Space Charge Measurement Equipment for Full-scale HVDC Cables Using Electrically Insulating Polymeric Acoustic Coupler

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ABSTRACT
A new, very sensitive device for space charge measurements on full-size cable is proposed. The measurement employs the basis of the Pulsed Electro-Acoustic (PEA) method, in which an acoustic signal is produced due to the interaction between the pulsed electric field and space charge. A polymeric material was used as an acoustic coupler that also isolates the cable and the measurement device electrically. It was found that the new type of device with polymeric coupler has a four times higher sensitivity than the conventional PEA device. The isolation from the cable body was proved to be advantageous for easily connecting the probing pulse voltage to the measurement section of the cable through its insulation screen (outer screen electrode) while applying a DC high voltage to the conductor. Feasibility of the new PEA device was examined by using a cable with 20 mm-thick insulation. It was shown experimentally that PEA measurements performed at a voltage as low as 5 kV provided clear charge patterns. As a result of this, the accuracy of the electric field calculation was estimated to be 0.25 kV/mm or better, which leads to 2% of accuracy at 250 kV operating voltage.

Index Terms — high voltage DC transmission, space charge, polymer insulated cable, pulsed electroacoustic measurement.

1 INTRODUCTION
LONG distance power transport for offshore wind power generation and international interconnection is applied mainly in Europe, both land and submarine power cable installation is advancing. Also, in Asian countries, High Voltage DC (HVDC) submarine power cable connections are being realized or in the planning stage [1]. The ASEAN Power Grid is believed to be advantageous to maintain stability in demand and supply in the future [2]. DC cables are advantageous for long-distance transmission because they do not generate reactive power and have a large power capacity. However, it is well known that space charge may be formed under DC high voltage application [3]. The locally concentrated space charge disturbs the electric field distribution and negatively affects the dielectric strength [4]. This was particularly significant in solid polymer insulated cables, which were being developed to replace conventional oil-impregnated cables [5]. Therefore, countermeasures have been taken to suppress space charge, such as by adding nano-fillers into the insulation [6].

During the development process of insulation materials, sheet-like samples or mini-cables are used to evaluate the insulating performance by space charge measurement. On the other hand, it is highly desirable to directly measure the char-
characteristics of full-size cables in order to confirm whether the insulation performance assessed by using small-scale specimens is reflected in the final manufactured products. Therefore, the authors of this paper are of the opinion that space charge measurement on full-size products is highly desirable.

The pulsed electroacoustic (PEA) method is one of the powerful tools for space charge measurement. A narrow pulse voltage is superimposed across the insulation that is stressed with a high DC voltage. An acoustic pressure wave is produced when an electric pulse field interacts with a space charge. A piezoelectric device mounted outside the insulation captures the wave [7].

To apply the pulse voltage together with a high DC voltage, a coupling capacitor is necessary. However, when a full-scale cable is used as a sample, the length required to connect the terminals for applying DC high voltage increases the capacitance of the sample (or decreases the impedance of the sample), resulting in poor coupling. In case the cable is longer than a few meters, the cable specimen can no longer be regarded as a lumped capacitor, and numerous reflections may occur when the pulse voltage is supplied at the cable terminal. In addition, if the size of the coupling capacitor is large, a considerable inductance is generated between the sample and the pulse voltage source, and the frequency response of the measurement system will be impaired [8]. Considering that full-size cables are often tested at voltages between 500 and 1,000 kV, the above points are critical for measuring space charge depending on the rated voltage.

Previously, the Central Research Institute of Electric Power Industry in Japan proposed a suitable method for measuring the internal charge of full-scale power cables while applying a high DC voltage [9, 10]. The proposal eliminates the need for a separate coupling capacitor, as the cable specimen itself can function as a pulse coupler.

However, in the proposed device, the sensitivity was not sufficient when applied to a full-scale cable. This was due to insufficient acoustic matching on the path from the sample to the piezoelectric transducer. In this paper, we propose a new measurement cell considering a better acoustic impedance matching among components with different acoustic characteristics.

