Study on the relationship between photon number and discharge magnitude of corona discharge based on ultraviolet imaging method

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Abstract. In order to improve the accuracy of discharge detection of a domestic ultraviolet (UV) imager, the relationship between the photon number and the discharge magnitude was established. In this paper, the rod-plate gap model was selected as the research object. By using the domestic ZT301 UV imager, the characteristics of photon number and discharge magnitude varied with voltage intensity, observation distances and instrument gains were studied. Experimental results show that the photon number and the discharge magnitude are nonlinear increased with the increasing of voltage. By changing the observation distance and gain, fitting curves of the photon number and the discharge magnitude were obtained, which still satisfied the nonlinear increasing relationship. The research results lay a foundation for practical engineering applications of the domestic UV imager.

1. Introduction
The solar-blind UV imaging detection is a visualized surface discharge detection method for high-voltage equipment, which has many advantages such as long detection distance, non-contact and accurate positioning of discharge position [1-2]. In recent years, it has been widely used in the discharge detection of high voltage equipment in power system [3-7]. At present, “spot area” is recommended to be used as the discharge quantification parameter [6] in the discharge detection of laboratory. However, it is necessary to quickly draw a preliminary diagnosis conclusion in the field when detecting discharge in engineering practice and it requires higher requirements for front-end equipment to take the “spot area” as the discharge quantization parameter for diagnosis. In order to improve the diagnostic efficiency, the front-end UV detection equipment is recommended to use the “photon number” as the discharge quantization parameter.

In practical engineering applications, “the apparent discharge magnitude” measured by the partial discharge detector is a key parameter of quantifying discharge intensity. Therefore, by studying and establishing the relationship between the photon number and the discharge magnitude, the accurate evaluation of the discharge intensity under the conditions of long-distance and non-contact will be realized[8].When using the “solar-blind” UV imager to detect the corona discharge intensity of the equipment, the instrument gain should be adjusted according to the discharge intensity due to the different voltage levels of the equipment being observed. Since the voltage level and gain have a
certain influence on the photon number, it is necessary to conduct an in-depth study on the relationships between the discharge magnitude and the voltage level and the photon number [9-12]. At present, the manufacturers of UV imager have not given an exact definition of the photon number. Therefore, it is difficult to theoretically analyze the variation characteristics of the photon number without scientific calculation methods and theoretical basis [3].

Based on the above research status, the rod-plate gap model was selected as the research object in this paper. Under different discharge intensity, the observation distance and the gain, the ZT301 UV imager produced by China Rayiee Power Technology (Beijing) Co., Ltd was used to record the UV video signal and the XD5102Y pulse current partial discharge detector produced by Hangzhou West Lake Electronics Research Institute was used to measure the discharge magnitude. The relationships between the discharge magnitude and the voltage level and the photon number were analyzed and acquired. At the same time, the fitting analyses about the relationships between the photon number and the discharge magnitude under different observation distances and gains were carried out.

The relevant research results of this paper are helpful for the normalization of quantitative parameters, laying a foundation for the quantitative analysis of discharge severity by using ZT301 UV imager in subsequent engineering applications and providing a useful reference for setting related evaluation guidelines of UV imaging detection in the future.

2. Construction of the test system and test methods

2.1. Test model and construction of the test system
The test ambient temperature was 25°C, the relative humidity was about 50% and the air pressure was standard atmospheric pressure. The rod-plate gap discharge model was selected as the research object in the test and the schematic diagram of testing system is shown in figure 1.

![Schematic diagram of testing system](image)

Figure 1. Schematic diagram of testing system.

In figure 1, the rod-plate model is used to simulate corona discharge of air gap. The diameter of the rod electrode is 3cm, its head is conical, and the radius of the tip is about 2mm. The diameter of the plate electrode is 40cm, and the rod-plate gap distance is set to 10cm. The UV imager is ZT301 produced by China Rayiee Power Technology (Beijing) Co., Ltd, and its basic parameters are shown in table 1. The UV imaging detection technology based on the solar blind could filter the interference of solar noise and meet the high sensitivity detection of the UV signal generated by discharge in the daytime.
In order to study the relationship between partial discharge and the photon number, the partial discharge detector is used to measure the corona discharge while measuring the photon number, the type of which is the XD5102Y pulse current partial discharge detector produced by Hangzhou West Lake Electronics Research Institute, with a bandwidth of 10k-500kHz. In consideration of convenience and safety, a current transformer with the same bandwidth as the partial discharge detector is used in the partial discharge measurement system for signal acquisition.

