Partial discharge observation of a complex insulation structure model and residual space charge characteristics investigation under repeated lightning impulses

Li Lu | Satoshi Ichimura | Toshiaki Rokunohe

Research & Development Group, Hitachi Ltd., 1-1, Omika-cho, 7-chome, Hitachi-shi, Ibaraki-ken 319-1292, Japan

Abstract
In this research, the authors concentrated on a rarely studied part in the power transformer's insulation structure: the connection part of radial and axial spacers. An experimental model was constructed to simulate this part. It was experimentally observed that the partial discharge starting in the oil gap created by the axial and radial spacers. Characteristics of the abovementioned partial discharge under repeated lightning impulses were also investigated. A longer interval time seemed to accelerate the insulation property deterioration of the constructed model, which is contrary to those reported in other studies. It was because that the partial discharge occurrence was prevented by the residual space charge at the surface of oil/insulation if the time interval of the repeated impulses was not long enough. Therefore, it is proposed that a long enough interval time or a polarity test is expected in the factory test to exclude the influence of the residual space charge and understand the real insulation property of power transformers.

1 | INTRODUCTION
Partial discharge (PD), if occurring in an oil-immersed power transformer, is considered to damage insulators, so a PD test and phenomenon analysis is required for understanding the insulation reliability of a transformer. Since the insulation structure in a transformer is complicated and the insulation characteristics at different parts are different, models like needle-plate or spherical electrode-plate [1–4], turn-to-turn [5–7], section-to-section [5–7] are used for simulating various parts of the real structure to well understand the insulation characteristics of a transformer.

The insulation characteristics of not only the above models but those models simulating other structures should also be considered. Figure 1(a) shows an image of the main insulation structure of an oil-immersed transformer. An insulation pressboard (PB) cylinder was put between high voltage (HV) and low voltage (LV) windings. The PB stacks are inserted between the coils to adjust the mechanical force. The image in the left column in Figure 1(a) is the enlarged image of the winding including the PB stacks. Transfer of the metallic impurities onto the top surface of the PB stacks is possible and might degrade the insulation property of the winding resulting in an initial failure of transformers.

On the other hand, it is well known that one kind of manufacturing defects, metallic impurities left inside the transformer, can seriously jeopardize the reliability of the transformer insulation. The influence of the metallic impurities has been studied a lot [7–11]. The electric field concentration around metallic impurities triggers PD and possibly leads to breakdown (BD). The PB stacks are inserted between the coils to adjust the mechanical force. The image in the left column in Figure 1(a) is the enlarged image of the winding including the PB stacks. Transfer of the metallic impurities onto the top surface of the PB stacks is possible and might degrade the insulation property of the winding resulting in an initial failure of transformers.
Therefore, an experimental model simulating the insulation structure of the connection part of axial and radial spacers including the created oil gap and a metallic impurity was made and used to investigate PD occurrence.

In addition, in the factory test of a transformer before delivery, lighting impulse should be applied to verify the dielectric strength of the transformer insulation. According to the IEC standard, IEC-60076-3, various types of lightning impulses should be repeatedly applied to transformers several times. The BD occurrence during this multiple times lightning impulses has been reported. The cumulative effect of repeated impulses is considered to greatly affect insulation materials and electrical equipment, and it leads to degradation or even premature failure [2, 12–14]. Although the mechanism has not been clear until now, one of the cumulative effects is the thought to be driven by the residual space charge. Simple models simulating a power transformer's insulation structure [1–7] were used for studying this effect. Few investigations, however, have used a complex insulation structure model, that is one including multiple insulation layers, such as the abovementioned model considering spacers, insulation paper (IP)-covered electrodes and PB barriers, is still less. Moreover, the time interval between continuous different lightning impulses is not specified in the IEC standard. Therefore, the PD phenomenon occurring when the abovementioned complex structure model was subjected to several times of lightning impulses was investigated in this research. The influence of the residual space charge was also analysed.

2 | EXPERIMENTAL CONDITION

2.1 | Experimental model

The insulating structure between HV and LV windings was simulated by an experimental model with the mixing-in of metallic impurity (see Figure 2(a)), which was assumed to investigate the influence of the two weak points mentioned above. The schematic diagram of the experimental model is shown in Figure 2(b).