In the conventional type of cell, a block of aluminum serves as an acoustic coupler. In the new PEA device, the aluminum was replaced by an insulating material, i.e. polystyrene. This material has relatively low acoustic attenuation compared to the cable insulation and an acoustic impedance that matches better the acoustic impedance of the cable insulation. Combined with a polyvinylidene-difluoride (PVDF) piezoelectric transducer and metallic backing material, the acoustic energy transmission has been highly improved, leading to a high sensitivity. Furthermore, the polymer acoustic coupler has the added advantage of creating a galvanic isolation between the measurement cell and the insulation screen (outer screen electrode) of the cable to which the high voltage pulse is applied. The feasibility of this new PEA device was verified on a full-scale cable specimen.

2 EXPERIMENTAL METHOD

2.1 MEASUREMENT CELL

In the pulsed electroacoustic method, a pulsed voltage is applied across an insulator, and the acoustic signal generated by the interaction between the charge and the pulsed electric field is measured by a piezoelectric sensor [11]. The position and magnitude of the charge are estimated from the delay time and signal intensity of the acoustic signal. The magnitude of the signal detected by the piezoelectric sensor depends on the combination of the acoustic impedances and losses of the materials that make up the cell.

Figure 1 illustrates the acoustic energy transfer for both the classic and proposed methods. An acoustic coupler is required to transfer the acoustic signal to the piezo sensor. This acoustic coupler acts as a delay line, preventing the spike noise generated by a high voltage pulse to interfere the space charge signal. As it functions as an electrode and must make contact with the insulating system, a metal conductor such as aluminum has conventionally been employed.

When the measured object is a polymer such as polyethylene, the acoustic matching with the metal coupling medium is poor, resulting in a reflection and a reduction in acoustic energy transfer rate. Furthermore, a reflection occurs at the end of the metallic coupling medium when a polymer piezoelectric material such as PVDF is employed as a sensor.

In order to avoid multiple reflections in the sensor and broaden the frequency range, the conventional method often uses a polymer as the backing material behind the acoustic sensor. The acoustic impedance of the backing material is close to that of the acoustic sensor. As a result, most of the signal received by the acoustic sensor propagates into the backing material.

On the other hand, in the proposed method, a polymer such as PMMA or Polystyrene (or rubber for a very thick insulation) is used for the acoustic coupler. This improves the acoustic matching between the measurement object and the acoustic coupler.

A good acoustic matching among the insulation material, acoustic coupler and the PVDF sensor is obtained. Additionally, a high-acoustic-impedance material is used as the backing material, resulting in a positive reflection at the back of the sensor. As a result, the sound pressure at the sensor is approximately twofold in comparison with the incident sound pressure. Brass or copper may be employed as the backing material. There may be some more solutions in terms of the backing structure.

Assuming acoustic impedances \( Z_0 \) to \( Z_3 \) as indicated in Figure 1, we can briefly compare the sound pressure of the new PEA cell and the classic PEA cell, ignoring multiple reflections and acoustic attenuations. The sound pressure at the sensor is represented as:

\[
p \propto \frac{Z_2 Z_3}{Z_1 + Z_0} \cdot \frac{Z_2 Z_3}{Z_2 + Z_1} \cdot \left(1 + \frac{Z_3 - Z_2}{Z_3 + Z_2}\right)
\]
Figure 1. Illustration of the acoustic energy transfer. PE: PolyEthylene, PVDF: PolyVinylidene-DiFluoride. Approximate values of the acoustic impedances of the insulation ($Z_0$), coupler ($Z_1$), sensor ($Z_2$) and backing material ($Z_3$) are indicated. Materials are assumed to be acoustically loss-less.

The relation between the new PEA cell ($p_{new}$) and classic PEA cell ($p_{classic}$) can be expressed by:

\[
\frac{p_{new}}{p_{classic}} = \frac{2.6}{0.62} \approx 4.3
\]  

The sensitivity can be expected to increase by a factor of four. As will be described in section 2.2, this type of acoustic coupler is advantageous as well to apply a probing pulse voltage on the cable.