### 2.2. Test methods

Control variable method was adopted in the test, and the relevant test steps and methods are as follows:

1) First to study the relationship between discharge magnitude and voltage. Before the formal test, the partial discharge measurement system was calibrated with 1000pC signal by calibration pulse generator, then the AC high voltage was applied to the rod electrode, the voltage increasing step length is 5kV. Because the breakdown voltage for 10cm gap is around 52kV, in this paper, we study the variation characteristics of discharge magnitude at 11 voltage points with the effective voltage values of 0, 5, 10, 15, …, 50kV.

2) The relationship between photon number and discharge magnitude is explored under different gains. The UV imager used in the test can achieve the observation distance of 10-40m in practical engineering applications. Maintain voltage at the same level under the 11 voltage points mentioned above, and observe the discharge characteristics at 10, 15 and 20m, respectively. During the actual use of instrument, its gain regulation scope is generally within 50%-90%. Therefore, under various observation distances above, regulate the gains of UV imager to 50%, 70% and 90%, respectively. The classic UV images shot by the instrument under different observation distances and gains are as shown in figure 2.

![Figure 2](image-url)

**Figure 2.** Typical UV images under different observation distances and gains.

3) Corona discharge has certain random property, and the photon number fluctuates within certain scope. Therefore, in the test, 1min video signals of UV imager at each test point are recorded. Then, related software is used to randomly capture 50 frames of video image from the video. Finally, read the photon number shown in each frame of image, and calculate the average value.

### 3. Test analysis

3.1. **Relations of discharge magnitude and voltage with photon number**

In the laboratory environment, when the test conditions stay the same and the test object is applied with the same voltage, it can be regarded that the discharge magnitude is constant.
Adjust the observation distance to 10m and instrument gains to 50%. Gradually increase the voltage, when the voltage reaches around 15kV, the UV imager starts to observe weak discharge at the tip of rod electrode which is the high-voltage side and the photon number is low, most faculae are scattered spots, and the average apparent discharge detected by the partial discharge detector is 80pC. When the voltage reaches 30kV, a “squeaky” discharge sound can be heard in short distance, the photon number shown on the UV imager increases significantly, and the average value of discharge is around 119.45pC. With the increase of voltage, the photon number and discharge magnitude increase accordingly. When the voltage reaches 50kV, the average photon number is 153, and the average apparent discharge reaches 210pC.

Repeat the above test for 3 times, and each voltage increase interval is 10 minutes. According to the test, the numerical values of photon number and discharge magnitude present great repeatability under the same voltage. Based on the test data, figure 3 shows the curves of the relationship among discharge magnitude, photon number and voltage in the above test.

![Figure 3. Relation curves of photon number and discharge magnitude with voltage.](image)

According to figure 3, when the voltage reaches 10kV, with the gradual increase of voltage, the photon number and discharge magnitude also increase accordingly, but it presents certain nonlinearity. The discharge magnitude increases sharply at first, but when the voltage reaches around 15kV, the increase rate of discharge magnitude slows down. In summary, the change of voltage can be well characterized by discharge magnitude.

Based on the above test data, figure 4 shows the curve of the relationship between discharge magnitude and photon number.

![Figure 4. Relation curve of photon number with discharge magnitude.](image)
According to figure 4, the discharge magnitude will increase with the growth of photon number, and the photon number can be used as a parameter to well represent the change of discharge magnitude.

3.2. Relationship between photon number and discharge magnitude under different observation distances

Different photon numbers are measured under different observation distances, while the observation distance does not affect the intensity of discharge.

Set the observation distance at 10, 15 and 20 m respectively, and set the instrument gain at 70%. Record the photon numbers measured under various discharge magnitude, and the test results are shown in figure 5.

![Figure 5. Relation curves of photon number with discharge magnitude under different observation distances.](image)

Figure 5 shows that, under the same discharge, the bigger the observation distance is, the less photons are measured. Under the same observation distance, with the increase of discharge, the photon number measured by the instrument still maintains a relationship of nonlinear increasing with the discharge, which indicates that the photon number is still can be used to describe the discharge degree under different observation distances.

