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Space Charge Measurement for a 27-mm-Thick Cross-Linked Polyethylene Sample Using the Pulsed Electroacoustic Method

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Cross-linked polyethylene (XLPE) is used in electric power cables as insulation. The maximum thickness of an XLPE layer is 27 mm in a 500 kV class electric power cable. The pulsed electroacoustic (PEA) method is widely used to measure the space charge distribution in dielectric materials. When measuring the space charge distribution in dielectric materials using the normal PEA method, the acoustic wave (PEA signal) from which the space charge profile is obtained is detected by a piezoelectric device in the system. Usually, the sample thickness is less than 10 mm in a normal PEA system. When a thicker sample is used, the space charge measurement is very difficult to obtain with a normal PEA system, because the amplitude of the acoustic wave from the upper electrode decreases with thickness compared with that of the acoustic wave from the lower electrode. Using a redesigned PEA system, space charge distributions have been measured in the 27-mm-thick XLPE sample in a 1 kV/mm DC electric field. The experimental results show that the redesigned PEA system can detect a PEA signal from the lower and upper electrodes in the 27-mm-thick XLPE sample. The deconvolution technique applied to the dispersion in the thick XLPE sample has also been improved.

1. Introduction

The pulsed electroacoustic (PEA) method is a nondestructive space charge measurement technique used to determine the space charge behavior inside dielectric materials. Space charge measurement techniques are widely applied to investigate the dielectric and electric phenomena in polymeric insulating materials.[(1)] Cross-linked polyethylene (XLPE) is used in electric power cables as insulation. The maximum thickness of the XLPE layer is 27 mm in a 500 kV class electric power cable. The PEA method is also used to measure the space charge distribution in XLPE for power cables. Some measurement techniques for space charge distribution in coaxial cables in full-scale power cables have been developed.[(2,3)] They could also be important techniques to measure the space charge distribution in thick XLPE samples for power cables. When measuring the space charge distribution in dielectric materials using the normal PEA

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system, the acoustic wave (PEA signal) from which the space charge profile is obtained is detected by a piezoelectric device in the system. Usually, the sample thickness is less than 10 mm in a normal PEA system.(3)