Figure 2 shows the practical structure of the cell. Either polymethylmethacrylate (PMMA) or cross-linked polystyrene (XLPS) was used as the acoustic coupler. A 110 µm-thick PVDF film was used as the piezoelectric sensor. An aluminum film (11 µm-thick cooking foil) was used to obtain contact between the upper electrode of the PVDF sensor and the shielding box. Either brass or lead, 15 mm in diameter was used as the backing material, its length being 30 mm or more depending on the insulation thickness of the object.

2.2 PULSE GENERATOR

Figure 3 shows the schematic diagram of the prototype pulse generator. In order to apply a pulse voltage to the cable insulation, a 47 nF capacitor is charged with 1 kV DC voltage. By applying an appropriate driving pulse to the gate of a field-effect transistor (Cree, C2M0080170P), drain-source is short-circuited to produce $-1$ kV as an output. A matching resistor (50 / 75Ω) is used to avoid multiple reflections across the feeder cable.

Figure 4 shows the pulse voltage with a 75 Ω feeder line applied to the outer screen of the cable object, with a load impedance of 90 Ω. Details of the voltage application will be described in the next section. It is seen that the pulse voltage was appropriately applied and a pulse voltage of $-0.9$ kV was measured at the cable outer screen.

2.3 APPLICATION OF DC AND PULSE VOLTAGES TO THE CABLE

Because of the semi-conductive nature of the outer screen electrode, a probing pulse can be applied to the measurement section making use of the cable itself as coupling impedance,
while the shield layer is kept at ground potential in terms of DC potential [10].

Figure 5 shows the guard electrodes which are wound around the outer semi-conducting shield on both sides of the measurement section. The guard electrodes are connected through a short wire in order to maintain the same potential between them. The probing pulse is applied across the gap between the guard electrode and metallic shield wrapped on the rest of the cable.

Previously, the high-voltage probing pulse was applied to the measurement section via a metallic acoustic coupler. Therefore, the space charge signal had to be transmitted over an optical fiber link to ensure isolation from the ground potential [12]. In the method proposed here, since the acoustic coupler is an insulator, the pulse voltage can be applied directly to the shield layer without using an optical fiber link. The acoustic signal is boosted by a commercially available amplifier (Spectrum Instrumentation, SPA-1232), with a frequency range between DC and 10 MHz.

3 RESULTS

3.1 COMPARISON OF SENSITIVITY

Figure 6 compares the sensitivities of the conventional and new measurement cells by using 9-mm thick insulation applying 10 kV DC and 0.5 kV probing pulse. In both measurements, the coaxial cable that functions as the DC feeder line was used as the coupling impedance of the probing pulse. In both cases, PMMA was interposed in the acoustic propagation path to have the same contact condition with the cable, as well as to have the same way of applying the pulse voltage.

Waveforms as measured through a 60 dB amplifier are indicated in the same figure. In order to briefly compare the sensitivity, the intensity of the first peak that comes out of the outer screen was quantified. As a result, it was found that the proposed structure provides about four times the sensitivity of the conventional one.

3.2 WAVEFORM ACQUISITION

Figure 7 shows the signal as acquired when a DC -50 kV and a pulse voltage of 0.9 kV with a width of 400 ns was applied to a 20 mm-thick XLPE cable insulation. The 80,000 times of acquisitions were averaged to obtain a single waveform. The outer radius of the inner screen and the inner radius of the outer screen were approximately 28 mm and 48 mm, respectively. A 55 mm thick cross-linked polystyrene block (sound velocity of about 2400 m/s) was used as the acoustic coupler. The coupler also acts as a delay line, delaying the acoustic signal by approximately 20 µs with respect to the spike noise associated with the pulse application. This very long delay time is useful to avoid overlap of the acoustic signal with the tail of the spike noise.

The converted acoustic signal strength at the input of the amplifier, i.e., the PVDF sensor output, was 4 µV at the first peak that represents the induced charge at the outer screen. As is indicated, the acoustic signal was almost completely free from the spike noise.

