Equivalence analysis of multiple monitoring methods for partial discharge

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Abstract. In order to study the relationship between the amplitude (mV) and the discharge (pC) of a typical fault of a tip discharge in a partial discharge. Therefore, three different groups of tip electrode models (tip-tip, tip-plate, tip-ball) were simulated. The relationship between magnitude and discharge volume and voltage was obtained by using amplitude detection method (Ultra High Frequency Method, Acoustic Emission Method and Transient Earth Voltage method) and Pulse Current Method respectively. Kendall correlation analysis found that the amplitude and the voltage of the AE Method in the three amplitude detection methods are closest to the variation trend of the discharge quantity and the voltage of the Pulse Current Method. Exploring the equivalence between the amplitude and the discharge of the most accurate detection means, the mathematical model with the best fit is the Sum of Sin Functions.

1. Introduction
In recent years, with the increasing demand for electricity from all walks of life, the power grid not only needs to provide a large amount of electricity, but also needs to ensure the quality of electricity. Switchgear as one of the important protection units, its stable operation determines the safety of more users, maintaining its normal operation is still a problem worth exploring. In switchgear cabinets, busbar and metal components are prone to lead to sharp partial discharge because of some problems such as inadequate fabrication such as burrs, too long screw and irregular chamfer. Long-term power frequency and high voltage will inevitably affect the normal operation of switchgear cabinets to a certain extent, so the detection of partial discharge is particularly important.
Nowadays, pulse current method is a mature method to detect partial discharge. Its principle is that the discharge inside high voltage insulation equipment causes charge transfer to generate current pulse in the experimental circuit, and then collects data and judges the degree of partial discharge according to the detected current pulse intensity. Pulse current method is one of the most original methods of partial discharge measurement. Up to now, it is still the mainstream method of partial discharge detection because of its abundant information of current pulse and its incomparable advantages in other detection techniques such as easy quantification. It is the only standard test method among countries, but it also has obvious disadvantages: (1) it is vulnerable to current interference, higher requirements for experimental environment, (2) low measurable frequency, narrow frequency band, (3) weak anti-interference ability, will become less sensitive with the increase of capacitance, (4) At present, it is mostly used in off-line detection projects.
In the process of partial discharge, not only pulse current, but also ultrasonic, light, gas and other substances can be produced, so other detection methods are becoming popular in recent years, such as Ultra High Frequency (UHF) method, Acoustic Emission (AE) method, Transient Earth Voltage (TEV) method and so on. The basic principle of UHF method is that when partial discharge occurs, it produces a very steep pulse current, whose rise time is less than 1ns, and excites electromagnetic waves with frequencies up to several GHz. Through UHF sensor, it can detect electromagnetic waves in the range of 300-3000MHz produced by partial discharge, so as to obtain information of location and intensity of partial discharge [1]. The advantage is that it is not interfered by the electromagnetic signal of the conventional frequency, it is not sensitive to the corona discharge interference in the air and the signal propagation attenuation is small. The principle of the AE method is that when the partial discharge produces sound wave, a kind of pressure will be formed instantaneously, and an ultrasonic pulse will be generated, the information of partial discharge can be obtained by using the sound wave detected by the ultrasonic probe in the range of 20-200 KHz. Its advantage is that it has better anti-interference ability, and is sensitive to the type of medium and is basically not affected by electrical interference [2, 3]. The detection principle of TEV method is a method of partial discharge judgment by detecting the transient ground voltage generated by partial discharge (so-called TEV is the electromagnetic wave generated by partial discharge propagates to the surface of equipment along the breakpoint of shielding structure, generates current on the surface, and then forms the induced voltage to the ground on the surface of equipment). The channel measurement frequency band is 10 kHz-100 MHz, which has the advantage that the electromagnetic signal has less attenuation during propagation along the surface of the object due to no significant interference source [4].