The image in Figure 2(a) shows the model as seen from the top of the PB stacks. The HV electrode was a bare electrode. Positive voltage was applied to it during the application of lightning impulses. The LV electrodes were symmetrically placed on and under the radial spacers, like the arrangement of coils in real transformers, and covered with IPs. Since the factory test is generally carried out with negative lightning impulse voltage, HV voltage was applied on the bare electrode to simulate this negative voltage test. To prevent puncture breakdown occurrence for observing the inception position of the PD, the LV electrodes were covered with 3.3 mm thicknesses of IPs. Moreover, seven pieces of PBs each 0.8 mm thick were used as the insulation barrier. The PB stacks were constructed by two pieces of PBs each 1.6 mm thick. The thicknesses of 0.8 and 1.6 mm used here were respectively the thicknesses of the main insulation cylinder and the PB stacks really used in a transformer, to reflect the real PD occurrence condition. The thickness of the axial spacer was 8 mm. As shown in Figure 2(b), the total thicknesses of each insulation components between HV and LV electrodes were 5.6 mm for PB insulation barrier, 3.2 mm for PB stacks, 8 mm for axial spacer and 3.3 mm for IP, respectively. The effective oil gap thickness between the HV and LV electrodes was estimated to be 14.2 mm. It was calculated by PB with 8.8 mm, oil with 8 mm and IP with 3.3 mm which is arranged in series between HV and LV electrodes. The thickness of 8.8 mm for PB is considered equal to the combined value of the PB insulation barrier of 5.6 mm and the PB stacks of 3.2 mm. The thickness of the oil was regarded as 8 mm, equal to the thickness of the axial spacer, as shown in Figure 2. The dielectric constants of the mineral oil, IP and PB with 2.2, 3.5 and 4.7, respectively, were used for calculation. Although the distance between the HV and LV electrodes was not the practical distance that used in the transformer, a same level electrical field was expected to be simulated.

Moreover, to prevent PD occurrence from the oil gap created by the bare electrode and the PB barrier, a large enough radius of the bare electrode was used.

The metallic impurity (copper slice) was put onto the top surface of the PB stacks. The layout of the metallic impurity on the surface of the PB stacks is shown in the left column in Figure 2(a). To fix the metallic impurity, part of it was bent and inserted into the PB stacks. The length, width, and thickness of the metallic impurity on the top surface of the PB stacks were...
respectively 1.6, 0.45, and 0.2 mm. Okabe’s research proved that the layout of the metallic impurity as shown in Figure 2 is the most likely to cause PD [7]. Therefore, the most serious layout for triggering PD was adopted in the consideration of using the metallic impurity. The distance between the metallic impurity and the edge of the radial spacer was 15 mm so that the PD caused by these two weak points could be observed separately and simultaneously.

In some transformers, a gap length as much as 3.2 mm is created. Since the PD occurrence rate decreases as the length of the oil gap decreases [15, 16], the expected maximum oil gap length of 3.2 mm was adopted in this experiment to investigate the possibility of the PD occurrence in a real transformer.

The density of the PB was about 1.2 g/cm³. The PB and IP were treated by degassing, drying, and oil impregnation to ensure a moisture content less than 0.5%, which satisfies the standard of IEC 60641–2.

### 2.2 Test circuit and partial discharge observation

Figure 3 shows the PD test setup and measurement methods. The experimental model was put into the experimental tank with the height of 740 mm, width of 710 mm and length of 800 mm, and sank into the mineral oil completely. Positive lightning impulse voltage was generated by a 1500 kV impulse voltage generator (IG), and the voltage waveform was measured by a voltage divider (HIGHVOLT; 1200 kVImp) (see Figure 3(a)).

The peak value of the applied impulse voltage increase time and delay time were automatically read by a software system, Digital Impulse Analyzer, according to the standard of IEC60060-1(2010).

To correctly detect the PD inception voltage (PDIV), detection of both electrical and optical signals was carried out. In addition, image of the discharge light was used for understanding the PD inception position. The voltage of the PD signal detected by both two methods was recognized as the PDIV. The electrical signal of PD was detected by a high frequency current transformer (CT) (Pearson Electronics, Inc.).