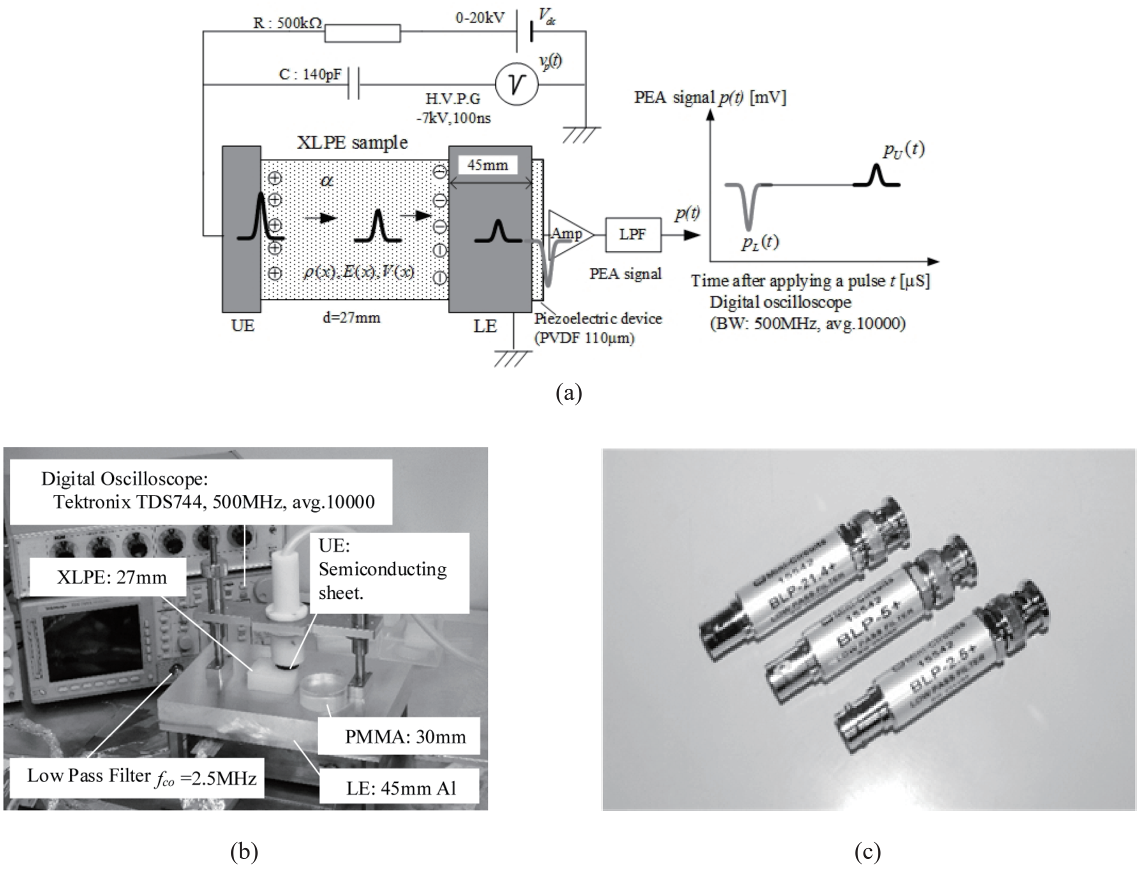
When a thicker sample is used, a space charge measurement is very difficult to obtain by the PEA method because the amplitude of the PEA signal from the upper electrode (UE) decreases strongly due to the thickness in comparison with that of the PEA signal from the lower electrode (LE). The acoustic waves in an XLPE sample would be attenuated and dispersed inside the dielectric material, and the amplitude of the PEA signal from the interface between the sample and the voltage applied to the UE is affected by the combination of acoustic impedances of all materials.(4) The amplitude of the acoustic wave from the UE exponentially deceases with the thickness of the sample. To detect the acoustic wave from the UE in a thick sample, a high-voltage pulse generator and a low-pass filter (LPF) circuit were adopted in the redesigned PEA system.

In this paper, the improvement of equipment and the experimental results obtained by space charge measurement in a redesigned PEA system on a 27-mm thick XLPE sample are reported.

2. Experimental Methods

2.1 PEA system

Figure 1(a) shows a redesigned PEA system. When measuring the space charge distribution in a sample using the normal PEA method, the Columbic force acts on the charges in the sample



(a)

(b) (c)

Fig. 1. Experimentally assembled PEA system for thick dielectric materials. (a) Redesigned PEA system, (b) photograph of PEA electrode, and (c) photograph of coaxial low pass filters (BNC type).

and generates an acoustic wave through the pulse voltage v_p superimposed on the applied voltage V_{dc}. The acoustic wave propagates and is detected as an electric signal (PEA signal) $p(t)$ by a piezoelectric device in the system. Figure 1(a) also shows the space charge profile.

A pulse voltage superimposed on the DC voltage is applied to the sample, which is sandwiched between the parallel plate electrodes. The amplitude of the PEA signal is proportional to the space charge density. The acoustic wave propagates within the aluminum electrode and reaches the piezoelectric device attached to the ground electrode (LE).

Figures 1(b) and 1(c) show photographs of an electrode system and LPFs in the experimentally assembled PEA system for a thick sample, respectively. The semiconducting sheet with a diameter of 35 mm used as the UE and the silicone oil on the sample surfaces are utilized for the matching of acoustic impedance and acoustic contact. The semiconducting sheet presses the sample with the metal electrode with the same diameter of 35 mm (B-3). The time variation of the PEA signal is recorded by a digital oscilloscope. It is possible to convert the position and density of the space charge by signal processing (deconvolution).[7] A 110-µm-thick PVDF piezoelectric film (Kureha Chemistry Co., Ltd.), amiplifiers of 500 MHz bandwidth and a digital oscilloscope (Tektronix TDS744) were adopted for the system. Three types of coaxial LPFs (Mini Circuits Corp., BLP-21.4+, BLP-5+, and BLP-2.5+) were used, and these had cutoff frequencies (f_{co}) of 24.5, 6.0, and 2.75 MHz, respectively.

