Two-stage Partial Discharge Location Method Based on Defect Recognition Pre-screening

Hai-bin TAN\textsuperscript{1}, Sheng BAO\textsuperscript{2,*}, Yue-huan SUN\textsuperscript{1}, Shu-jun ZHOU\textsuperscript{1}, Xiao-yan WANG\textsuperscript{3} and Li ZHANG\textsuperscript{2}

\textsuperscript{1}State Grid Shandong Electric Power Company Yantai Power supply Company, Yantai, China
\textsuperscript{2}School of Electrical Engineering Shandong University, Jinan, China
\textsuperscript{3}State Grid Shandong Electric Power Company Construction Company, Jinan, China
*Corresponding author

Keywords: Gas insulated substation, Partial discharge location, Convolutional neural network, Defect recognition pre-screening.

Abstract. Partial Discharge (PD) detection of gas insulated substation (GIS) must be done before commissioning, this is an important guarantee to reduce the incidence of post-commissioning faults. Fast and accurate partial discharge location is the key to improve test efficiency. Therefore, a two-stage partial discharge location method based on pre-screening of defect recognition is proposed in this paper. The convolution neural network (CNN) is used to supervise and train the signal atlas recorded by GIS withstand voltage test. By identifying the discharging atlas, the types of defects can be distinguished. Based on analysis of the typical discharging defects in GIS and their affiliated area, a law of partial discharge detection area screening is established which can be used to exclude some gas chambers from consideration. Ultra High Frequency Time Difference of Arrival (UHF TDOA) positioning method is then used to carry out further positioning analysis to determine the accurate position of PD. The analysis shows that, combined with the pre-screening of defect recognition in GIS, the location judgment area can be effectively reduced and the complexity of positioning can be lowered.

Introduction

GIS are widely used in today's power system. Its internal components are fully enclosed and integrated. GIS are not affected by the external environment. They are small in size, have excellent insulation and arc extinguishing performance, safe and reliable operation, small maintenance workload and long maintenance cycle\textsuperscript{[1]}. Therefore, the puncture test is particularly important before the commission of GIS. Through the detection and analysis of partial discharge signal gained in the puncture test, it can be judged whether the equipment meets the requirements of operation and whether it needs to be repaired back to the factory, which greatly reduces the incidence of failure after operation\textsuperscript{[2]}. Defect location after discharge is a very important step. By locating the partial discharge point, the location of equipment to be repaired can be further determined, and the repair can be implemented quickly. The delay and economic loss caused by repeated tests can be avoided, and the efficiency of substation acceptance check can be improved.

The removal of partial discharge defects of GIS equipment before commissioning mainly includes two parts: locating the discharge points and disintegrating and maintaining the defective parts. Locating the PD point is the most critical, accurate and effective positioning is the guarantee of the healthy operation of equipment. Partial discharge localization of GIS equipment has been studied by many scholars. Ultrasound localization method mainly uses the time delay between ultrasonic signals or between ultrasonic signals and electric pulse signals caused by discharge to locate\textsuperscript{[3]}. UHF positioning method mainly focuses on the analysis of the high frequency components of the signal. Compared with the ultrasonic signal, its time delay is easier to grasp, and it has the characteristics of strong anti-interference ability and high sensitivity\textsuperscript{[4]}. Paper\textsuperscript{[5]} suggests that the relationship between
the propagation path of electromagnetic wave generated by partial discharge and the location of partial discharge source is found by studying the excitation characteristics of electromagnetic wave, and a locating method based on the propagation path characteristics of electromagnetic wave is proposed. If the location target area can be reduced, it is obviously more conducive to the localization of partial discharge defects in GIS. According to this idea, the method of screening the gas chamber range of GIS faults according to the protective action of equipment is put forward in paper [6], which effectively improves the positioning accuracy. However, this method is only applicable to the situation that the equipment is in operation, and it is not available to apply this method in the stage of withstand voltage test before GIS is put into operation.

There is a certain mapping relationship between the location of partial discharge and the type of defect. For example, the suspended potential defect will not appear in the gas chamber with Switchgear, but will occur in the shield loosening of circuit breaker chamber, PT/CT chamber insulation support loosening or offset, and bus chamber insulation support loosening or offset [7-8]. This provides a new idea to screen out partial discharge location area in withstand voltage test stage. As a way to obtain the location area, the pre-positioning stage is based on the recognition of discharge type. In order to handle unstructured partial discharge image data obtained in the test, one-dimensional CNN in depth learning can quickly and accurately recognize the type of partial discharge according to the image data [9]. In reference [10], deep convolution network is also used to recognize the discharge pattern. The methods are verified to have an advantage in recognition time, anti-interference ability and recognition rate.