The impulse discharge light was detected by remote PD detection equipment. The PD was expected to occur at the top surface of the PB stacks, so a photomultiplier tube (PMT) and a digital camera were put on the top of the experimental tank (see Figure 3(b)), and directed towards the experimental model to capture the PD light through a window of the tank. The window was made by a transparent acrylic resin with thickness of 40 mm. There was no obstacle between the measurement devices that is, camera and PMTs, and the window. Moreover, no supported device was used to help the PMT to receive the optical signal. The distance between the camera and the model was about 400 mm. The PMT and the digital camera were put inside a shield box reducing the influence of electromagnetic noise. Two PMTs were used. One was used for the measurement and the other one, blindfolded, was used for the identification of the electromagnetic noise. An LED light was also set outside of the experiment tank to identify the inception position of the PD immediately after it occurred.
On the other hand, the residual space charge was obtained from the value measured by the electrometer (Takeda Riken: TR8651) when the contact of relay 2 changed from C to D after each lightning impulse. First the current flows $i_1$ and $i_2$ at times $t_1$ and $t_2$ were measured, and then the residual space charge was calculated using following equations [17, 18].

$$i = \frac{V}{R}$$  \hspace{1cm} (1)

$$i = i_0 \exp \left( -\frac{t}{\tau} \right)$$  \hspace{1cm} (2)

$$Q = i_0 \tau$$  \hspace{1cm} (3)

Where $R$ is a constant resistance of 100 MΩ, $V$ is the voltage measured by the electrometer, $\tau$ is the relaxation time constant, $i_0$ is the initial current and $Q$ is the residual space charge. The value of $R$ is decided by the measurement circuit.

By the use of above equations, the relaxation time constant $\tau$ using currents of $i_1$ and $i_2$ and times of $t_1$ and $t_2$ will be as follows.

$$\tau = \frac{t_1 - t_2}{\ln(i_2) - \ln(i_1)}$$  \hspace{1cm} (4)

### RESULTS AND DISCUSSION

First, we aimed at the observation of the inception position of the PD in this complex model. Then, the influence of the residual space charge on the occurrence of the PD was investigated by using different time intervals between two lightning impulses. The measurement of the residual current flow after impulses application was carried out.

#### 3.1 PD inception at the oil gap created by spacers and around the metallic impurity

The impulse voltage started from a voltage too low to lead to PD and increased in steps of about 15 kV until PD occurred. It needs to be explained here that the maximum voltage of the impulse generator was set at about 600 kV and the applied voltage increased with 2% per step. Therefore, the increased applied voltage was a little less or more than 15 kV.

Figure 4 shows images of the experimental model and the first PDs that occurred in the oil gap and around the metallic impurity. The PDIV of the PD occurring in the oil gap was 291 kV and that of the PD occurring around the metallic impurity was 408 kV.

The electrical and optical signals of no PD was observed, PD observed at 291 and 408 kV, which measured by the CT and PMTs, are shown in Figures 5 and 6. Enlarged figures of
the electrical signal obtained between 1.8–2 μs are also shown in Figure 5(a–c). The pulse bandwidth of the electrical signals was about 50 ns at both 291 and 408 kV. Comparable to those observed in other studies [19–21], the obtained value of bandwidth indicates that the PD in Figure 4(b) was correctly measured. The signals detected by the PMT2 in Figure 6(a–c) were the electromagnetic noise. The optical measurement results also indicate that the PD light was correctly observed at 291 and 408 kV.

The influence of the metallic impurity inside a transformer was worried about and investigated a lot, but the oil gap created by the axial and radial spacers was a matter of less concern. Our experimental results, however, proved that PD can occur in the oil gap created by the axial and radial spacers. Moreover, in this experiment, the voltage of PD occurring in the oil gap is lower than that of PD triggered by the metallic impurity. Of course, it should also be mentioned here that the PD induced by a metallic impurity depends on many parameters, such as size, shape, nature, and so on.

Moreover, it was found that the PD beginning in the oil gap crept along the edge of the axial spacer, went through the top surface of the PB stacks, and at last reached the main insulation barrier. Of course, the streamer also reached the LV electrodes but was not able to be observed by the camera. If the insulation barrier and the IP covering the electrode are not thick enough, breakdown can occur. Meanwhile, the discharge light around the metallic impurity was brighter than that observed in the oil gap at the same voltage, which means that the discharge energy caused by a metallic impurity is larger than that of the PD starting in an oil gap. The PD triggered by the metallic impurity propagated straight from the HV electrode to the LV electrode. It therefore seems that breakdown is more likely to be caused by PD due to a metallic impurity than by PD beginning in an oil gap. However, we should know that even if there are no metallic impurities left inside the insulation structure, PD beginning in an oil gap can lead to breakdown.

