Research on quantitative method of GIS partial discharge

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Abstract. Optical method is a commonly used method for detecting partial discharge in electrical equipment. How to use photometric quantitative detection is one of the most urgent problems to be solved. Based on the in-depth analysis of the physical meaning of the integral value of the PD optical signal, it is concluded that the linear integral value of the signal is linear with the apparent discharge. The experimental results show that the integral value of the PD photometric signal at different polarities and different distances is linear with the apparent discharge. The larger the gap distance between the needle and the plate electrode is, the larger the slope is. The linear relationship between the average primary integrated value of the PD photometric signal and the average apparent discharge is different. With the increase of the applied voltage, the PD discharge intensity and the pulse repetition rate increase, and the phase interval of the PD becomes wider. The actual air gap volume of the PD becomes larger, and the variation interval becomes wider, that is, the apparent discharge amount distribution interval becomes wider, and the maximum value and the minimum value of the distribution interval become larger. Therefore, it is possible to obtain the PD apparent discharge amount by using the photometric signal, and it is effective and feasible to quantitatively detect the internal PD of the GIS by optical method.

1. Introduction

Since partial discharge is one of the important parameters for characterizing the insulation state of electrical equipment, accurate detection of electrical equipment PD is the key to realize on-line monitoring and state assessment of insulation status of electrical equipment [1]. At present, methods for detecting PD of electrical equipment mainly include pulse current method, ultra-high frequency method, chemical detection method, and optical method. The PD pulse current method is currently the only quantitative detection method recommended by the academic community. However, due to its narrow detection frequency range and weak anti-interference ability, it has low detection accuracy in large-scale field and is usually only used for quantitative detection in low-interference environments [2]. On the contrary, UHF detection has high sensitivity and strong immunity, but its quantitative problem still plagues many scholars. The chemical detection method can reflect the overall degree of PD, but the detection period is long and does not meet the online monitoring requirements. At present, most PD detection methods acquire PD signals from outside the electrical equipment. Due to the complexity of some electrical equipment, it is difficult to accurately determine the location of the PD.

In recent years, the optical measurement method [3] is used to detect PD as the mainstream. The PD is measured by detecting the optical signal generated by the PD light effect. It is not affected by electromagnetic interference, and has high sensitivity. The biggest advantage is that it can accurately
detect and judge the PD position inside the complex structure. The optical method has been successfully used for PD detection in GIS, but this method is only for qualitative detection of PD, and cannot be used for quantitative judgment of PD discharge level, which is the main bottleneck encountered by this method [4-5]. In literature [6-8], the relationship between the amplitude of the photometric method and the apparent discharge under corona discharge and creeping discharge is studied respectively. It is concluded that the two have a linear relationship, but they are not analysed and explained from the theory. Therefore, based on the above basics, based on the theory, the relevant experimental platform is established, and the comparison between PD photometry and pulse current method under the needle-plate electrode model is carried out. The relationship between the integral value and the apparent discharge is studied. The reader is provided with a reference method for quantitative detection of PD using photometry.

2. Theoretical Analysis of the Relationship between Signal and Discharge Quantity in optical method

The photometric method uses a photoelectric converter to convert a photo sensor to a weak optical signal generated by a PD and convert it into an electrical signal output. In this paper, a photomultiplier tube is used as a photoelectric converter, and its working principle is shown in Figure 1.

![Photomultiplier tube output equivalent circuit](image)

**Figure 1.** Photomultiplier tube output equivalent circuit

When the working voltage of the photomultiplier tube is constant, the anode output current can be expressed by the following formula:

\[ i(t) = GS_d P_s(t) \]  

(1)

Where \( i(t) \) is the anode output current, \( G \) is the current gain, \( S_d \) is the photocathode sensitivity, and \( P_s(t) \) is the optical signal power.