2.2 PEA signal from a thick XLPE sample

Observing a PEA signal from the UE is the most serious defaulting in measuring a thick sample. The generation and propagation of acoustic waves in PEA measurements are shown in Eqs. (1)–(6). Here, x and t are the position and time, respectively. Equation (1) shows that the PEA signal is detected by the piezoelectric device. In this case, d and $\rho(x)$ represent the sample thickness and space charge density, respectively, and $E(x)$ is the electric field generated through to the applied voltage. When the pulse voltage $v_p(t)$ is superimposed on the applied voltage, the pulse electric field $e_p(t)$ induces a Columbic force on each charge in the sample. $e_p(t)$ is shown in Eq. (2). The acoustic waves $p_L(t)$ and $p_U(t)$ are generated at the LE interface within the sample, and the UE interface is described by Eqs. (3)–(5):[4]

$$p(t) = p_L(t) + p_S(t) + p_U(t), \tag{1}$$

$$e_p(t) = v_p(t)/d, \tag{2}$$

$$p_L(t) = K\frac{Z_L}{Z_L + Z_S}\varepsilon E(0)\, e_p(t), \tag{3}$$

$$p_S(t) = K\frac{2Z_L}{Z_L + Z_S}\int_0^d \rho(x)\, e_p\left(t - \frac{x}{c_S}\right) e^{-ax} dx, \tag{4}$$

$$p_U(t) = -K\frac{2Z_L}{Z_L + Z_S}\frac{Z_S}{Z_S + Z_U}\varepsilon E(d)\, e_p\left(t - \frac{x}{c_S}\right) e^{-ad}, \tag{5}$$

where Z_L, Z_S, and Z_U are the acoustic impedances of the LE, sample, and UE, and ε and α are dielectric constant and attenuation coefficient of the acoustic wave in the sample, respectively. K is a constant that converts pressure into an electric signal in the piezoelectric device. The dispersion phenomena are not considered in these equations.

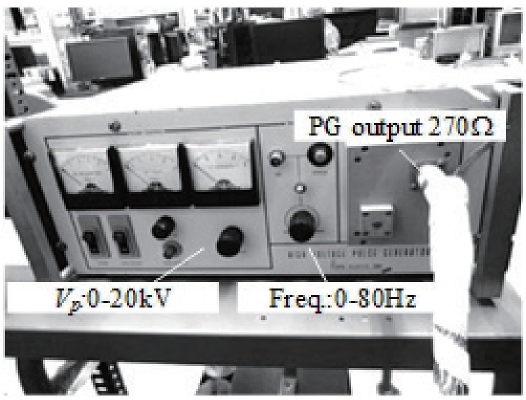
It can be seen that the attenuation of $p_S(t)$ and $p_U(t)$ in Eqs. (4) and (5) corresponds to the sample thickness. The attenuation increases with x exponentially. When the thickness reaches 27 mm, the detection of acoustic waves generated in the UE is very difficult. Therefore, a countermeasure for this attenuation becomes very important.

2.3 Countermeasures for the attenuation of acoustic waves

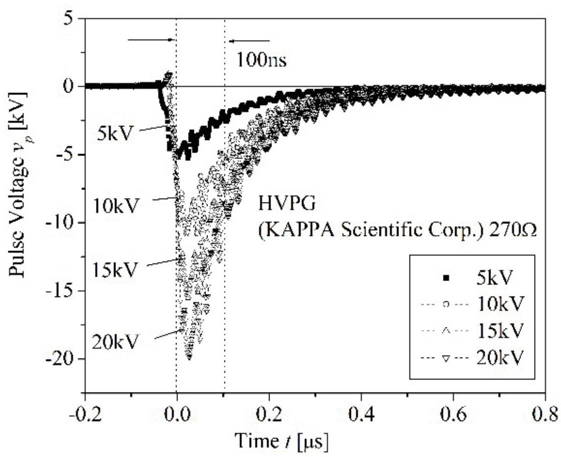
The amplitude of acoustic waves should be increased as the countermeasure of attenuation. In the following equation, $p'(t)$ defines the magnitude of the acoustic wave (pressure) generated at the electrode interface in the PEA method when there is no space charge inside the sample. Equation (6) is derived from the electromagnetic theory. The terms ε, V_{dc}, v_p, d, and t represent the dielectric permittivity of the sample, the DC voltage applied to the sample, the height of the pulse voltage, the thickness of the sample, and time, respectively.

