1 \) is greater than \( L_2 \). When \( \Delta t \) is smaller than 0, the signal first reaches sensor \( A \), meaning that \( L_1 \) is smaller than \( L_2 \). Therefore, equations (6) and (7) have comprehensively considered the case that \( L_1 \) is greater than \( L_2 \) and smaller than \( L_2 \). It can be seen from (7) that the positioning accuracy is determined by the accuracy of \( \Delta t \). In addition, the positioning accuracy is also affected by the ultrasonic propagation velocity \( c \). E.g., when the accuracy of \( \Delta t \) reaches \( \pm 0.1 \) ms, the positioning accuracy is about \( \pm 0.16 \) m, which is enough to meet the GIL fault location requirements.

\[
\begin{align*}
\frac{c \Delta t}{L_1} &= L_1 - L_2 \\
L &= L_1 + L_2 \\
L_1 &= \frac{1}{2}(L + c \Delta t) \\
L_2 &= \frac{1}{2}(L - c \Delta t)
\end{align*} 
\]  

(6)

V. ANALYSIS OF MULTIPLE PROPAGATION PATH

Fig.13 shows the typical PD defects in GIL, i.e. protrusion discharge on the conductor, metal particle discharge and gap discharge at three junction points [29]–[33]. The multiple propagation path of ultrasonic needs to be considered as the location of different defects is different. The path of the ultrasonic signal from the discharge point to the shell is different under different discharge types. E.g., the ultrasonic by protrusion discharge will be transmitted in almost vertical direction, while the discharges involving the insulator will be transmitted through the insulator and most of the signal attenuates.

Multiple propagation path of the ultrasonic wave could affect the accuracy of fault location. This can be illustrated in Fig.14. From the discharge point \( B \) to the detection point
C, there are multiple paths for ultrasonic signal. There is one path that needs the shortest time. The shortest time path is related to the location of discharge point and the propagation speed of ultrasonic in gas and metal materials. Therefore, when these factors change, especially the discharge position, the signal detected by the sensor may be significantly different, so it is necessary to analyze this characteristic.

The time of ultrasonic signal from B to C can be expressed by (10).

\[ t_s = \frac{h}{v_g \cos \varphi} + \frac{x - h \tan \varphi}{v_m} \]  

(10)

It is important to know the minimum \( t_s \). From the above case, it can be seen that when the relative position of the discharge point and the detection point is determined (namely the value of \( h \) and \( x \) is determined), there is a quantitative relationship between the minimum \( t_s \) and \( \varphi \). Let the partial derivative of \( t_s \) to \( \varphi \) be 0, as shown in (11), then \( \varphi \) will make \( t_s \) minimum. Suppose an auxiliary function \( f(\varphi) \), as shown in (12). When \( f(\varphi) \) is equal to the ratio of \( v_m \) to \( v_g \), as shown in (13), (11) is equal to 0, so \( t_s \) gets the minimum value.

\[ \frac{\partial t_s}{\partial \varphi} = \frac{h \tan \varphi - h (\tan^2 \varphi + 1)}{v_g \cos \varphi - \frac{v_m}{v_m}} \]  

(11)

\[ f(\varphi) = \frac{(\tan^2 \varphi + 1) \cos \varphi}{\tan \varphi} \]  

(12)

\[ f(\varphi) = \frac{v_m}{v_g} \]  

(13)

Fig.16 shows the relationship between \( f(\varphi) \) and \( \varphi \) under specific condition of \( x = 6 \) m and \( h = 0.5 \) m. It can be seen that when \( v_m > 10v_g \), the deviation of angle \( \varphi \) is within 0.1 rad, which can be ignored. The propagation speed of ultrasound in SF6 gas is much lower than in metal, so the shortest propagation path of discharge ultrasonic signal is approximately propagating to metal shell vertically and then to the detection point. In Fig.17, the relationship between the shortest arrival time \( t_s \) and \( x \) under different \( h \) is calculated.
$h = 0.5\ m$ means the discharge happens near the high-voltage conductor; $h = 0$ means the metal shell and $h = 0.3\ m$ means in the middle between conductor and shell.