The change trend of data points in figure 5 presents approximately exponential change. The Matlab curve fitting tool (cftool) is used for fitting and analysis of above data, and the exponential function is used as the fitting formula:

\[
n(q) = Ae^{bq}
\]

where, \( q \) is the discharge magnitude, \( A \) and \( b \) are constant coefficients. The fitting function expression and fitting goodness \( R^2 \) (the scope of \( R^2 \) is within 0-1, and the closer the value of \( R^2 \) is to 1, the better fitting degree of the regression curve to the observed value) are shown in table 2.

Table 2. Fitting function expressions of photon number to discharge magnitude under different observation distances.

| Observation Distance (m) | Fitting Function Expression | Fitting Goodness \( R^2 \) |
|--------------------------|-----------------------------|--------------------------|
| 10                       | \( n(q) = 14.47e^{0.01299q} \) | 0.9665                   |
| 15                       | \( n(q) = 14.97e^{0.01126q} \) | 0.9537                   |
| 20                       | \( n(q) = 8.876e^{0.01311q} \) | 0.9687                   |

In table 2, the \( R^2 \) value closes to 1, which indicates that its fitting formula presents high fitting degree with actual data. Analysis of data under other distances shows that the photon number and discharge magnitude also approximately satisfy the characteristics of exponential change. The value of coefficient \( b \) is generally between 0.01-0.02.
3.3. Relationship between photon number and discharge magnitude under different gains

Different photon numbers are measured under different instrument gains, while the instrument gains do not affect the intensity of discharge.

Set the instrument gains at 50%, 70% and 90% respectively, and the observation distance is 15m. Record the photon numbers measured under various discharge magnitude, and the test results are shown in figure 6.

![Figure 6. Relation curves of photon number with discharge magnitude under different gains.](image)

Figure 6 shows that the bigger the gains are, the more photons are measured under the same discharge magnitude. Under the same gain, with the increase of discharge, the photon number measured by the instrument still maintains a nonlinear increasing relationship with the discharge magnitude, which indicates that the photon number is still used to describe the discharge degree under different gains.

The change trend of data points in figure 6 presents approximately exponential change. The Matlab curve fitting tool (cftool) is used for fitting and analysis of above data, and the exponential function is used as the fitting formula:

\[ n(q) = C e^{dq} \]  

(2)

Where, \( q \) is the discharge magnitude, \( C \) and \( d \) are the corresponding constant coefficients. The fitting function expression and fitting goodness \( R^2 \) are shown in Table 3.

Table 3. Fitting function expressions of photon number to discharge magnitude under different gains.

| Instrument Gain (\%) | Fitting Function Expression | Fitting Goodness \( R^2 \) |
|----------------------|-----------------------------|---------------------------|
| 50       | \( n(q) = 11.51 e^{0.01161q} \) | 0.9665                   |
| 70       | \( n(q) = 14.97 e^{0.01126q} \) | 0.9537                   |
| 90       | \( n(q) = 2.774 e^{0.02592q} \) | 0.9687                   |

In table 3, the \( R^2 \) value closes to 1, which indicates that its fitting formula presents high fitting degree with actual data. Analysis of data under other gains shows that the photon number and discharge magnitude also approximately satisfy the characteristics of exponential change. The value of coefficient \( d \) is generally between 0.01-0.03.

4. Conclusions

In order to improve the accuracy of corona discharge detection with the UV imaging technology, we explored relations of discharge magnitude and voltage with photon number, and the relationship between photon number and discharge under different observation distances and gains. Furthermore, by combining the test data, we obtained the curves of how the photon number and discharge change with different variables, and draw the following conclusions:
(1) With the increase of voltage, the photon number and discharge also increase accordingly, but they present certain nonlinearity.

(2) The discharge magnitude will increase with the growth of photon number and selecting the photon number as a parameter can well represent the change of discharge magnitude.

(3) With the change of observation distances and gains, the photon number and discharge magnitude still satisfy the relationship of nonlinear increasing function, and the photon number is still can be used to describe the discharge degree.

(4) Under different observation distances and gains, the nonlinear curve relationship between the photon number and discharge can be fit with exponential function, which has important reference value to realize the engineering applications of the domestic UV imager used in this paper.

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