These methods rely on their respective advantages to compensate for the shortcomings of the pulse current method, and it is worthwhile to further explore these methods. Document [5] simulates and analyses the relationship between UHF method and pulse current method output under four typical fault models in GIS. Document [6, 7] explores the relationship between UHF signal calibration and discharge quantity of partial discharge fault types in oil. These studies only use UHF as an amplitude detection method, the detection method is relatively single, and the domestic research on the use of AE discharge detector is less. Using UHF, AE and TEV three kinds of amplitude detection methods to carry out experiments at the same time, we can study the results and accuracy of the three detection methods, and establish the equivalence function relationship with the pulse current method.

2. Analysis method

2.1 Kendall correlation analysis

In order to explore the correlation between the Amplitude-Voltage trend and the Discharge quantity-Voltage trend of the three amplitude detection methods, Therefore, the Kendall correlation coefficient was used to study in Matlab. In statistics, the Kendall correlation coefficient is a statistical value used to measure the correlation between two random variables. The correlation value is often expressed by τ. It tests the statistical dependence of two random variables by calculating the correlation coefficient. The kendall coefficient has a value range of -1 to 1. When τ is 1, it means that two variables have a highly consistent rank correlation, when τ is 0, it means that the two variables are independent of each other, when τ is -1 , indicating that the two variables have completely opposite level correlations[8]. Therefore, among the three amplitude detection methods, the Amplitude-Voltage trend with τ closest to 1 is the most consistent with the Discharge quantity-Voltage trend, and the detection method is more accurate.

2.2 Fitting degree analysis

In order to explore the mathematical relationship between amplitude and discharge quantity, three mathematical models, Polynomial, Sum of Sin Functions and Exponential, were selected to compare the goodness of fit. The Polynomial function model is $y=ax^2+bx+c$. The Sum of Sin Functions model is $y=a_1\sin(b_1x+c_1)+a_2\sin(b_2x+c_2)$. The Exponential function model is $y=ae^{bx}+ce^{dx}$.

Goodness of Fit is the fit of the regression line to the detected value. It mainly consists of Sum of Squares for Error (SSE), Root Mean Squared Error (RMSE), Coefficient of determination ($R^2$), and
Degree of Freedom Adjust ($R^2_{adj}$).

1. Sum of Squares for Error (SSE) expression is

$$SSE = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2$$  \hspace{1cm} (2.1)

SSE represents the dispersion of observations and fitted values, and the closer the value is to 0, the better the degree of fit. Where $n$ is the number of samples, $y_i$ is the observed value, and $\hat{y}_i$ is the sample regression fitted value, which is the estimated value of the regression line.

2. Root Mean Squared Error (RMSE) expression is

$$RMSE = \sqrt{MSE} = \sqrt{\frac{SSE}{n}} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2}$$  \hspace{1cm} (2.2)

RMSE represents the deviation between the observed value and the sample value. The smaller the RMSE is, the closer it is to 0, the better the degree of fit. Among them, the MSE is the mean square error, which is the ratio of the sum of the squares of the data to be fitted and the fitted values to the number $n$ of fittings.

3. Coefficient of determination ($R^2$) expression is

$$R^2 = \frac{SSR}{SST} = \frac{SSR}{SST - SSE} = 1 - \frac{SSE}{SST}$$  \hspace{1cm} (2.4)

$R^2$ represents the degree to which the data to be fitted is distributed around the regression line of the original data, and the larger the value, the closer to 1 indicates that the degree of fit is optimal. Where SSR is the sum of the squares of the difference between the fitted data and the mean of the data to be fitted, and SST is the sum of the squares of the difference between the data to be fitted and the mean.

4. Degree of Freedom Adjust ($R^2_{adj}$) expression is

$$R^2_{adj} = 1 - \frac{SSE/(n-k-1)}{SST/(n-1)}$$  \hspace{1cm} (2.7)

$R^2_{adj}$ represents the corrected decision coefficient, and the closer the value is to 1, the highest the degree of fit. Where $n-k-1$ is the degree of freedom of the sum of squares of residuals, and $n-1$ is the degree of freedom of the sum of squares.