It can be seen that for different $x$ and $h$, the ultrasonic positioning method has a good location accuracy if the time resolution of the sensor is in the order of micrometer. The relationship between the shortest arrival time and the location of the discharge point and the detection point is given quantitatively, which can provide important support for the follow-up discharge fault location research.

**VI. CONCLUSION**

The following conclusions can be obtained through this research.

1) The attenuation degree of ultrasonic signal in UHV GIL is exponentially related to the propagation distance. The attenuation coefficient is about $0.234\ dB/m$, namely the amplitude of ultrasonic signal is half attenuated for each $26\ m$ forward propagation. When the ultrasonic signal passes through the insulator and expansion joint, the signal amplitude is mostly decayed. It indicates that sensors should be installed on both sides of insulator and expansion joint to eliminate their influence.

2) At small internal breakdown energy in UHV GIL, the breakdown signal can be detected by the sensor less than about $30\ m$ away from the breakdown point. When the detection error of adjacent sensors is controlled within $10\%$, the distance between sensors should be greater than $3.8\ m$. Therefore, the appropriate sensor spacing should be between $3.8\ m$ and $30\ m$. The number of sensors are determined by the length of GIL.

3) The propagation path of shortest time is determined by the propagation velocity of ultrasound in SF$_6$ gas and metal shell. When the ratio of the two is more than $10\times$, the shortest time path can be approximately considered to firstly travel vertically from the conductor to the metal shell, then to the sensors.

**ACKNOWLEDGMENT**

Fei Ye would like to thank the support of the test site provided by CEPRI and the theoretical analysis assistance from Dr. Zheng.

**REFERENCES**

[1] L. Wang, W. Zhang, X. Tan, W. Chen, S. Liang, and C. Suo, “Research and experiments on an external miniaturized VFTO measurement system,” *Sensors*, vol. 20, no. 1, p. 244, Dec. 2019.

[2] Z. Chen, L. Zhang, H. Liu, P. Peng, Z. Liu, S. Shen, N. Chen, S. Zheng, J. Li, and F. Pang, “3D printing technique-improved phase-sensitive OTDR for breakdown discharge detection of gas-insulated switchgear,” *Sensors*, vol. 20, no. 4, p. 1045, Feb. 2020.

[3] R. Benato, C. Di Mario, and H. Koch, “High-capability applications of long gas-insulated lines in structures,” *IEEE Trans. Power Del.*, vol. 22, no. 1, pp. 619–626, Jan. 2007.

[4] Y. Shu and W. Chen, “Research and application of UHV power transmission in China,” *High Voltage*, vol. 3, no. 1, pp. 1–13, Mar. 2018.

[5] T. Magier, M. Tenzner, and H. Koch, “Direct current gas-insulated transmission lines,” *IEEE Trans. Power Del.*, vol. 33, no. 1, pp. 440–446, Feb. 2018.

[6] B. X. Du, H. C. Liang, J. Li, and Z. Y. Ran, “Electrical field distribution along SG6/N2 filled DC-GIS/GIL epoxy spacer,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 25, no. 4, pp. 1202–1210, Aug. 2018.

[7] W. Chen, “The new technological developments of UHV AC power transmission equipment,” in *Proc. ICHVE*, Sep. 2016, pp. 1–6.

[8] J. Zhong, “Research on the key technology of 1100 kV SF6 gas-insulated metal-enclosed transmission line,” in *Proc. IECPE-ST*, Oct. 2017, pp. 30–33.

[9] F. Álvarez, F. Garnacho, J. Ortego, and M. Sánchez-Urán, “Application of HFC7 and UHF sensors in on-line partial discharge measurements for insulation diagnosis of high voltage equipment,” *Sensors*, vol. 15, no. 4, pp. 7360–7387, Mar. 2015.

[10] J. Liu, G. Zhang, J. Dong, and J. Wang, “Study on miniaturized UHF antennas for partial discharge detection in high-voltage electrical equipment,” *Sensors*, vol. 15, no. 11, pp. 29434–29451, Nov. 2015.

[11] L. Norebega, E. Costa, A. Serres, G. Xavier, and M. Aquino, “UHF partial discharge location in power transformers via solution of the maxwell equations in a computational environment,” *Sensors*, vol. 19, no. 15, p. 3435, Aug. 2019.

