Measuring space-charge in HVDC cables

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High voltage DC (HVDC) power cables are often used for submarine transmission. Its insulation might produce internal space charges under high DC voltages, which distort the electrical field and could lead to insulation failure. Such a space-charge formation is considered to be significant in extruded polymer insulated DC cables. During the development of DC polymer insulated cables, it is essential to show that no significant space-charge is formed.

Pulsed electroacoustic (PEA) method is one of powerful tools for space charge measurement. A sharp pulse voltage is superposed across the insulation that is applied with a high DC voltage. The pulse electric field interacts to space charge to produce acoustic pulse wave. The wave can be captured by a piezoelectric device that is mounted outside the insulation [1].

In order to apply the pulse voltage together with high DC voltage, a coupling capacitor is needed. However when a full size cable is subjected as a specimen, it needs a certain length to attach terminals for high DC voltage application, which makes the capacitance of the specimen larger. In fact the cable specimen can no more be recognised as a lumped capacitor, and multiple reflection may take place if the pulse voltage is applied at the terminal. In addition, the scale of the coupling capacitor may be so significant that a large inductance may be produced between the specimen and pulse voltage source, leading to the loss of frequency characteristics of the measurement system.

As full size cables are normally tested under voltages between 500 and 1000 V, depending on the rated voltage, the above problems are very significant in performing the space charge measurement. The authors once proposed a suitable method for measuring the internal charge while applying a voltage to full-scale power cables [2, 3].

Fig. 1 shows a schematic diagram of the space charge measurement device for full size cable. It basically employs the principle of the pulsed electroacoustic (PEA) method. A part of the cable specimen is removed with metallic shield, and a piezoelectric device is mounted. A high voltage pulse is applied across the piezoelectric device and the shield layer. As the piezoelectric device is applied with a high voltage pulse, it is placed on a floating potential. The signal is transferred through the analogue optical signal link. The guard electrodes wrapped on the semiconducting shield layer are to retain a uniform potential distribution between these two electrodes.

A high DC voltage is applied at the terminal. For acoustic coupling an oil layer is interposed between the specimen and aluminium block, in which the piezoelectric sensor is embedded. As the pulse voltage is applied from the ground side of the specimen, no coupling capacitor is needed. In fact, as described below, cable specimen itself plays a roll of coupling impedance. The measurement system can be represented by an equivalent circuit as shown in Fig. 2, in terms of the pulse response. $Z_{x1}$ and $Z_{x2}$ represent the impedance looked from the measuring point, depending on the frequency component. The cable specimen may make resonance, if the pulse voltage has a certain frequency component. In such a case, the impedance synthesised by $Z_{x1}$ and $Z_{x2}$ may be very high, so that the reduction in the voltage across $C_x$ takes

![Fig. 1: Measurement system layout.](image)
place. In addition, as the resonance is corresponding to multiple reflections across the cable specimen, the shape of the applied single pulse may be disturbed because of ringing.

Resolution of the measurement

Resolution of the space charge depends on the width of the pulse voltage. To make it simple, it is assumed that the space charge distribution can be represented by a Gaussian function. It can be interpreted into time domain by using the sound speed of cross-linked polyethylene (2000 m/s) that is used as the insulation.

In this article, two cases, i.e., 25 ns and 100 ns in half width, will be taken into account. These are corresponding to 50 μm and 200 μm, respectively.

Response dependent on the length of the cable specimen

In order to retain a certain spatial resolution, a pulse voltage with an appropriate frequency component should be applied at the measuring point. Assuming that the voltage source produces a pulse voltage with a flat frequency spectrum, the frequency spectrum at the measuring point was estimated. Fig. 2 shows the equivalent circuit of the system including the specimen and feeder cable.

The cable specimen is considered as a distributed circuit of finite length with open ends. L1 and L2 are the lengths to the end terminal from the measurement point. As only a short length of the cable specimen is subjected to the measurement, the measuring point can be represented as a lumped capacitance CX.

The cables with L1 and L2 in length can be recognized as frequency dependent impedances Zx1 and Zx2 respectively, when they are looked from the measuring point. The system is thus simplified as to be a circuit composed of one small capacitance and two frequency dependent impedances. The impedance of the cable fragment with an open end and L1 in length is described as (eqn. 1, 2)

\[
Z_{x1} = Z_0 \frac{e^{j\frac{\pi}{2}L_1}}{e^{j\frac{\pi}{2}L_1} - e^{-j\frac{\pi}{2}L_1}}, \quad Z_{x2} = Z_0 \frac{e^{j\frac{\pi}{2}L_2}}{e^{j\frac{\pi}{2}L_2} - e^{-j\frac{\pi}{2}L_2}}, \quad Z_x = Z_{x1} / / Z_{x2}
\]

Eqn. 1.

Fig. 2: Equivalent circuit.