Since the optical signal generated by the PD is a pulse signal, it is known from the equation (1) that the anode output current is also a pulse signal, wherein the influence of the photomultiplier tube anode-to-ground capacitance on the pulse signal is not negligible. The output circuit and equivalent circuit diagram are shown in Figure 1. Available from equivalent circuits:

\[ u(t) = Ce^{-\frac{t}{\tau_1}} + e^{-\frac{t}{\tau_1}} \int i(t)e^{\frac{t}{\tau_1}} dt \]  

(2)

Where \( u(t) \) is the output voltage of the photomultiplier tube, \( \tau_1 = R_1C_1 \), and \( C \) is a constant. Differentiating the output voltage can be obtained:
\[ u'(t) = -\frac{C}{\tau_1} e^{-\frac{t}{\tau_1}} - \frac{1}{\tau_1} \int i(t) e^{\frac{t}{\tau_1}} dt + i(t) \] \quad (3)

The simultaneous (2) and (3) versions are available:

\[ u(t) + \tau_1 u'(t) = \tau_1 i(t) \] \quad (4)

The simultaneous (1) and (4) are available:

\[ P_s(t) = \frac{1}{\tau_1 GS_d} [u(t) + \tau_1 u'(t)] \] \quad (5)

According to the above derivation, the light energy \( E \) absorbed by the PD photo sensor can be obtained as follows:

\[ E = \int_{t_1}^{t_2} P_s(t) dt = \frac{1}{\tau_1 GS_d} \int_{t_1}^{t_2} [u(t) + \tau_1 u'(t)] dt \] \quad (6)

The signal of a single PD optical method is indicated by \( A \), and the simultaneous (6) can be obtained:

\[ E = \frac{1}{\tau_1 GS_d} \int_{t_1}^{t_2} u(t) dt \] \quad (7)

It can be seen from the attenuation characteristics of the optical signal in the medium that the relationship between the light energy \( E_{\text{light}} \) released by the primary PD and the received light energy \( E \) can be expressed by the following formula [9]:

\[ E = \mu e^{-k_\varepsilon \rho L} E_{\text{light}} \] \quad (8)

Where \( \mu \) is the absorption coefficient of the photo sensor, \( k_\varepsilon \) is the gas absorption coefficient, \( L \) is the distance between the sensor and the PD source, and \( \rho \) is the gas density. The simultaneous (3.47) and (3.48) versions are available:

\[ \int_{t_1}^{t_2} u(t) dt = \mu GS_d \tau_1 e^{-k_\varepsilon \rho L} E_{\text{light}} \] \quad (9)

When the working voltage of the photomultiplier tube is constant, and the relative positions of the photo sensor and the PD discharge source are constant, \( \mu, G, e^{-k_\varepsilon \rho L} \) and \( S_d \) are constant. It can be seen that the integrated value of the photometric signal substantially characterizes the light energy released by the PD.
There are two main reasons why PD produces a light effect. One is charged particle composite luminescence, PD generates a large number of charged particles. When charged particles with opposite charge signs meet, it is possible to recombine and release energy in the form of light radiation. Second, charged particles cause luminescence, PD the generated free charged particles are accelerated by a strong electric field. When the freely charged particles collide with the neutral particles, the kinetic energy of the freely charged particles is transferred to the neutral particles for excitation, and when the excited neutral particles return to the ground state, they are absorbed. The energy is released in the form of radiant light. The reason why the light effect is generated by the PD is that the light energy released by the PD is essentially converted from the PD discharge energy [10-12]. Therefore, the relationship between the light energy $E_{\text{light}}$ released by the PD and the PD discharge energy $E_f$ can be referred to as the luminous efficiency $\eta$. The luminous efficiency $\eta$ is a physical quantity describing the efficiency of conversion of discharge energy into light energy in the principle of light source, which is defined as:

$$\eta = \frac{E_{\text{light}}}{E_f}$$

(10)

The luminous efficiency $\eta$ is related to the characteristics of the luminescent medium, the electric field strength $E$, the electrode spacing $l$, and the environmental factors. For the pulse type discharge, it is also related to the duration $t_c$ of the discharge current pulse, and the discharge energy has little influence on the luminous efficiency $\eta$, which can be approximated in The luminous efficiency $\eta$ at different discharge energies is a constant under certain other influencing factors.