[12] F. Han, X. Yu, M. Al-Dabbagh, and Y. Wang, “Locating phase-to-ground short-circuit faults on radial distribution lines,” *IEEE Trans. Ind. Electron.*, vol. 54, no. 3, pp. 1581–1590, Jun. 2007.

[13] S. Coenen and S. Tenbohlen, “Location of PD sources in power transformers by UHF and acoustic measurements,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 19, no. 6, pp. 1934–1940, Dec. 2012.

[14] T. Wang, X. Wang, and M. Hong, “Gas leak location detection based on data fusion with time difference of arrival and energy decay using an ultrasonic sensor array,” *Sensors*, vol. 18, no. 9, p. 2985, Sep. 2018.

[15] H.-L. Liu, “Acoustic partial discharge localization methodology in power transformers employing the quantum genetic algorithm,” *Appl. Acoust.*, vol. 102, pp. 71–78, Jan. 2016.

[16] H. Dadashi Ilkhechi, M. H. Samimi, and R. Yousefvand, “Generation of acoustic phase-resolved partial discharge patterns by utilizing UHF signals,” *Int. J. Electr. Power Energy Syst.*, vol. 113, pp. 906–915, Dec. 2019.

[17] D. Antony and G. S. Punekar, “Noniterative method for combined acoustic-electrical partial discharge source localization,” *IEEE Trans. Power Del.*, vol. 33, no. 4, pp. 1679–1688, Aug. 2018.

[18] S. Siddar, “Nondestructive analysis of Debonds in a composite structure under variable temperature conditions,” *Sensors*, vol. 19, no. 16, Aug. 2019, Art. no. 3454.

[19] R. Chen, “Computational fault time difference-based fault location method for branched power distribution networks,” *IEEE Access*, vol. 7, pp. 181972–181982, 2019.

[20] W. Chen, “The new technological developments of UHV AC power transmission equipment,” in *Proc. ICEPE-ST*, vol. 103, pp. 371–374, Mar. 2016.

[21] D. Antony and G. S. Punekar, “Noniterative method for combined acoustic-electrical partial discharge source localization,” *IEEE Trans. Power Del.*, vol. 33, no. 4, pp. 1679–1688, Aug. 2018.

[22] W. Rui, S. Quaye, M. Dazhong, and X. Heiugang, “Line impedance cooperation strategy identification method for grid-tied inverters under weak grids,” *IEEE Trans. Smart Grid*, vol. 11, no. 4, pp. 2856–2866, Jul. 2020.

[23] J. Liang, T. Jing, H. Niu, and J. Wang, “Two-terminal fault location method of distribution network based on adaptive convolution neural network,” *IEEE Access*, vol. 8, pp. 54035–54043, 2020.

[24] X. H. Zhang, Y. Li, L. Li, J. Gao, and N. Guo, “Multi-scale analysis and pattern recognition of ultrasonic signals of PD in a Liquid/Solid composite of an oil-filled terminal,” *Energies*, vol. 13, no. 2, p. 366, Jan. 2020.

[25] B. Zhang, X. Li, T. Wang, and G. Zhang, “Surface charging characteristics of GIL model spacers under DC stress in C4F7N/CO2 gas mixture,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 27, no. 2, pp. 597–605, Apr. 2020.

[26] Z.-L. Zhou, J. Zhou, X. Cai, Y.-C. Rui, L.-J. Chen, and H.-Q. Wang, “Acoustic emission source location considering refraction in layered media with cylindrical surface,” *IEEE Trans. Nonferrous Met. Soc. China*, vol. 30, no. 3, pp. 789–799, Mar. 2020.

[27] K. Prajna and C. M. Mukhopadhyay, “Fractional Fourier transform based adaptive filtering techniques for acoustic emission signal enhancement,” *Nonstruct. Eval.*, vol. 39, no. 1, p. 51, Jan. 2020.