Since the oil gap concentrated in this research has not been studied much, we analysed the electric field concentration in the oil gap. A 2D simulation using the finite element method was carried out. The distribution of the electric field intensity at the connection part is shown in Figure 7. The colour bar on the right side of the figure shows the intensity of the electric field. Here, we adopted the percentage of the applied voltage to express the electric field concentration. From the enlarged image of the oil gap, it was found that two smaller oil gaps A and B were generated between radial and axial spacers (see Figure 7(a)). Therefore, electric fields of both two gaps were investigated. The values of the electric field shown in Figure 7(b) are maximum values ($E_{\text{max}}$) of the averaged electric fields in 1 mm distance along the electric field direction. In transformer design, this evaluation method is often used. The values of $E_{\text{max}}$ in oil gaps A and B were 6.6% and 7.2%/mm that is 19.2 and 21.0 kV/mm at 291 kV, respectively. In addition, the $E_{\text{max}}$ around the metallic impurity was also investigated, which was 9.8%/mm that is, 28.5 kV/mm at 291 kV.
In consideration of the magnitude of the electric field, if the PD occurred in the oil gap, the PD should also be observed around the metallic impurity. However, at the lower voltage of 291 kV, the PD was only observed in the oil gap. A weak point must exist in the oil gap. In [22], it was found that the electric field concentrated at the tip of the cellulose fibre protrusion on the surface of IPs. Thus, the insulation property of the oil gap deteriorated under the lightning impulse application [22]. It has also been reported by other researchers that the insulation property is easily influenced by the surface condition, especially under the lightning impulse application [23, 24]. Therefore, the surface condition of the PB at the connection part was investigated by a microscope (see Figure 8). It was found that a lot of cellulose fibres exist on the PB's surface. Moreover, the size as large as 226.4 μm was observed. Since the oil gap was small, the influence of the cellulose fibre protrusions was significant [9, 25]. Therefore, the cellulose fibre protrusions are considered to lead to the PD occurring in the oil gap at a lower applied voltage.

Based on the experiment and the simulation results, we think that high electric field generated in the oil gap created by axial and radial spacers and caused PD. Therefore, we propose that this oil gap should be taken into consideration in the transformer design process.

| Times | First experiment | Second experiment |
|-------|-----------------|------------------|
|       | Voltage (kV)    | PD [4 min]       | Voltage [kV]    | PD [30 min] |
| 1     | 255             | N/A              | 251             | N/A         |
| 2     | 269             | N/A              | 263             | N/A         |
| 3     | 291             | PD               | 288             | PD          |
| 4     | 290             | N/A              | 293             | PD          |
| 5     | 290             | N/A              | 289             | PD          |
| 6     | 290             | N/A              | 289             | PD          |
| 7     | 290             | N/A              | 284             | PD          |
| 8     | 289             | PD               | 286             | PD          |
| 9     | 290             | N/A              | 282             | PD          |
| 10    | 290             | N/A              | 283             | PD          |
| 11    | 291             | PD               | 280             | PD          |
| 12    | 291             | PD               | 279             | PD          |
| 13    | 291             | N/A              | –               | –           |
| 14    | 291             | PD               | –               | –           |
| 15    | 291             | N/A              | –               | –           |
| 16    | 291             | N/A              | –               | –           |
| 17    | 291             | PD               | –               | –           |

### 3.2 Influence of repeated lightning impulses

The PD inception in the oil gap was investigated using two different time intervals between two continuous applied lightning impulses. In the factory test, time interval of 4 min was used. Meanwhile, it is reported that the relaxation time of the residual space charge left on the PB surface was 869.14 s in [2]. To completely exclude the influence of the space charge, a longer time of 30 min was regarded as reasonable. Therefore, the time intervals of 4 and 30 min were used in this research. When the PD occurred around the metallic impurity, it also occurred in the oil gap, and the residual space charge due to PD starting around the impurity was hard to be separated from that due to PD starting in the gap. Therefore, the PD that occurred around the metallic impurity will not be discussed here. To ensure the first experiment did not affect the second experiment, the time interval between two experiments was set over 24 h. Moreover, the moisture content of the oil, which was about 5 ppm, was measured for each experiment and no obvious difference was found. Degassing was carried out with enough time before each experiment to reduce the gas content to a safe level. In addition, since the dispersion of PDIV of different models is large as it is well known, all the experiments in this research were carried out on one model.