The PD discharge energy $E_f$ can be calculated by the equation (11):

$$E_f = \frac{1}{2} u_i q$$

(11)

Where $u_i$ is the peak of the initial discharge voltage of PD and $q$ is the amount of PD apparent discharge. The relationship between the light energy $E_{\text{light}}$ released by the PD and the PD apparent discharge amount $q$ can be expressed by the following formula:

$$E_{\text{light}} = \frac{\eta u_i}{2} q$$

(12)

The simultaneous (9) and (12) are available:

$$\int_{t_1}^{t_2} u(t)dt = \frac{\mu \eta GS_d \tau^2 e^{-k \rho L} \eta}{2} u_i q$$

(13)

If $k = \frac{\mu \eta GS_d \tau e^{-k \rho L}}{2} u_i$, $A = \int_{t_1}^{t_2} u(t)dt$, the above formula can be abbreviated as:

$$A = k q$$

(14)
It can be seen that the primary integral value of the PD photometric signal is linear with the apparent
discharge amount, wherein the slope $k$ and the working parameters of the photomultiplier tube, the
relative position of the photo sensor and the PD source, the distance between the electrodes, and the
initial discharge. Voltage peaks and environmental factors are related.

3. Experimental system and experimental method
In order to study the relationship between PD apparent discharge and photometric signal, PD signal was
measured by pulse current method and optical method. The experimental platform consists of a double-
shielded sealed box, a PD source artificial model, a PD pulse current and photoelectric signal
measurement system, and a non-smooth power test power supply. The experimental wiring is shown in
Figure 2.

![Figure 2. Correction circuit](image)

The PD pulse current signal measurement uses a series impedance of 50Ω to input the pulse signal
into the digital storage oscilloscope through the high frequency cable. The PD photometric method uses
a fluorescent fiber optic sensor to receive the optical effect signal generated by the PD, and then couples
and transmits the optical signal induced by the fluorescent fiber to the photodetector by using the
transmission type ordinary optical fiber, and the photodetector converts the optical signal into a voltage
signal. Finally, the pulse current signal is input to the digital storage oscilloscope via the high frequency
cable. The photodetector uses a H9656-02 photomultiplier tube (PMT) with a spectral response range
of 300-880 nm and a peak sensitivity wavelength of 500 nm. The acquisition and storage signals are
recorded by a high-speed digital oscilloscope (Tektronix DPO7104 oscilloscope, analog bandwidth
1GHz, maximum sampling rate 20GS/s, storage depth 40M), which can meet the requirements of PD
optical signal and pulse current signal acquisition.

According to the IEC60270 standard pulse current method, the pulse voltage amplitude $U$ and the
apparent discharge amount $q$ are proportional to each other, and the measurement circuit is corrected to
obtain the pulse voltage amplitude and the apparent discharge amount proportional coefficient $K$,
thereby measuring the pulse according to the pulse current method. The voltage amplitude $U$ calculates
the apparent discharge amount $q$. The discharge quantity correction circuit is shown in Figure 2. A
partial discharge calibrator is connected in parallel with the sample to generate a pulse signal with a
known discharge amount on the sample. The peak value of the pulse voltage across the 50Ω sense
resistor can be measured by a digital oscilloscope. Adjusting the output of the partial discharge calibrator
can obtain the relationship between $U$ and $q$, and obtain the calibration curve shown in Figure 3 by
fitting.
Experiment procedure:
(1) The fluorescent fiber sensor was fixed at a position of 100mm from the defect model, and the initial discharge voltage $U_{\text{initial}}$ was initiated and the breakdown voltage $U_{\text{breakdown}}$ was broken by a uniform boosting method. A total of five voltage values $U_1$, $U_2$, $U_3$, $U_4$ and $U_5$ are selected as the test voltage between the two voltage values.

(2) The high-speed oscilloscope is used to collect the PD signal at the same time measured by the photometric method and the pulse current method.

(3) PD signals acquired according to the method of (2) under $U_1$, $U_2$, $U_3$, $U_4$ and $U_5$, respectively, and after the discharge is stabilized.

According to the above steps, the PD test under four insulation defects [13] was performed separately.

4. Experimental results and analysis
The PD apparent discharge amount $q$ can be obtained by obtaining a calibration curve in Figure 3, as follows:

$$q = 5.235U + 4.183$$

Where $U$ is the amplitude of the primary PD voltage waveform detected on the 50Ω non-inductive resistor. The integral value of the PD photometric signal can be calculated by the following formula:

$$A = \Delta t \sum U_i$$

Where $A$ is the primary integrated value of the photometric signal, $U_i$ is the i-th value of the primary PD waveform measured by optical method, and $\Delta t$ is the sampling time interval.