$$p'(t) = \frac{1}{2}\varepsilon\left(\frac{V_{dc}}{d} + \frac{v_p(t)}{d}\right)^2 = \frac{1}{2}\varepsilon\left(\frac{V_{dc}}{d}\right)^2 + \varepsilon\frac{V_{dc}}{d}\frac{v_p(t)}{d} + \frac{1}{2}\varepsilon\left(\frac{v_p(t)}{d}\right)^2 \tag{6}$$

The second and third terms in Eq. (6) depend on the magnitude of the pulse voltage. These terms clearly show that $v_p(t)$ increases to increase the amplitude of $p'(t)$. Therefore, a high-voltage pulse generator is necessary, and its output voltage must be approximately ten times as large as the normal PEA system. A high-voltage pulse generator (Kappa Scientific Corp.) was adopted for this study. The pulse generator uses a thyratron switch. The photograph and output waveforms of the pulse generator are shown in Figs. 2(a) and 2(b), respectively. The graph in Fig. 2(b) confirms that it is possible to generate a pulse of about −20 kV at a peak value.



(a)



(b)

Fig. 2. (a) High-voltage pulse voltage generator and (b) its pulse waveform.

2.4 Attenuation of the acoustic wave (B-4)

The attenuation of acoustic wave α depends on the frequency. The attenuation of the acoustic wave is caused by absorption due to the viscosity of the sample. The attenuation coefficient α of the absorption due to viscosity is represented by the following equation, which was derived by Storks. The terms ρ', c, η, and f represent the density of the medium, the speed of the acoustic wave, the viscosity of the medium and the frequency of the acoustic wave:[5]

$$\alpha = \frac{8\pi^2 \eta f^2}{3\rho' c^3}. \tag{7}$$

The attenuation indicates the increase in the proportion due to the square of the frequency in Eq. (7). It also shows that low-frequency components in the PEA signal $p(t)$ are not attenuated. Although the resolution of the space charge measurement is reduced, the LPFs may be adopted to reduce the attenuation of the PEA signal. The three types of coaxial LPFs shown in Fig. 1(c) are used to control the attenuation of the PEA signal.

3. Results

The PEA signals in 27-mm-thick XLPE samples were measured by a normal PEA system using LPFs and the high-voltage pulse generator as the countermeasure of signal attenuation under DC voltage (V_{dc} : 0–20 kV). The peak voltage of the high-voltage generator was set at V_p: −7 kV. The thickness of the LE, which was made of aluminum of the normal PEA system, was 10 mm.

Figures 3(a)–3(c) show the PEA signals obtained using LPFs with different cutoff frequencyies (f_{co} = 24.5, 6.0, and 2.5 MHz). These figures show that the PEA signals of the UE were detected and increased proportionally to the applied voltage. The PEA signal of the UE was detected 13.6 μs after the pulse voltage application. This showed that the UE PEA signal was successfully detected by the high-voltage pulse voltage and LPFs. The relative amplitude of the UE PEA signal increased with the decrease in the cutoff frequency of the LPFs.

4. Discussion

Figure 4 shows the ratio between the PEA signals of the LE and UE (P_U/P_L), which decreases with the cutoff frequency of the LPF in a 27-mm-thick XLPE sheet under 20 kV. The plot shows that the UE and LE PEA signals can be measured on the screen of a digital oscilloscope using the LPF with 2.5 MHz cutoff frequency (f_{co}). When the width of the pulse voltage is 100 ns, the optimum cutoff frequency of the LPF is considered to be 10 MHz or more. However, even if the cutoff frequency is 6 MHz and P_U/P_L is less than 1/5, it is difficult to process deconvolution. For these reasons, it is necessary to use an LPF with low cutoff frequency for the measurement (A-2).