Figure 8 shows the acoustic signal waveforms obtained by applying DC 5, 10, 20, 30, 40 and 50 kV. It can be seen that the acoustic propagation time between the two screen electrodes was approximately 10 µs. It is remarkable that even though the pulse voltage was not very high, the signal was
clear even at a DC voltage of only -5 kV that corresponds to 0.25 kV/mm in average field strength.

Figure 8. Acoustic signal waveforms as acquired with 20 mm-thick insula-
tion, applying DC 5, 10, 20, 30, 40 and 50 kV, pulse ~0.9 kV 400 ns. Intensity
is input equivalent of the amplifier (PVDF output).

3.3 SIGNAL PROCESSING

Although the basics of signal processing can be found in the
literature [12-13], we refer to Figure 9 for an overview. The
difference between signals before and after changing the DC
voltage is attributed only to the charges on the screen elec-
trodes, assuming that no change occurs in the space charge
distribution during that time. Details are provided in [14]. The
indicated waveform (a) is the waveform acquired by applying
DC -50 kV and subtracting the waveform acquired immediately
after the conductor was grounded. This processing was
done in order to remove the potential effect of any pre-existing
space charge and extract only the signals at the electrodes.

From the obtained differential signal (a), the one from the
outer screen side is extracted using an appropriate window
function waveform (b)). This can be considered as the impulse
response of the measurement system (including pulse
waveform). This signal, namely $s_0(r_0,t)$, is proportional to the
charge on the outer screen electrode, represented as:

$$q_0 = \varepsilon_0 V_0 \frac{1}{\ln r_0}$$  \hspace{1cm} (3)

where $r_0$ and $r_1$ are the positions of the outer and inner screen
electrodes, $\varepsilon_0$ is the vacuum permittivity, $V_0$ is the relative
permittivity of the cable insulation and $V_0$ is the equivalent
applied voltage when acquiring the above reference waveform.$q_0$ has the same dimension as the surface charge density in the
cylindrical coordinate system.

The entire signal is normalized (deconvolved) by this wave-
form, as it can be considered as the impulse response of the
measurement system (including pulse waveform). This process
results in waveform (c). In this process, the dual-domain
deconvolution that combines time and frequency domain cal-
culations has proved to be efficient, as described in [15,16].

Three peaks can be seen in waveform (c), the first peak at
0.8 μs represents the induced charge at the outer screen; the
second peak at 10.4 μs represents the charge at the inner
screen. The third peak represents an artifact caused by the
reflection at the conductor surface that should be eliminated
from the analysis. Using appropriate window functions, the
first and second signals, namely $s_1(r_0,t)$ and $s_2(r_0,t)$, are
extracted as shown in diagram (d).

The amplitude of an acoustic signal (sound pressure) gener-
ated at r decreases with the square root of the radius as it
propagates to the outer screen, due to the divergence of the
acoustic wave. Therefore, the reduction in sound pressure is
represented as $\sqrt{r/r_0}$. On the other hand, the pulsed electric
field at $r$ is $r_0/r$ compared to that on the external electrode.
Considering both the divergence of the acoustic wave and the
divergence of the electric field, the sensitivity to unit charge
density at position $r$ (assuming no acoustic absorption) is
represented as $\sqrt{r/r_0}$. The charge density ratio of the inner to
the outer screen is $r_0/r_1$. Considering the propagation charac-
teristics of sound in addition, the signals from the inner and
outer screen electrodes can be related as:

$$S_1(r_0, \omega) = (r_0/r_1)^{3/2} \cdot S_1(r_0, \omega) \cdot \exp(-\gamma(\omega) \cdot (r_0 - r_1))$$  \hspace{1cm} (4)

$$\gamma = \alpha(\omega) + j \frac{\omega}{c(\omega)}$$  \hspace{1cm} (5)

where $S_1$ is the Fourier transform of $s_1$, $\omega$ is the angular fre-
quency, and $\alpha$ and $c$ are frequency-dependent attenuation
constant and sound velocity. The normalized spectrum of the
signal detected when there is a charge of $q_0$ at position $r$ is:

$$S_2(r, \omega) = \sqrt{r/r_0} \cdot (r_0/r_1) \cdot S_1(r_0, \omega) \cdot \exp(-\gamma(\omega) \cdot (r_0 - r))$$  \hspace{1cm} (6)