3. The relationship between pulse current method parameters and other detection parameters

According to the IEC60270 standard, the pulse current method expresses the degree of discharge by the apparent discharge quantity $pC$. UHF, TEV, and AE can represent the partial discharge intensity by the amplitude $mV$ \cite{9}(can be converted to $mV$ by the formula $dB=20\times\log(mV)$).

Referring to the common tip discharge types of switchgear cabinets, three common types of tip discharges were simulated: tip-tip discharge model, tip-plate discharge model and tip-ball discharge model \cite{10}. At the same voltage level, the PDS800 partial discharge detector and the JFD-251 partial discharge detector were used for detection, the amplitude and discharge quantity during partial discharge are obtained separately, so as to explore the equivalence relation between the two, and define the amplitude parameter as $P(mV)$ and the discharge parameter as $Q(pC)$.

3.1 Experimental process

Because the acrylic sheet has good insulation performance and the material is transparent and easy to observe, it is used as a bracket in the model. The pointed electrode is a cone having a bottom radius of
15 mm and a height of 40 mm, the spherical electrode has a diameter of 50 mm, the plate electrode has a length of 150 mm, a width of 120 mm, and a thickness of 10 mm. All the outer layers of the electrode are tightly covered with tin foil to ensure good electrical conductivity. On this basis, a set of partial discharge detection test platform for analog switchgear is built, as shown in Figure 1.

![Wiring diagram of partial discharge detection by TEV, AE, UHF method and pulse current method](image)

**Figure 1.** Wiring diagram of partial discharge detection by TEV, AE, UHF method and pulse current method

Maintain the three metal electrode models: tip-tip, tip-plate, and tip-ball spacing is 30 mm. In the three pairs of models, the tip electrode is connected to the high voltage, and the other end is grounded. The voltage is slowly applied to observe the electrode phenomenon. The relationship between the applied voltage and the discharge quantity pC data and the data relationship with the amplitude mV at the same voltage are recorded. The data were analyzed and found that the trend of pC and mV values between the electrode models at the same voltage level was similar, so the fitting figure was analysed [11, 12].

### 3.2 Experimental results and analysis

#### 3.2.1 Tip-tip discharge model

The relationship between the discharge quantity Q obtained by the pulse current method and the applied voltage U is as shown in Figure 2(a). It can be seen that the discharge quantity starts to increase sharply at 10 kV until the growth slows down at 17 kV and begins to stabilize until breakdown. UHF, TEV, and AE are used to obtain the relationship between the amplitudes of $P_{UHF}$, $P_{TEV}$, $P_{AE}$ and the applied voltage U. Since UHF and AE have small changes with respect to the amplitude of TEV at the same voltage, in order to better compare the discharge development trend measured by each detection method, the UHF and AE amplitude data are reasonably amplified by 1000 times and 40 times respectively. The new curve is placed in the figure as shown in Figure 2(b). It can be seen from the figure that the TEV method first detects the change of amplitude. The UHF method grows slowly at 17 kV until breakdown, while the AE method shows a large increase at 19 kV.
Figure 2 shows the relationship between the feature quantities under the tip-tip model. From Fig. 2(a) and (b), it can be observed that the trends of $Q-U$ and $P-U$ are roughly the same. The Kendall coefficients of the three detection methods are $\tau_{AE} = 0.9173$, $\tau_{TEV} = 0.9439$, $\tau_{UHF*1000} = 0.9888$. The more the $\tau$ value is closer to 1, the higher the correlation. Therefore, in the tip-tip discharge model, the discharge trend of the UHF method is closest to the trend of the pulse current method.