Three PEA signals were observed between the LE and UE PEA signals in Figs. 3(a)–3(c). These PEA signals were a multireflection of the LE PEA signal in the 10-mm-thick LE. Figure 5 shows a schematic diagram of the propagation of PEA signals and the multireflection of the LE PEA signal in the measurement. When the pulse voltage is applied at t = 0, two acoustic waves are generated at each interface between the electrode and the sample. The two waves propagate toward the piezoelectric device attached to the LE. The LE PEA signal reaches the piezoelectric element

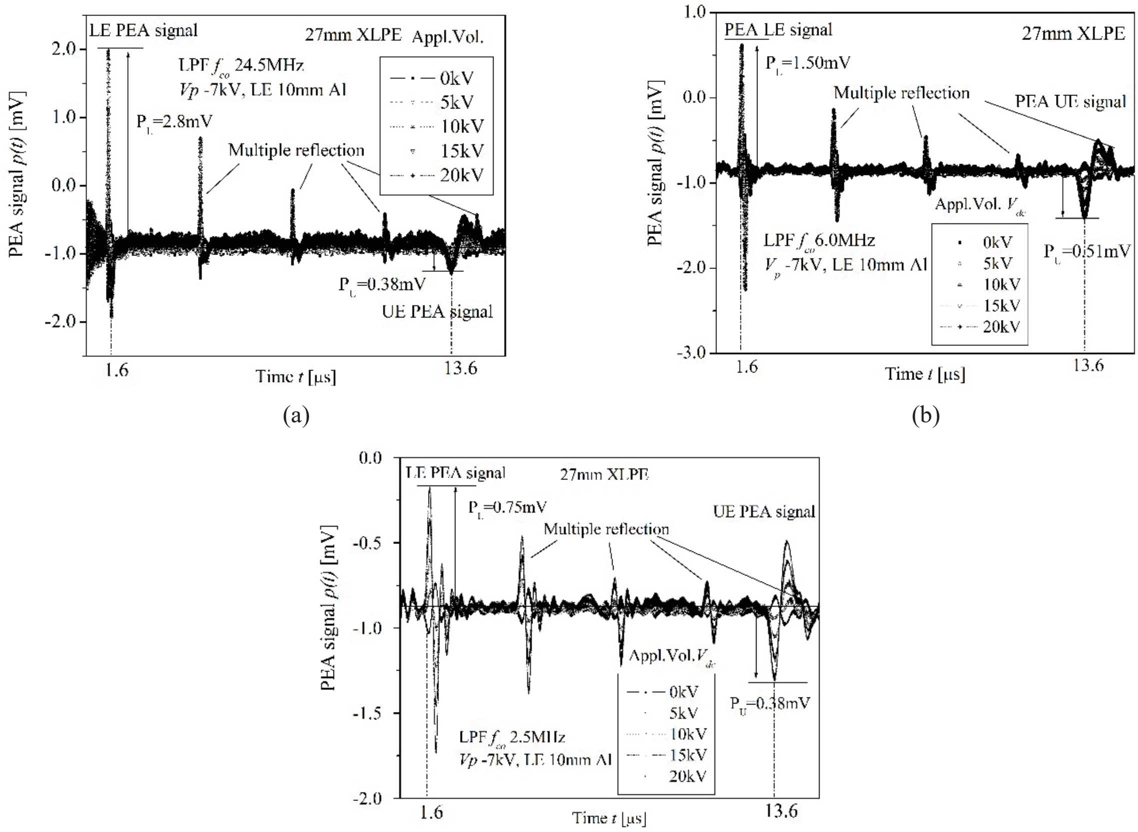


Fig. 3. Cutoff frequency dependence of the PEA signal in 27-mm-thick XLPE sheet under DC electric voltage (V_{dc}: 0–20 kV; V_p: −7 kV; Cutoff frequency f_{co} = 24.5, 6.0, 2.5 MHz, the thickness of LE is 10 mm in the PEA system). (a) XLPE (f_{co} = 24.5 MHz), (b) XLPE (f_{co} = 6 MHz), and (c) XLPE (f_{co} = 2.5 MHz).