A component of the transfer matrix in discrete form is rep-
resented as:

$$h_{jk}(r_j, t_k) = IFT\left[\sqrt{r/r_0} \cdot (r_0/r_1) \cdot S_1(r_0, \omega_k) \cdot \exp(-\gamma(\omega_k) \cdot (r_0 - r))\right]$$  \hspace{1cm} (7)

where $IFT$ denotes inverse Fourier transform. The signal (de-
convolved by using $s_0$ as the reference signal) corresponding to
the charge distribution $q(r)$ is:

$$\begin{bmatrix}
\frac{s_{up}(t_1)}{s_{ug}(t_1)} \\
\vdots \\
\frac{s_{um}(t_n)}{s_{ug}(t_n)}
\end{bmatrix} \equiv S_{tgt}$$

$$= \begin{bmatrix}
h_{11} & \cdots & h_{1m} \\
\vdots & \ddots & \vdots \\
h_{n1} & \cdots & h_{nm}
\end{bmatrix} \begin{bmatrix}
q(r_1)/q_0 \\
\vdots \\
q(r_m)/q_0
\end{bmatrix} \equiv HQ$$  \hspace{1cm} (8)

Diagram (e) shows some of the components of the transfer
matrix. In practice, many more components are generated so
that the calculation result can be smoothly indicated. Several
methods are known for solving equation (8) [17,18]. When the
least-squares method is applied, the estimated value of the
charge distribution is:

$$\tilde{Q} = (H^*H)^{-1}H^*S_{tgt}$$  \hspace{1cm} (9)

where T denotes transposition. Electric field and potential can
be determined by integrating the charge distribution in the
radial direction.
3.4 CHARGE AND FIELD PROFILES

Figure 10 shows the measurement results of the full-scale (20 mm-thick insulation) cable at 5, 10, 20, 30, 40, and 50 kV DC. Figure 10 (I) shows the results when positive DC voltages were applied to the conductor, and Fig. 10 (II) shows the results for negative DC voltage. In both cases, the upper figure (a) shows the calculated charge distribution at each DC voltage. Even when the DC applied voltage was as low as 5 kV, the peaks at the screen electrodes are clearly seen. The lower figure (b) shows the electric field distribution. The dashed line shows the calculated Laplace field at 50 kV DC. Each electric field distribution seems similar to that of the Laplace electric field.

Figure 11 shows the charge density induced at inner and outer screen electrodes. Although these charges are surface charges the results measured with a finite spatial resolution have a dimension of volume charge density. Integrating each peak in the radial direction yields a dimension of surface charge density. Since there is almost no space charge in the insulation, the induced charges can be theoretically calculated assuming a Laplace field. The charge density shown in Figure 11 agrees well with the value calculated assuming a Laplace field. In addition the difference in charge density at 5 kV and 10 kV DC voltages is clearly discernible.

The results shown in Figs. 10 and 11 suggest that the charge and electric field distributions can successfully be calculated even at 5 kV DC. The profiles were quite similar when negative DC voltages were applied, as indicated in Fig. 10 (II).
Figure 12 shows the electric field distribution when +50kV (a) and -50 kV (b) DC were applied to the cable conductor for 1 hour, respectively, at room temperature. The solid line shows the electric field profile at 0 minute, and the dashed line shows the electric field profile at 60 minutes. In the meantime intermittent waveform acquisitions were performed every 15 minutes. As was expected, no significant change was observed because of the low applied voltage. However the result showed the stability of the measurement including signal processing.

4 DISCUSSION

4.1 MEASUREMENT CELL

It was experimentally demonstrated that the sensitivity of the newly proposed measurement cell with a polymeric acoustic coupler was about four times higher than that of the conventional type that uses a metal electrode as an acoustic coupling material. Moreover, the insulating acoustic coupler has the advantage that the cable under test and the measurement system can be electrically isolated. This makes it possible to create an axial potential difference in the outer screen electrode of the cable under test while keeping the measurement system at ground potential, realizing easier power supply to these devices.