The processes of the applied voltages in the first and second experiments are shown in Table 1. After the PD began, the applied voltage was fixed at its current value and repeated 17
times in the first experiment and 12 times in the second experiment.

Measurement results of PD occurrence are shown in Table 1. In both experiments, the applied voltage started from about 250 kV—a voltage which no PD was observed. The PD incepted at the voltage of 291 and 288 kV. As it was introduced above, voltage increasing step fluctuates, the voltage value of 291 and 288 kV could be regarded as a same voltage. We therefore thought that the influence of the impulse shot in the first experiment had completely disappeared and did not affect the PD inception in the second experiment more than 24 h later.

In the first experiment, the PD occurrence was observed at impulse voltage application times of 3, 8, 11, 12, 14 and 17. It is obvious that the PD was not constantly observed even though the applied voltage was fixed at a value at which PD had been observed.

In the second experiment, before the PD was observed, same time interval of 4 min was used. After the PD occurred, time interval of 30 min was used. The PD constantly occurred after the first PD occurrence. From these two experiments, it was found that the interval time affect the constant occurrence of the PD. It has been reported in [2] that the space charge resided at the surface of the oil/PB under DC voltages, therefore the space charge was also considered to remain at surfaces of the oil/PB and oil/IP after impulse voltage application. The residual space charge on the surfaces might prevent the PD occurrence, and it seemed that 4 min was not long enough for the residual space charge to dissipate but 30 min was.

Therefore, the residual space charge was investigated using the method introduced in Section 2.2. If the space charge resided on the surface of the IPs and PBs, it would flow through the 100 MΩ resistance and observed by the electrometer when the switch in relay 2 turned from C to D (see Figure 3(a)). In the second experiment, the flowed current was measured immediately after each impulse, with steps of 1 min. The residual voltage was measured by the electrometer and then calculated to current using Equation (1). Observed voltage was less than 100 mV after each impulse shot and stably and exponentially decreased as the time increased, which well matched the characteristics of the discharge of a capacitor. The amounts of residual space charges were calculated using Equations (1)–(3). Obtained results are shown in Figure 9, the amount of the residual space charge linearly increased as the repeated impulses times increased.

Relaxation time of the generated residual space charge was calculated using Equation (4) (see Figure 10). Even though at the first several impulses, no clear variation tendency of the relaxation time was found, the relaxation time constantly increased as the number of impulses shot increased from the 4th time. For the first PD it was 440 s, and after ten times shot it increased to about 970 s. It is reported in [2] that the relaxation time of the space charge at the surface of the pressboard in a pure mineral oil is 869.14 s. Compared with the reported relaxation time, the result in this experiment is reasonable. According to the measured relaxation time, it proved again that 30 min is enough to exclude the influence of the residual space charge.

Therefore, the increased amount of space charge was considered due to the deterioration of the oil.

To confirm the oil insulation deterioration, a third experiment was carried out. The time interval between the second and third experiments was also over 24 h. The experimental process and the PD occurrence after each impulse is shown in Table 2. It is found that the PDIV decreased to 248 kV, and frequency of the PD occurrence increased comparing with those observed in the first and second experiments. These results suggest that in the third experiment the oil had deteriorated.

4 | DISCUSSION

We proposed a model to explain the results observed in this research (see Figure 11). The connection part studied in this research can be simply expressed by three capacitors—made up of PB, oil and IP—series connected between HV and LV electrodes. The dielectric constants of the PB, oil and IP were respectively \( \varepsilon_1 \), \( \varepsilon_2 \) and \( \varepsilon_3 \).