The pulse current method parameter $Q$ and the UHF method parameter $P$ are fitted. The fitting conditions under the three mathematical models are shown in Table 1. The SSE and RMSE values of the Sum of Sin Functions are closest to 0, and $R^2$ and $R^2_{adj}$ are most oriented to 1, so the Sum of Sin Functions has the best fit. And determine the best fit mathematical model of $Q$ and $P$ under the tip-tip model as Sum of Sin Functions, the fitting figure is shown in Figure 2(c).

$$y = 3.7 \times 10^{-2} \sin(5.7 \times 10^{-3}x - 1.5) + 4.4 \times 10^{-2} \sin(1.1 \times 10^{-2}x + 5.5 \times 10^{-1})$$

3.2.2 Tip-plate discharge model

In the same way, under the tip-plate discharge model, the relationship between the discharge quantity $Q$ obtained by the pulse current method and the applied voltage $U$ is shown in Figure 3(a). It can be seen that $Q$ starts to change slightly from 10kV, and begins to increase greatly at 12.5kV, and the 14kV growth rate begins to decrease. The UHF and AE amplitude data are reasonably magnified 1000 times and 10 times as a new curve added to the P-U relationship diagram as shown in Figure 3(b). The observation curve shows that TEV and UHF start to increase slightly at 10kV, AE starts to increase...
from 12kV, and the TEV curve begins to settle at 13kV. While AE and UHF increase in different ranges at 12 kV, it is difficult to see which P-U curve is more in line with Q-U curve by observation.

Table 1. The goodness of fit of the mathematical model under the tip-tip model.

| Mathematical Model | SSE     | RMSE    | $R^2$  | $R^2_{adj}$ |
|-------------------|---------|---------|--------|-------------|
| Polynomial        | $4.2384e^{-4}$ | 0.007781 | 0.9495 | 0.935       |
| Sum of Sin Functions | $1.008e^{-5}$ | 0.001587 | 0.9988 | 0.9973      |
| Exponential       | $2.3829e^{-4}$ | 0.0063   | 0.9716 | 0.9574      |

Figure 3. shows the relationship between the feature quantities under the tip-plate model. The kendall coefficient are $\tau_{AE*40}=0.8989$, $\tau_{TEV}=0.822$, $\tau_{UHF*1000}=0.8819$. Therefore, in the tip-plate discharge model, the discharge trend of the AE method is closer to the pulse current method. The pulse current method parameter Q and the AE method parameter P are fitted, and the fitting condition is as shown in Table 2. The SSE value and RMSE value of the Sum of Sin Functions are the smallest closest to 0, and $R^2$ and $R^2_{adj}$ are most inclined to 1, and the fitting degree of the Sum of Sin Functions is optimal. It is determined that the best fit mathematical model of Q and P under the tip-plate model is

$$y=46.53\sin(3.3*10^{-4}x-5.5*10^{-2})+2.3\sin(2.9*10^{-2}x+1.3*10^{-2})$$
Sum of Sin Functions, and the fitting figure is shown in Fig. 3(c). The model coefficients are $a_1=46.53$, $b_1=3.3\times10^{-4}$, $c_1=-5.5\times10^{-2}$, $a_2=2.3$, $b_2=2.9\times10^{-2}$, $c_1=1.3\times10^{-2}$.

3.2.3 Tip-ball discharge model

Similarly, in the tip-ball discharge model, the relationship between the discharge quantity $Q$ obtained by the pulse current method and the applied voltage $U$ is as shown in Figure 4(a). It can be seen that the discharge quantity begins to increase slowly at 5kV until a large increase occurs at 15kV. The UHF and AE amplitude data are reasonably magnified 1000 times and 10 times as a new curve added to the $P$-$U$ relationship diagram as shown in Figure 4(b). It can be seen that UHF first started the amplitude change at 5kV, but the fluctuations in the subsequent changes are quite different from the $Q$-$U$ trend, and the AE started to increase significantly at 15kV.

![Relationship between discharge quantity and voltage](image1)

(a) Relationship between discharge quantity and voltage

![The relationship between amplitude and voltage](image2)

(b) The relationship between amplitude and voltage

![Functional relationship between discharge quantity and amplitude of AE detection method](image3)

(c) Functional relationship between discharge quantity and amplitude of AE detection method

Figure 4. shows the relationship between the feature quantities under the tip-ball model.