PMMA, which is easily available in the market, can be used as an acoustic coupler. However, since it has a relatively high sound velocity among polymers, it is necessary to make the coupler thicker in order to let it function sufficiently as a delay line to avoid the spike noise. Cross-linked polystyrene, which was used for the practical cable measurement in this study, is considered to be more suitable for this purpose because of its higher acoustic transparency and lower sound velocity compared to PMMA.

4.2 PROBING PULSE

Since the spike noise cannot be removed by taking an arithmetic average of the waveforms, the pulse voltage must be kept as low as possible to avoid interference with the space charge signal. The pulse voltage used in this experiment was only 0.9 kV, which is relatively low for a measurement of this insulation thickness. On the other hand, the pulse width can be freely changed to improve sensitivity by increasing the spectral intensity at low frequencies. In the measurements reported here 400 ns was chosen for realizing both a good sensitivity and a high repetition rate.

If the pulse voltage is low, the time required to charge the capacitor in Figure 3 can be shortened, and the pulse repetition rate can be increased. As long as the spike noise can be reduced, the number of averages can be increased to reduce the random noise. In our experiments, we achieved 80,000 waveform averages within 50 seconds due to the high repetition rate.

Even though many times of averaging may significantly reduce the random noise, a high dynamic range should be retained in order to capture both noise and acoustic signal in each acquisition. The A/D conversion with 15-bit resolution realized an apparent sensitivity of 1.5 nV per bit in terms of PVDF sensor output whereas as high as 20 µV of noise signal was captured as well in each acquisition.

These measurement conditions were determined by trial and error within the limitations of the hardware, so there is a possibility that more favorable conditions can be found. Since various signal processing has been performed for calculating the charge and electric field distribution, it is difficult to evaluate the effective sensitivity only by means of the signal-to-noise ratio of the originally acquired waveform. Therefore the accuracy evaluation was performed as will be described in the next section.

4.3 ACCURACY OF ELECTRIC FIELD ESTIMATION

The purpose of this series of experiments was to verify that sufficient sensitivity could be obtained for space charge measurement of full-scale cables. Due to the limitation of the facility a DC voltage much lower than the operating voltage was applied. Therefore almost no space charge evolution was found. However, induced charges on the screen electrodes were clearly observed under 50 kV DC. The Laplace field in the absence of space charge was reproduced even at DC volt-
ages lower than 50 kV, and there was no significant difference in the results even after multiple measurements. This suggests that the measurement performance was satisfactory, taking into account that the measurement system treats both induced charge and space charge in the same way.

It is remarkable that even at pulse voltage as low as 0.9 kV, the sensitivity was sufficient to calculate the charge and electric field distributions with an applied DC voltage of only 5 kV. Assuming the operating voltage to be 250 kV, this suggests that the charge distribution and electric field can be calculated with an accuracy better than 2%. The method will be further improved and applied to various cable samples to help evaluate insulation performance.

5 CONCLUSIONS

A new method that allows a sensitive and accurate measurement of space charge in full-size power cables was presented.

(1) The sensitivity of a new PEA cell using a polymeric acoustic coupler was proven to be four times higher than the conventional PEA cell that uses a metallic electrode as an acoustic coupler.

(2) Since the polymeric acoustic coupler electrically isolates the measuring system from the outer shielding layer of the cable, the pulse voltage can be applied onto the measuring section through the shielding layer while a DC high voltage is applied to the cable conductor.

(3) Data acquisition was successfully performed on a cable with 20 mm-thick insulation using 0.9 kV, 400 ns pulse voltages with 80,000 times of waveform averaging.

(4) Charge distribution and electric field distribution were successfully reconstructed using an appropriate deconvolution technique, taking into account frequency dependent acoustic attenuation and dispersion.

(5) As a result of the experiment applying up to 50 kV DC, the accuracy of the electric field estimation was found to be 0.25 kV/mm or better. Hence the accuracy of 2% can be obtained when the space charge measurements are performed at 250 kV assumed operating voltage.

REFERENCES


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