When the voltage \( V \) was applied between HV and LV electrodes, the applied voltages on the PB, oil and IP were respectively \( V_1 \), \( V_2 \) and \( V_3 \). Negative charges accumulated at the
TABLE 2  The value of PDIV of the PD occurrence in the oil gap and the observation of the PD in the 3rd experiment. Here the expression N/A means that no PD was observed

| Times | Voltage [kV] | PD [4 min] |
|-------|-------------|------------|
| 1     | 221         | N/A        |
| 2     | 234         | N/A        |
| 3     | 248         | PD         |
| 4     | 271         | N/A        |
| 5     | 271         | PD         |
| 6     | 295         | PD         |
| 7     | 295         | PD         |
| 8     | 323         | N/A        |
| 9     | 323         | PD         |
| 10    | 323         | N/A        |

FIGURE 11  Proposed model of the influence of residual space charge due to repeatedly applied impulses

oil/PB surface and positive charges accumulated at the oil/IP surface in the oil after lightning impulses. If the space charge could not be dissipated during the time between two impulses, a contrary electric field \( E_R \) would be generated, and the real electric field \( E \) applied on the oil would be as following equation.

\[
E = E_0 - E_R
\]

where \( E_0 \) is the electric field that no space charge exists.

The real value of the voltage \( V_2' \) applied on the oil would be \( V_2' < V_2 \). Therefore, the PD would not be initiated if the space charge resided on the surfaces of the oil/PB and oil/IP. Thus, inconstant PD occurrence was observed in the first experiment.

In the second experiment, the residual space charge disappeared after a long enough time interval was used, and the \( E_R \) did not exist. Therefore, the PD occurred continuously after each impulse. Moreover, as the oil deteriorated, the \( \varepsilon_2 \) would change to \( \varepsilon_2' \). It is generally known that the value is \( \varepsilon_2' < \varepsilon_2 \). Since the \( \varepsilon_1 \) and \( \varepsilon_3 \) did not change, the real applied voltage \( V_2'' \) on the oil would be \( V_2'' > V_2 \). Therefore, observed PDIV decreased and a higher frequency of PD occurrence in the third experiments was observed.

Although PD also occurred several times in the first experiment, these PDs might not be able to degrade the oil much. Therefore, inconstant PD was observed. The unclear change tendency of the first several times of space charge characteristics in the second experiment might be due to this reason.

On the other hand, it is reported by some researchers that a shorter time interval accelerated the oil deterioration [12,13, 26]. In our research, however, a longer time interval seemed to accelerate the oil deterioration. This difference might be due to the different structure of experimental models. In the studies by other researchers, bare electrodes were adopted in the experimental model. The use of a bare electrode enables the residual charge to disappear immediately. Therefore, larger numbers of PDs occur in a short time and this accelerates the oil deterioration.

A bare electrode is not used in the transformer, so the phenomenon observed in this research is closer to that really occurring in a transformer. Based on our experiments, we think that the residual space charge prevents the generation of PD if the time interval is not long enough. A shorter time interval repeated impulses test will not help users to understand the real insulation property of the transformer, therefore, long enough time interval during repeated impulse application is required. However, an interval time of 30 min is not possible in the factory test. On the other hand, the polarity test is also required by some users. Our results make the polarity test seem reasonable. Change of the polarity can exclude the influence of the residual space charge for understanding the real insulation property of the transformer. We therefore suggest that the polarity test be part of the factory test procedure.

5  CONCLUSION

In this research we made a complex insulation structure model to simulate the connection part of radial and axial spacers in transformers. The size and thickness of spacers really used in transformers were used in our experimental model. The PD occurrence due to two expected defects that is, oil gaps and metallic impurity, was investigated. PD inception was observed in the oil gap. As far as we know, this is the first time that PD occurrence in the oil gap created by radial and axial spacers was experimentally proved. The PD that started in an oil gap propagated along the edge of the spacers and finally reached the electrode, which can lead to breakdown. Therefore, we suggest that the oil gap created by radial and axial spacers in the transformer should be considered carefully in the transformer design process.

We also investigated the characteristics of the PD occurring after repeated lightning impulses. The influence of the residual space charge on the surface of the oil/insulation after repeated impulses on the PD inception was analysed. It was found that
the residual space charge prevents PD occurring. Therefore, to understand the real insulation property of a transformer, either a long enough time interval should be used in the factory test or the polarity test should be carried out.

ORCID

Li Lu https://orcid.org/0000-0002-1197-9870

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How to cite this article: Lu Li, Ichimura S, Rokunohe T. Partial discharge observation of a complex insulation structure model and residual space charge characteristics investigation under repeated lightning impulses. IET Sci. Meas. Technol. 2021;15:535–543. https://doi.org/10.1049/smt2.12054