The kendall coefficient are $\tau_{\text{AE}^{10}}=0.977, \tau_{\text{TEV}}=0.8989, \tau_{\text{UHF}^{1000}}=0.6591$. It can be seen that in the tip-ball discharge model, the discharge trend of the UHF method has a large deviation from the pulse current method, but the discharge trend of the AE method is closest to the pulse current method. The pulse current method parameter $Q$ and the AE method parameter $P$ are fitted, and the fitting condition of each model is shown in Table 3. The SSE value and RMSE value of the Sum of Sin Functions are the smallest closest to 0, and $R^2$ and $R^2_{\text{adj}}$ are most inclined to 1, and the fitting degree of the Sum of Sin Functions is optimal. It is determined that the best fit mathematical model of $Q$ and $P$ under the tip-ball model is Sum of Sin Functions, and the fitting figure is shown in Figure 3(c). The model coefficients are $a_1=6.8$, $b_1=4.6\times10^{-3}$, $c_1=-0.3$; $a_2=5.1$, $b_2=6.2\times10^{-3}$, $c_1=2.7$. 

![Sum of Sin Functions Equation](image4)
Table 2. Goodness of fit of mathematical models under the tip-plate model.

| Mathematical Model  | Goodness of Fit |
|---------------------|-----------------|
|                     | SSE  | RMSE | \( R^2 \) | \( R^2_{\text{adj}} \) |
| Polynomial          | 3.5483 | 0.7120 | 0.9519 | 0.9381 |
| Sum of Sin Functions| 0.6862 | 0.4142 | 0.9907 | 0.9791 |
| Exponential         | 2.9904 | 0.7060 | 0.9594 | 0.9391 |

Table 3. Goodness of fit of mathematical models under the tip-ball model.

| Mathematical Model  | Goodness of Fit |
|---------------------|-----------------|
|                     | SSE  | RMSE | \( R^2 \) | \( R^2_{\text{adj}} \) |
| Polynomial          | 0.3289 | 0.2168 | 0.9880 | 0.9845 |
| Sum of Sin Functions| 0.0034 | 0.0290 | 0.9999 | 0.9997 |
| Exponential         | 0.0232 | 0.0622 | 0.9992 | 0.9987 |

4. Conclusion

In the experiment, multiple test methods were used to test and collect data on three kinds of tip electrode models. The kendall coefficient is compared with the detection method which is the closest to the trend of pulse current method, and the optimal equivalence function relationship between amplitude (mV) and discharge quantity (pC) is fitted. The conclusion is obtained through research:

- The voltage was gradually applied to the experimental model, and the variation trend of the magnitude (mV) and discharge volume (pC) of the same kind of electrode model was similar.
- According to the Q-U and P-U trends of the three kinds of tip electrode models, the kendall correlation result indicates that the Acoustic Emission(AE) method is more accurate than the UHF method and the TEV method in PD detection with tip failure;
- According to the degree of fitting of the three mathematical models, the equivalence relationship between amplitude (mV) and discharge quantity(pC) is most consistent with the mathematical model of Sum of Sin Functions.

Therefore, based on the equivalence analysis using the tip discharge model, other fault defect models can be combined with other detection methods. This study is to find the best detection method for detecting other fault models, and to study the amplitude and discharge quantity. The functional relationship with a higher degree of fit provides the basis for research.

5. References

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Acknowledgments
This work has been supported by the planning project of Xiamen Municipal Science and Technology Bureau (Grant No.3502Z20173034) and the Project of Fujian provincial bus and special vehicle R & D Collaborative Innovation Center (Grant No. 2016BJC004) and Industry-University Cooperation Project of Fujian Science and Technology Department;Power Lithium Battery Variable Rate Balanced Charging Management System(Grant No.2019H6024) and the Project of Graduate Science and Technology Innovation of Xiamen University of Technology.