Therefore, a two-stage algorithm for partial discharge locating in the trial stage before GIS operation is presented in this paper. The discharge pattern recorded by experiment is used to recognize the discharge type of GIS by CNN model. According to the relationship between discharge type and discharge location, the area where partial discharge is impossible is excluded. Finally, the area to be analyzed is relatively focused, and the UHF TDOA locating method is used to locate the partial discharge point. The analysis shows that the proposed method is more effective and fast to determine partial discharge location in GIS.

Partial Discharge Type Recognition Based on CNN

CNN is a deep learning method specially designed for image classification and recognition. Its basic structure is usually composed of input layer, convolution layer, pooling layer, full connection layer and output layer. The process of discharging defect recognition in GIS based on convolution neural network includes the following three steps:

1) Preliminary extraction characteristics of convolutional layer

In the convolution layer, the convolution value is obtained by convolution calculation of input discharge atlas using convolution kernels (equivalent to filters). The convolution value generates several feature maps of input data through activation functions, which completes preliminary feature extraction. The convolution calculation formula is as follows:

\[ x'_j = f \left( \sum_{i \in M} x''_{ij} \ast k'_l + b'_l \right) \]  

(1)

In formula (1), \( x'_j \) denotes the \( j \)th feature graph of layer \( l \), \( M \) denotes the set of input feature graphs, \( \ast \) denotes the convolution operation, \( k'_l \) denotes the convolution core matrix of layer \( l \), \( b'_l \) denotes the feature bias of convolution core, \( f(\ast) \) denotes the activation function. Actually, the activation function is a non-linear excitation function, the ReLU activation function can effectively shorten the learning cycle and improve network training speed, so the activation function ReLU function expression is as follows:

\[ f(x) = \max(0, x) \]  

(2)
2) Main features of pool layer extraction

The function of the pooling layer is to extract the feature maps obtained by the convolution layer locally and twice, which can effectively reduce the number of training parameters and the dimension of the feature vectors output by the convolution layer, while retaining only the most useful feature information and reducing the over-fitting and noise transmission.

Secondary extraction operations include maximum pooling and average pooling. In view of the high sparsity of discharge waveform in GIS, the maximum pooling method for extracting image texture is chosen here, and the formula of the \( j \)th feature graph \( X_j' \) of the pooling layer in the \( l \)st layer is as follows:

\[
X_j' = f(\beta_j \text{down}(X_j^{l-1}) + b_j)
\]

In formula (3), \( \text{down}() \) is a downsampling function. \( \beta_j \) is the only multiplicative bias of feature graph \( X_j \) and \( b_j \) is the only additive bias of convolutional feature graph \( X_j' \).

3) Full-connection layer summarizes the features and completes defect type recognition.

Full connection layer uses classifier to recognize and classify by integrating the scattered features from the upper layer. Considering that GIS defect recognition belongs to multi-classification problem, this paper adopts Softmax classifier. Classification probability calculation of input sample \( x \) in Softmax regression is as follows:

\[
h_{\theta}(x^{(i)}) = \begin{bmatrix}
p(y^{(i)}=1|x^{(i)};\theta) \\
p(y^{(i)}=2|x^{(i)};\theta) \\
\vdots \\
p(y^{(i)}=k|x^{(i)};\theta)
\end{bmatrix} = \frac{1}{\sum_{j=1}^{k} e^{\theta_j x^{(i)}}} \begin{bmatrix}
e^{\theta_1 x^{(i)}} \\
e^{\theta_2 x^{(i)}} \\
\vdots \\
e^{\theta_k x^{(i)}}
\end{bmatrix}
\]

In formula (4), \( k \) is the number of classification categories, \( x^{(i)} \) is the \( i \)th sample, \( y^{(i)} \) is the corresponding label, \( \theta_1, \theta_2, \ldots, \theta_k \in \mathbb{R}^{m+1} \) is the model parameter, and \( \frac{1}{\sum_{j=1}^{k} e^{\theta_j x^{(i)}}} \) is the normalized probability distribution.

In this paper, the CNN model is constructed by referring to the network structure of references [9] and [10]. The input is the partial discharge defect map of GIS, and the classification category is set up as four typical defect types common to GIS: 1 free metal particle defect, 2 bubble defect, 3 suspension potential defect, 4 insulator surface contaminant defect, and the effect of model recognition can be referred to the example in reference [10], the accuracy of CNN model can reach more than 90\% for the type recognition of GIS discharge pattern. With the rapid development of detection technology, more unstructured image data will be collected in the field of GIS withstand voltage test, and more samples will be used for model training. The recognition accuracy will be further improved. Enhanced, and can ensure the real-time and effective completion of GIS discharge defect identification task.