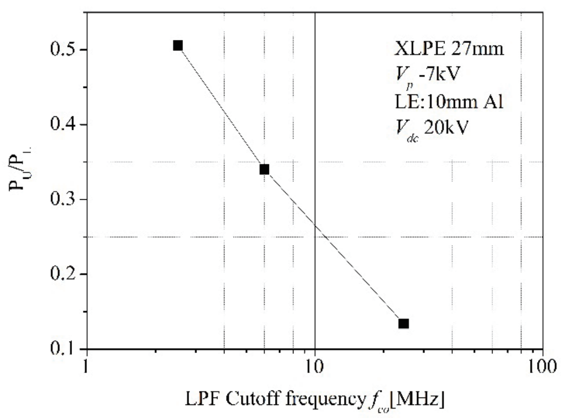


Fig. 4. Relationship between cutoff frequencies of a LPF and PU/PL in 27-mm thick XLPE sheet under V_{dc} = 20 kV DC voltage. (LPF f_{co} = 24.5, 6.0, 2.5 MHz ; the thickness of LE is 10 mm).

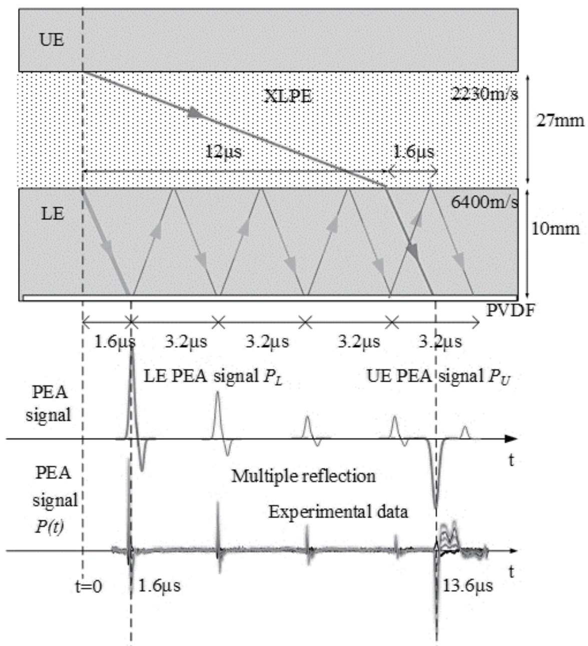


Fig. 5. Schematic diagram of the propagation of PEA signals in the LE in a 27-mm-thick XLPE sheet using a 10-mm-thick LE.

t = 1.6 μs after the application of the pulse voltage. This result reveals that the sound speed in the LE is 6400 m/s and that the LE PEA signal is reflected at both surfaces of the LE and reaches the piezoelectric device again at t = 1.6 + 3.2 μs. This reflection is repeated three times until the UE PEA signal arrives at the piezoelectric device at t = 13.6 μs. This means that the speed of sound in an XLPE sample is 2300 m/s. As the LE is thin relative to the sample, the speed of an acoustic wave in the LE is higher than that of an acoustic wave in the sample. The refraction is repeated three times until the UE signal reaches the piezoelectric element.

These three signals (multireflected signals) are measurement errors in the space charge distribution in the 27-mm-thick XLPE sheet. The propagation time of the acoustic wave in this XLPE sample is 12 μs ($\cong 27 \times 10^{-3}/2300$). To eliminate these errors in the multireflected signal, the minimum thickness of the LE is 38 mm ($\cong 6400 \times 12 \times 10^{-6}/2$). Therefore, a 45-mm-thick LE is adopted to remove these reflected signals as a countermeasure for multireflections.