At the same time, the pulse current method and the optical measurement method are used to collect the single PD signal waveform generated by the four types of insulation defect models. However, the signal waveforms obtained by the pulse current method for detecting the PDs generated by the four types of defect models are almost the same, and the optical detection method detects four types. The signal waveform obtained by the PD generated by the insulation defect model is also almost the same. Therefore, this paper only gives the single-shot PD signal waveform generated by the pulse current method and the photometric method to detect the defects of metal contaminants on the insulator surface.
Figure 4 shows the waveform of a single PD signal obtained by pulse current measurement through 50Ω detection impedance. Figure 5 shows the waveform of a single PD signal detected by optical method. The single-shot PD signal detected by the pulse current method is divided into two types: a positive polarity pulse and a negative polarity pulse, and the pulse polarity is related to the polarity of the high voltage end. The high voltage end is the positive pole. When the PD of the defect model occurs, the pulse current generated flows from the high voltage end to the low voltage end. At this time, the single PD signal waveform detected by the pulse current method is a positive polarity pulse. The high voltage end is the negative pole. When the defect model generates PD, the pulse current generated flows from the low voltage end to the high voltage end. At this time, the single PD signal waveform detected by the pulse current method is a negative polarity pulse. The photometric signal only has a positive pulse waveform, because the photometric signal reflects the change in optical energy released by the PD.
Because the distribution characteristics of the single-shot PD photometric signal and the apparent discharge amount increase with the increase of the discharge intensity under different defect models, this paper only gives the integral value of the PD photometric signal under the metal protrusion defect. The distribution interval with apparent discharge is shown in Figures 6 and 7. It can be seen from the figure that under the same experimental voltage, the integral value and the apparent discharge amount of a single PD signal at different times are not the same, but are distributed within a certain interval. As the applied voltage increases, the PD pulse repetition rate increases, and the signal increases. Both the primary integral value and the apparent discharge amount distribution interval are widened, and the maximum and minimum values of the distribution interval become large. Reason: PD only occurs in the local area near the discharge defect pole. Under AC voltage, the instantaneous voltage is greater than the initial discharge voltage value. The PD can be generated in the phase interval. According to the PD characteristics, the PD apparent discharge amount and the PD actually occur. Regarding the state of the region, the larger the air gap volume in which the PD actually occurs, the larger the apparent discharge amount.

Since the PD characteristics are related to many factors, the actual air gap volume of PD occurring in different phases is not the same, and has a certain randomness, but its volume always varies within a certain range. In general, when the applied voltage is increased and the discharge intensity and the pulse repetition rate are increased, the phase interval of the PD is widened, and the actual air gap volume of the PD is increased, and the apparent discharge amount distribution interval is widened. From equation
\( \alpha = \frac{d\tau(q)}{dq} \), it can be seen that the primary integrated value of the PD photometric signal is positively correlated with the apparent discharge amount, so that the primary integrated value and the apparent discharge amount exhibit similar distribution characteristics.

5. The establishment of the relationship between the integral value of the signal and the discharge amount

According to Figure 6 and Figure 7, the single-shot PD and the apparent discharge of the single-shot PD photometric signal at the same discharge intensity are distributed in a certain interval, and the single-shot PD photometric signal at different discharge intensities is once. There is an overlap region between the integral value and the apparent discharge amount distribution interval, so the primary integrated value and the apparent discharge amount of the single PD photometric signal cannot be used to characterize the PD discharge intensity. Therefore, this paper defines the average integral value \( A_{av} \) and the average apparent discharge amount \( q_{av} \) of the photometric signal, and uses \( A_{av} \) and \( q_{av} \) to indicate the parameters of the PD by the photometric method and the pulse current method, respectively. \( q_{av} \) is the average value of PD apparent discharge at different times (\( N_1 \)) of the same PD discharge intensity. According to statistics, the larger \( N_1 \) is, the smaller the fluctuation of \( q_{av} \) under the same PD discharge intensity, and \( q_{av} \) at this time can characterize the PD discharge intensity. Through a large number of experiments, it was found that when \( N_1 \geq 200 \), the fluctuation of \( q_{av} \) under the same PD discharge intensity is very small, so \( N_1 = 200 \) is taken. \( A_{av} \) is similar to the definition of \( q_{av} \), which is the average value of the integral value of the single PD photometric signal at \( N_2 \) different times at the same PD discharge intensity, where \( N_2 \) is also equal to 200. The formulas for \( q_{av} \) and \( A_{av} \) are as follows:

\[
q_{av} = \frac{\sum_{i=1}^{N_1} q_i}{N_1} \quad (17)
\]

\[
A_{av} = \frac{\sum_{j=1}^{N_2} A_j}{N_2} \quad (18)
\]