When a pulse voltage is applied through a coaxial cable with a characteristic impedance Zs, the reflection coefficient \( \Gamma \) at the application point (feeding point) is (eqn. 4).

\[
\Gamma = \frac{(Z_x + Z_0) - Z_s}{(Z_x + Z_0) + Z_s}
\]

Where Z is the combined impedance of Zx1, Zx2.

The applied voltage \( V_c \) across \( C_x \) is subsequently calculated by (eqn. 5, 6)

\[
V_c = \frac{(1 + \Gamma) \cdot jX_c}{Z_x - jX_c}
\]

\[
X_c = \frac{1}{2\pi f C_x}
\]

Where \( V_c \) is the voltage propagating through the feeder cable.

Cable specifications

- Capacitance at the measuring point

\[
\alpha = 2\pi f \alpha_0 \beta = 2\pi f / c
\]

Where:
- \( f \) = frequency
- \( c \) = propagation speed along the cable specimen
- \( \gamma \) = propagation constant dependent on frequency
(C): 30 pF, 300 pF
• Length of the cable specimen (l₁ and l₂): 2 m, 10 m
• Equivalent spatial resolution: 50 μm, 200 μm
• Characteristic impedance of the cable specimen (Z<sub>s</sub>): 20 Ω
• Attenuation coefficient of the cable specimen (α₀): 10 dB/MHz/km
• Propagation speed of the cable specimen (c): 160 m/μs

**Feeder cable**
• Characteristic impedance of the feeder cable (Z<sub>s</sub>): 50 Ω

Fig. 4 shows the calculation results. Graphs on the left side show frequency characteristics of the applied voltage across C<sub>x</sub>, and those on the right side show reproduced pulse waveforms in time domain.

If the cable specimen is as long as 10 m, it is seen that the resonance frequency is as low as 7 to 8 MHz. In such a case, a ringing is seen as displayed in (a) to (d). The ringing is more significant if the capacitance of the measuring point C<sub>x</sub> is larger.

In practice the measuring point is as short as several tens of cm. This corresponds to several tens of pF in capacitance. Therefore the ringing is not as significant as seen in (c) and (d), and does not affect the resolution.

Nevertheless it is recommended that the length of the measuring point be as short as possible to improve the sensitivity and reduce the effect of ringing.

Each profile is the response to a gaussian function with corresponding resolution and 1 in height, as the pulse wave applied to the feeder cable.

It is considered that the cable specimen should be extremely long in order to perfectly avoid the influence of multiple reflections at both ends, however in practical cases, where the measuring point is as short as several tens of cm and attenuation coefficient is as high as 10 dB/MHz/km, a realistic measurement with a resolution of several tens of μm can be performed without significant ringing.

Among all cases examined, it was seen that the half length of the cable specimen was most preferable when it was as short as 2 m.

Resonance takes place at high frequency in such a case but it is not significant because attenuation at high frequency reduces the degree of resonance. In addition high frequency component is not detected because of the limited frequency component of the applied pulse voltage.

If the cable specimen is longer, the resonance takes place at lower frequency, and as the result, ringing appears in the waveform in time domain. However even in such a case, ringing can be reduced if C<sub>x</sub> is small, or if the pulse voltage is as wide as it does not include the frequency component the ringing.

If the cable specimen is extremely short, the cable specimen can be recognised as a lumped capacitance as well as the measuring point. As Z<sub>s</sub> in such a case increases massively as the cable specimen becomes shorter, the voltage across C<sub>x</sub> is reduced, leading to the reduction in sensitivity.

Therefore, there is a range of preferable length of the cable specimen. If the total
length of the cable specimen is longer than the preferable length, the equivalent length in terms of pulse frequency can be adjusted by creating slits in the metallic shield. Even in such a case, it is not necessary to remove the semiconducting layer at the slit.

**Conclusion**

We proposed a method to measure space charge distribution in full size polymeric HVDC cables. It basically employs the pulsed electroacoustic method which needs a coupling capacitor to apply a sharp pulse voltage across the insulation as well as applying a high DC voltage. In order to avoid to use the capacitor that would be very large in scale in the case of full size cable measurement, we proposed to use the cable specimen itself as a pulse coupler. However as the cable is finite in its length, it may work as a resonator and disturbs the pulse voltage across the insulation, depending the frequency component of the pulse voltage. A calculation in frequency domain exhibited that the resonance is significant when the cable is as long as 10 m. Longer cable may cause resonance at low frequency but it would be less significant because of attenuation thorough the cable specimen. A good pulse waveform across the insulation was seen when the cable length was as short as 2 m, however it is considered that too short cable specimen would lead to the reduction in the sensitivity.

**References**


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**Fig. 4:** Frequency dependence of the applied voltage across the capacitance $C_x$ at measuring point (left) and reproduced applied voltage across $C_x$ in time domain (right).