The space charge distributions are measured by the redesigned PEA system with a 45-mm-thick LE. Figure 6 shows the PEA signals in a 27-mm-thick XLPE sheet under DC voltage (V_{dc}: 0–20 kV). It is clear that the signals due to reflection are eliminated using a 45-mm-thick LE. In the normal PEA signal, the high-frequency component makes a waveform pulse shape. However, when high-frequency components are removed by the LPF, the vibration of waveforms increases as shown in Fig. 6 (A-3).

The thickness of the LE made of Al is 45 mm. Since the sound velocity of acoustic waves in Al is 6400 m/s, after the PEA signal from the LE reaches the piezoelectric device, the signal is reflected at the lower part of the LE and again passes through the inside of the LE. The signal is reflected at the upper part of the LE and reaches the piezoelectric device. The time to reach the piezoelectric device is 14 μs. If the sound velocity of the sample is 2300 m/s, the sample thickness that can be measured in 14 μs is 32.2 mm. Therefore, the measureable maximum thickness of XLPE is about 32 mm in this system. To measure a sample of XLPE up to 40 mm, a 56-mm-thick EL made of Al is required (B-1).

The conventional deconvolution processing cannot be used in a 27-mm-thick XLPE sheet due to the acoustic wave dispersion in the XLPE sheet.[6,7] To remove the attenuation and dispersion, two impulse responses are adopted for deconvolution processing.[8] In the deconvolution process, the attenuation coefficient [$\alpha(f)$] and dispersion coefficient [$\beta(f)$] can be calculated by the two impulse

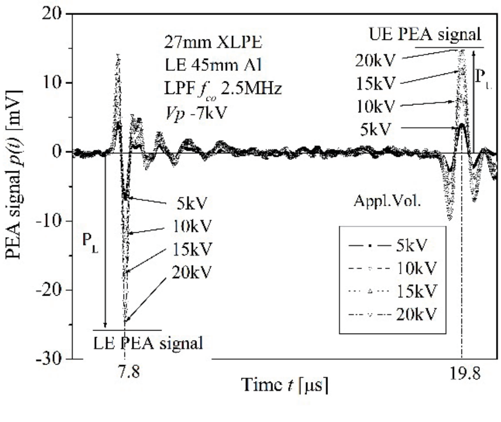


Fig. 6. PEA signals in a 27-mm-thick XLPE with a 45-mm-thick aluminum LE under DC voltage (V_{dc}: 0–20 kV; V_p: −7 kV; LPF f_{co}: 2.5 MHz, 45-mm-thick LE).