Since the average primary integral value \( A_{av} \) and the average apparent discharge amount \( q_{av} \) of the PD photometric signal can uniquely characterize the PD discharge intensity, a one-to-one correspondence between \( A_{av} \) and \( q_{av} \) can be found by establishing a relationship curve between \( A_{av} \) and \( q_{av} \). Realize the quantitative detection of PD in GIS by optical method.

Since this paper controls the PD discharge intensity by controlling the test voltage, 200 single-shot PD signals at the same voltage obtained by the pulse current method and the photometric method under the same conditions are used formula (15),(16),(17)and (18) calculate the average primary integral value
$A_{av}$ and the average apparent discharge amount $q_{av}$ of the PD photometric signal corresponding to the PD discharge intensity, change the test voltage, and obtain the PD optical signal average under different PD discharge intensities. One integral value $A_{av}$ and an average apparent discharge amount $q_{av}$.

![Graph showing the relationship between integral value and apparent discharge under different defects](image)

**Figure 8.** Relationship between the integral value of the signal and the apparent discharge under different insulation defects

Figure 8 shows the relationship between the average primary integral value $A_{av}$ of the PD photometric signal and the average apparent discharge $q_{av}$ under different defects obtained through a large number of experiments. The least square method is used to linearly fit the average primary integral value $A_{av}$ and the average apparent discharge amount $q_{av}$ of the PD photometric method. The linear goodness of fit $R^2$ is above 0.98. The fitting results show that $A_{av}$ and $q_{av}$ are linear. The main reason for the linear relationship between $A_{av}$ and $q_{av}$ is that as the applied voltage increases, the insulation defect causes the PD to be more intense, but the properties of the PD do not change, causing the intensity of the optical effect to increase proportionally with the increase of the PD discharge energy.

Comparing Figure 8(a) the relationship between the average integral value of the PD photometric signal and the average apparent discharge under different pin gap distances, it can be seen that the larger
the gap distance, the average signal and the average apparent discharge. The slope $k$ of the linear relationship is larger. The reason is that the larger the gap distance is, the free travel of the freely charged particles increases, and the probability of ionization caused by the collision of the unit number of freely charged particles with the neutral particles increases, so that the luminous efficiency $\eta$ of the charged particles due to the composite increases; On the other hand, the larger the gap distance, the larger the initial discharge voltage $u_i$ of the PD, and since $k$ is proportional to the luminous efficiency $\eta$ and the initial discharge voltage $u_i$, the slope $k$ increases as the gap distance increases.

Comparing Figures 8 (a), (b), (c) and (d), it can be seen that the linear relationship between the average primary integrated value of the PD photometric signals and the average apparent discharge is different for different insulation defect types. The reason is: the discharge properties of different insulation defect types PD are different, so that the luminous efficiency $\eta$ caused by PD is different, since $k$ is positively correlated with the luminous efficiency $\eta$, so that the average integral value and average of the PD photometric signals of different insulation defect types are averaged. The linear relationship curve corresponding to the discharge amount is different.

| Defect type | Experimental voltage /kV | $A_{av}$/ns·V | $q_{av}$/pC | $q_{av}$/pC | error/% |
|-------------|--------------------------|--------------|-------------|-------------|--------|
| Metal protrusion defect | 5 | 39.6 | 161.7 | 148.6 | 8.8 |
| | 6 | 67.0 | 280.9 | 291.4 | 3.6 |
| | 7 | 85.4 | 360.8 | 378.3 | 4.6 |
| Air gap defect between insulator surface and high voltage conductor | 13 | 6.83 | 275.9 | 271.5 | 1.6 |
| | 16 | 27.9 | 935.6 | 901.2 | 3.8 |
| | 18 | 46.8 | 1525.7 | 1410.8 | 8.1 |
| Metal particle defects on insulator surface | 4.5 | 4.84 | 100.6 | 109.2 | 7.9 |
| | 5.5 | 15.7 | 326.1 | 315.5 | 3.4 |
| | 6.5 | 21.3 | 481.8 | 467.1 | 3.1 |
| Free metal particle defect | 7 | 50.7 | 217.7 | 191.5 | 13.8 |
| | 7.5 | 67.3 | 286.8 | 312.5 | 8.0 |
| | 8 | 89.7 | 380.3 | 360.2 | 5.7 |