[28] W. Zhang, H. Jia, G. Gao, X. Cheng, P. Du, and D. Xu, “Backscattering layers on electroacoustic properties of the acoustic emission sensors,” *Appl. Acoust.*, vol. 156, pp. 387–393, Dec. 2019.
[29] Z. Li, W. Ding, Y. Liu, Y. Li, Z. Zheng, W. Liu, and K. Gao, “Surface flashover characteristics of epoxy insulator in C$_4$F$_7$N/CO$_2$ mixtures in a uniform field under AC voltage,” IEEE Trans. Dielectr. Electr. Insul., vol. 26, no. 4, pp. 1065–1072, Aug. 2019.

[30] H.-Y. Zhou, G.-M. Ma, Y. Wang, C.-R. Li, Y.-P. Tu, S.-P. Ye, B. Zhang, X.-F. Guo, and X.-L. Yan, “Surface charge accumulation on 500kV cone-type GIS spacer under residual DC voltage,” IEEE Trans. Dielectr. Electr. Insul., vol. 25, no. 4, pp. 1230–1237, Aug. 2018.

[31] P. Wenger, M. Beltle, S. Tenbohlen, U. Riechert, and G. Behrmann, “Combined characterization of free-moving particles in HVDC-GIS using UHF PD, high-speed imaging, and pulse-sequence analysis,” IEEE Trans. Power Del., vol. 34, no. 4, pp. 1540–1548, Aug. 2019.

[32] R. Piccin, A. Mor, P. Morshuis, A. Girodet, and J. Smit, “Partial discharge analysis of gas insulated systems at high voltage AC and DC,” IEEE Trans. Dielectr. Electr. Insul., vol. 22, no. 1, pp. 218–228, Feb. 2015.

[33] F. Zeng, Z. Lei, X. Yang, J. Tang, Q. Yao, and Y. Miao, “Evaluating DC partial discharge with SF6 decomposition characteristics,” IEEE Trans. Power Del., vol. 34, no. 4, pp. 1383–1392, Aug. 2019.

YE FEI was born in Ezhou, Hubei, China, in 1981. He received the M.S. degree in power system and automation from North China Electric Power University in 2007, where he is currently pursuing the Ph.D. degree in high voltage and insulation technology. He is also working with the China Electric Power Research Institute, Wuhan. His research interest focuses on high-voltage primary equipment technology.

YUNPENG LIU (Member, IEEE) was born in Jinzhai, Anhui, China, in 1976. He received the B.Eng. and Ph.D. degrees in electrical engineering from North China Electric Power University, Baoding, China, in 1999 and 2005, respectively. From 2006 to 2009, he worked as a joint Post-doctoral Fellow with the China Electric Power Research Institute and the State Grid Wuhan High Voltage Research Institute. He is currently a Ph.D. Supervisor and a Professor with North China Electric Power University. His research interests are UHV transmission, and fault detection and diagnosis of electric equipment.

JIANGBO CHEN was born in Wuhan, Hubei, China, in 1978. He received the Ph.D. degree in high voltage and insulation technology from Wuhan University in 2006. He is currently working with the China Electric Power Research Institute, Wuhan. His research interest focuses on high-voltage primary equipment technology.

LIN CHENG was born in Wuhan, Hubei, China, in 1981. He received the Ph.D. degree in high voltage and insulation technology from the Huazhong University of Science and Technology in 2015. He is currently working with State Grid Electric Power Research Institute Wuhan Nari Company Ltd. His research interest focuses on high-voltage primary equipment technology.

MENGQI LI was born in Wuhan, Hubei, China, in 1987. He received the M.S. degree in high voltage and insulation technology from Wuhan University in 2013. He is currently working with State Grid Electric Power Research Institute Wuhan Nari Company Ltd. His research interest focuses on high-voltage primary equipment technology.

YI LIU was born in Xiangtan, Hunan, China, in 1980. He received the M.S. degree in high voltage and insulation technology from Hunan University in 2006. He is currently working with State Grid Electric Power Research Institute Wuhan Nari Company Ltd. His research interest focuses on high-voltage primary equipment technology.

MINFENG SHAO was born in Huanggang, Hubei, China, in 1987. He received the M.S. degree in high voltage and insulation technology from Wuhan University in 2012. He is currently working with the China Electric Power Research Institute. His research interest focuses on high-voltage primary equipment technology.

VOLUME 8, 2020