Two-stage Partial Discharge Location Method

Establishment of the Basis of Partial Discharge Detection Area Screening

The key of pre-screening is to determine whether there is a universal relationship between the type of discharge defect and the location of the area, that is, to find out whether a defect in GIS is limited to a few fixed gas chambers, so as to further exclude areas where discharge is impossible. The pre-screening process includes inputting the discharge map of withstand voltage test, using the CNN model to determine the defect type, excluding some chambers based on the regional distribution of typical discharge defects in GIS, and narrowing the location range. This paper summarizes the
existing technical reports on the test site, data records and a large number of academic papers, and finds some rules.

Free metal particulate defect: discharge caused by irregular movement of free metal particles in equipment can be divided into SF₆ gas dielectric breakdown caused by metal particles and flashover caused by surface discharge of insulator caused by movement of metal particles on insulator surface. Discharge examples of this defect are summarized. Defects mainly occur in chambers with high voltage conductors.

Bubble defect: it mainly includes bubble defect in insulator and air gap defect at the interface between insulator and high voltage conductor. Summarizing the discharge examples of this defect, it can be found that bubble defect mainly concentrates in the basin insulator area, and other areas such as main bus air chamber and circuit breaker air chamber will be excluded.

Suspension Potential Defect: the shielding electrodes in GIS will loosen with the vibration caused by switching action and other reasons, which will result in this kind of defect. Summarizing the discharge examples of this defect, it can be found that the suspension potential defect generally does not occur in the gas chamber with disconnector, but will occur in shielding loosening occurs in circuit breaker chamber, PT/CT chamber insulation support loosening or offset, bus chamber insulation support loosening or offset.

Insulator surface contamination defects: the discharge is mainly caused by the movement of pollutants from GIS equipment to the surface of insulators, which changes the distribution of electric field intensity inside GIS equipment. Summarizing the discharge examples of this defect, it can be found that the insulator surface contamination defects mainly concentrates on busbar air chamber and CT air chamber, and other areas such as switch air chamber and circuit breaker air chamber will be excluded.

The selection basis for partial discharge detection regions are shown in Table 1:

| Mapping relationship between defect type and discharge location | Types of Discharge Defects | Insulator surface contamination |
|---------------------------------------------------------------|---------------------------|--------------------------------|
| Free metal particles | Bubble defect | Suspension potential | It usually occurs in circuit breaker chamber, PT/CT chamber and bus chamber |
| Near the High Voltage Conductors of the Gas Chambers | Other areas except bus air chamber and circuit breaker air chamber | It usually occurs in bus air chamber and CT air chamber |

From Table 1, it can be seen that when locating the location of partial discharge in GIS accurately, the region pre-screening process based on the discharge pattern is based on the corresponding relationship between the types of discharge defects and the common discharge locations. The reconstruction of search range has been completed before the location algorithm is run, which is beneficial to the realization of fast and accurate positioning about partial discharge in GIS.

**UHF TDOA Location Method**

UHF TDOA location method is the simplest and relatively high positioning accuracy method in GIS partial discharge positioning. The location can be achieved by receiving the time difference of electromagnetic wave signals detected by sensors. The UHF sensor has strong anti-interference ability and high detection sensitivity. Therefore, this paper also uses UHF TDOA method for subsequent positioning analysis.

Assuming that the location area has been locked into a gas chamber in the internal structure of GIS, the unique discharge location can be determined by the time difference of arrival of discharge signals obtained by sensors on both sides of the gas chamber. Figure 1 is a schematic diagram of two-terminal TDOA location method.
In the figure, point A and point B are signal points of sensor detection, point \( f \) is partial discharge point. \( L_{AB} \), electromagnetic wave propagation velocity \( v \), signal arrival time of monitoring point A is \( t_1 \), signal arrival time of monitoring point B is \( t_2 \), which are known variables, then signal propagation equation is as follows:

\[
\begin{align*}
&L_f + \frac{L_{af}}{v} = t_1 \\
&L_{ab} - \frac{L_{af}}{v} = t_2
\end{align*}
\]  

(5)

The distance between discharge point \( f \) and point A is obtained by equivalent transformation of equation (5):

\[
L_{af} = \frac{(t_1 - t_2) \cdot v + L_{ab}}{2} = \frac{(t_1 - t_2) \cdot v + L_{af} + L_{gf}}{2}
\]  

(6)

When the area to be located is not a single gas chamber, the complexity of location calculation is greatly increased. Taking the relatively complex T-shaped area (three-terminal structure) as an example, the analysis is carried out. Figure 2 is a schematic diagram of the three-terminal TDOA location method.