6. Validity Verification of Quantitative Detection of Partial Discharge in GIS by Photometric Method

In order to verify whether the relationship between the average primary integral value $A_{av}$ and the average apparent discharge amount $q_{av}$ of the PD photometric signal obtained in Figure 8 can be used for quantitative detection of GIS internal PD by optical method. In this paper, PD experiments of four typical defects in GIS are carried out under three different discharge intensities, and simultaneous detection by optical method and pulse current method. The experimental results are shown in Table 1. The average apparent discharge amount calculated in the table is represented by $\bar{q}_{av}$, and the error of $\bar{q}_{av}$ and $q_{av}$ is defined as:

$$error = \frac{|q_{av} - \bar{q}_{av}|}{q_{av}}$$ (19)
7. Conclusion
From the above experimental results, it is known that, based on the accurate identification of the insulation defect, the average apparent discharge amount calculated by the average integral value of the photometric method and the average apparent discharge amount corrected by the pulse current method are within 14%. At the same time, according to the research results of this paper, it is shown that the PD optical measurement signal can accurately identify the internal insulation defects of GIS. Therefore, it is effective and feasible to quantitatively detect the internal PD of GIS by optical measurement.

References
[1] WANG Chang-chang, LI Fu-qi, GAO Sheng-you, Electrical equipment online monitoring and fault diagnosis [M]. Beijing, China: Tsinghua University Press, 2006.
[2] Tang Ju, Wu Jian-rong, ZHOU Ran, et al. Relationship between VHF signals and discharge magnitude of partial discharge from needle plate electrode [J]. High Voltage Engineering, 2010, 36 (5): 1083 - 1089.
[3] XU Yang, YU Ming, CAO Xiao-long, et al. Optical pulse method for partial discharge measurement and the comparison with electrical current method [J]. High Voltage Engineering, 2001, 27 (4): 3 - 5.
[4] WANG Can-lin, LIAO Yong-li, WANG Li-ming, et al. Relationship between the UV corona pulses and the corona current pulses [J]. High Voltage Engineering, 2007, 33 (7): 88 - 91.
[5] HE Wei, CHEN Tao, YANG Fan, et al. Faulty insulator online monitoring system based non-touching UV pulse method[J]. High Voltage Engineering, 2006, 32 (10): 39 - 42.
[6] DU Lin, CUI Ting, SUN Cai-xin. Detecting AC corona discharges with the UVTRONR2869 type ultraviolet sensor [J]. High Voltage Engineering, 2009, 35 (2): 272 - 276.
[7] WANG Jin-gang. Study of detecting ultraviolet radiation of discharge on high voltage apparatus and its application [D]. Chongqing, China: Chongqing University, 2008.
[8] Beroual A, Buret F. Optical detector of electrical discharges [J]. IEE Proceedings-G: Electronic Circuits and Systems, 1991, 38 (5): 620 - 622.
[9] ZHANG Zhan-long, WANG Ke, TANG Ju, et al. Detection method for corona discharge of transformers on ultraviolet pulse [J]. Automation of Electric Power Systems, 2010, 34 (2): 84 - 88.
[10] SI Wen-rong, LI Jun-hao, YUAN Peng, et al. Current situation and development of optical detection for partial discharge [J]. High Voltage Engineering, 2008, 44 (3): 261 - 264.
[11] Muto K. Electric-discharge sensor utilizing fluorescent optical fiber [J]. IEEE Journal of Light Wave Technology, 1989, 7 (7): 1029 - 1032.
[12] Mangeret R, Farenc J. Optical detection of partial discharge using fluorescent fiber [J]. IEEE Transactions on Electrical Insulation, 1991, 26 (4): 783 - 789.
[13] ZHU Ning, ZHANG Ming-xuan, XU Xiao-qing. Decomposition Characteristics of SF6 and Partial Discharge Recognition for Inflatable DC Wall Bushing under Negative DC Conditions [J]. High Voltage Engineering, 2019: 1 - 10.