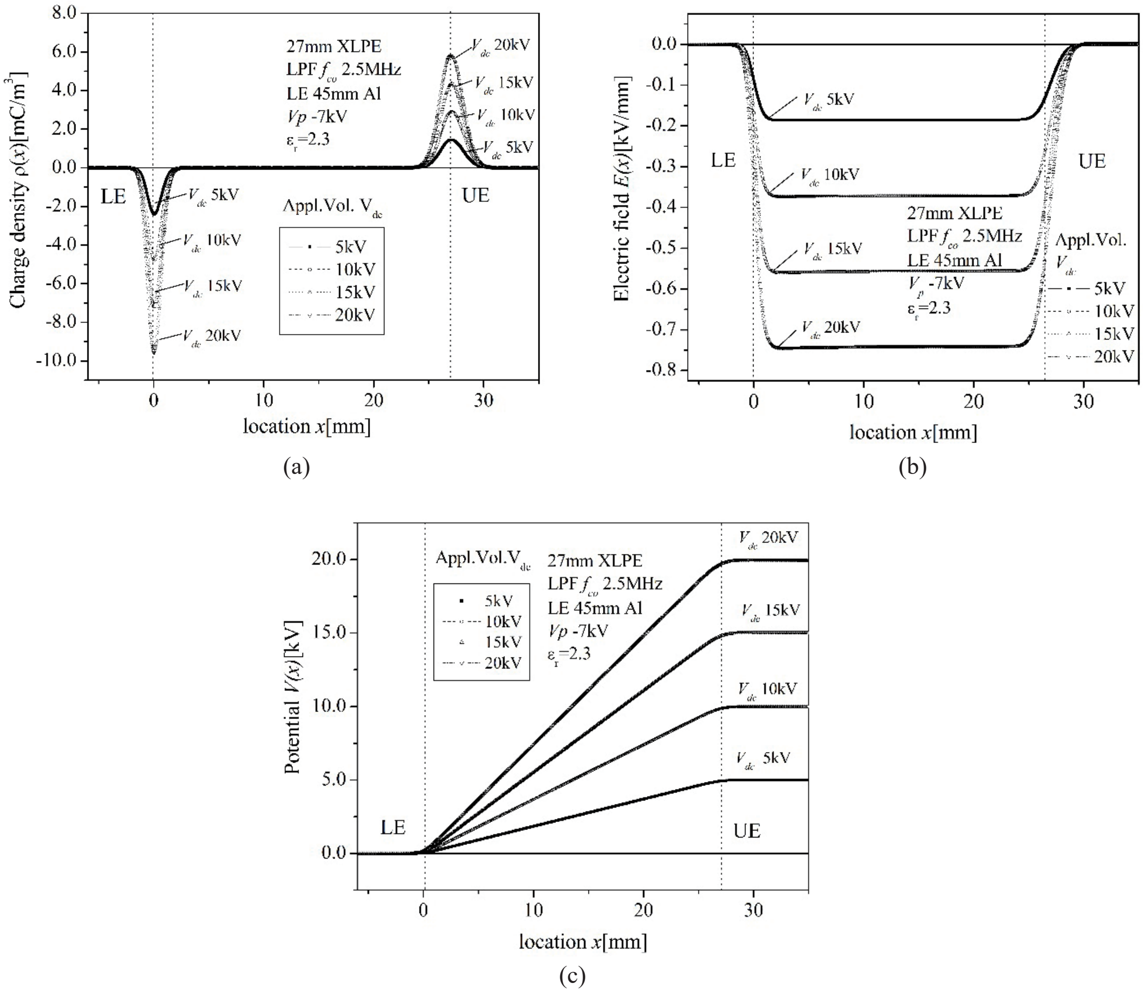


Fig. 7. (a) Space charge, (b) electric field, and (c) potential distributions in 27-mm-thick XLPE under a DC electric field (V_{dc}: 0–20 kV, V_p: −7 kV, LPF f_{co}: 2.5 MHz, LE 45 mm, reference waveform: 5 kV data).

responses, $P(f, x)$ of the LE [$P(f, 0)$] and UE $\{P(f, d) = P(f, 0) \exp[\alpha(f)d - j\,\beta(f)d]\}$. The terms f, x, j, and d represent the frequency, the position in the sample, the imaginary unit and the sample thickness, respectively. The impulse responses at the position x, $\{P(f, x) = \mathrm{P}(f, 0) \exp[\alpha(f)x - j\beta(f)x]\}$, can be calculated by $\alpha(f)$ and $\beta(f)$. The space charge distribution $\rho(x)$ is calculated using the whole impulse response $P(f, x)$ (B-6).

Figure 7 shows the space charge, electric field, and potential distribution in the XLPE. The LE and UE PEA signal waves under 5 kV were used as the impulse response for the deconvolution processing.

The error due to the magnitude of v_p in the space charge distribution measurement is shown in the third term of Eq. (6). Because the minimum pulse voltage of −7 kV is required to obtain a clear PEA signal with an applied voltage of 5 kV in a 27-mm-thick XLPE sample, the error due to the magnitude of v_p is considered to be not small under the low electric field (A-1).

4. Conclusions

A PEA system has been redesigned to measure the space charge distribution in a 27-mm-thick XPLE sample. The acoustic wave signals of the space charge distribution have been measured in a 27-mm-thick XLPE sample under DC voltages from 0 to 20 kV.

The following methods were applied as countermeasures to reduce the influence of the attenuation of acoustic waves in the thick XLPE: a high-voltage pulse generator (−7 kV peak, 100 ns width), a LPF with a cutoff frequency of 2.5 MHz, and a 45-mm-thick aluminum electrode.

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