Assuming that the partial discharge point \( f \) is located in the AD region, and the parameter \( \varepsilon \) is introduced to make \( L_{af} = \varepsilon L_{AD} \), and that the three points A, B and C are the signal points detected by the sensor, and the arrival times of the signals are \( t_1 \), \( t_2 \) and \( t_3 \) respectively, the signal propagation equation is as follows:

\[
\begin{align*}
&(1 - \varepsilon)L_{AD} + L_{BD} = (t_2 - t_0) v \\
&(1 - \varepsilon)L_{AD} + L_{CD} = (t_1 - t_0) v \\
&\varepsilon L_{AD} = (t_1 - t_0) v
\end{align*}
\]  

(7)

The distance between discharge point \( f \) and point A is obtained by equivalent transformation of equation (7):

\[
L_{af} = \frac{(t_1 - t_2 + t_1 - t_0) v + L_{AD} + L_{BD} + L_{CD}}{4}
\]  

(8)

Comparing formula (6) and formula (8), it can be found that, when the location area is different, even if the same location algorithm is used, the final location result will be different. The structure sketch of two-terminal GIS is equivalent to the simplest location area after pre-screening, and the structure sketch of three-terminal GIS is equivalent to the original location area. When the location result of the two-terminal TDOA method is correct, it is obvious that the location result of the three-terminal structure has errors. Only when \( t_2 = t_3 \), the discharge point \( f \) coincides with point D and \( L_{BD} = L_{CD} \), the location result is the same in both cases. However, under given presupposition conditions, if \( t_2 > t_3 \), \( L_{BD} > L_{CD} \) will obviously cause \( L_{af} \) to deviate from the correct discharge position. Therefore, according to the analysis of the above results, it can be seen that the screening basis of partial discharge detection area makes the discharge location area more centralized, which
can simplify the two-dimensional structure of GIS positioning calculation to the greatest extent, reduce the complexity of positioning objects, and effectively achieve accurate positioning.

Summary
Aiming at the problem of partial discharge location in the test phase of GIS commissioning, a two-stage location method based on pre-screening of defect recognition effectively combines defect identification with partial discharge location. With the input of discharge detection atlas, it can not only quickly identify the types of discharge defects, but also complete the further compression of the location area in real time, so the global location cannot be carried out. It can also reduce the number of sensors needed for localization to a certain extent, and find the location of partial discharge source more effectively and quickly.

Acknowledgement
This research was financially supported by State Grid Corporation Science and Technology Project (SGSDYTOOFCS1800412).

References
[1] Chien-Yi Chen, Cheng-Chi Tai, Ching-Chau Su, Ju-Chu Hsieh, Jiann-Fuh Chen, GIS partial discharge examination and classification from the on-line measurements. 2008 International Conference on Condition Monitoring and Diagnosis. Beijing, 2008: 21-24.
[2] Tianhui Li, Boyan Jia, Chaomin Gu, Discharge location technology in handover test of UHV GIS. 2017 4th International Conference on Electric Power Equipment-Switching Technology (ICEPE-ST). Xi'an, 2017: 791-794.
[3] Liang He, Shengtao Li, Dianbo Zhou, Analysis method of abnormal condition in GIS based on ultrasonic detection. 2016 International Conference on Condition Monitoring and Diagnosis (CMD). Xi'an, 2016: 570-573.
[4] X. Hu, M. D. Judd and W. H. Siew, A study of PD location issues in GIS using FDTD simulation. 45th International Universities Power Engineering Conference UPEC2010. Cardiff, 2010: 1-5.
[5] Tianhui Li, Mingzhe Rong, Dingxin Liu, Study on propagation characteristics of partial discharge-induced UHF signal in GIS with L shaped structure. 2013 2nd International Conference on Electric Power Equipment - Switching Technology (ICEPE-ST). Matsue, 2013: 1-4.
[6] Haibo Mao, Guopeng Ma, Qingfeng Xu, Research on Fast Fault Location Method for UHV GIS, J. Electric Age. 2018(11).
[7] Operations and Maintenance Department of State Grid Corporation, General Management Regulations for Substation Detection of State Grid Corporation-Detailed Rules for UHF Partial Discharge Detection, Z. State Grid Corporation. Beijing, 2016.
[8] Operations and Maintenance Department of State Grid Corporation, General Management Regulations for Substation Detection of State Grid Corporation-Detailed Rules for Ultrasound Partial Discharge Detection, Z. State Grid Corporation. Sichuan, 2016.
[9] Gaoyang Li, Mingzhe Rong, Xiaohua Wang, Partial discharge patterns recognition with deep Convolutional Neural Networks. 2016 International Conference on Condition Monitoring and Diagnosis (CMD). Xi'an, 2016: 324-327.
[10] Li G, Rong M, Wang X, Partial discharge patterns recognition with deep Convolutional Neural Networks. 2016 International Conference on Condition Monitoring and Diagnosis (CMD). IEEE, 2016.