Review of research on partial discharge detection techniques of high voltage switchgear

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Abstract. Partial discharge inside a high-voltage switchgear can cause serious accidents. Partial discharge detection can reduce the incidence of accidents. This article summarizes the current research status of common high-voltage switchgear partial discharge detection technologies (Transient Earth Voltage or TEV, Ultrasonic or AE and Ultra-High Frequency or UHF), introduces the research status of partial discharge model identification and localization of PD source, and finally looks forward to future research directions.

1. Introduction
Partial discharge (PD) is an electrical discharge in an insulating medium [1]. Partial discharge of some weak parts in the insulation of power equipment under the action of a strong electric field is a common problem in high-voltage insulation. High-voltage switchgear is widely used in power systems and residential electricity. During long-term operation, the internal insulation of the switchgear will inevitably have insulation degradation, resulting in a reduction in electrical insulation strength and even failure. Various types of insulation defects in high-voltage switch cabinets often pass through the partial discharge stage before they eventually cause breakdown. Therefore, the operating status and insulation level of the switch cabinet can be well diagnosed by detecting partial discharge, which can effectively improve the reliability of the switch cabinet operation [2].

This article reviews several partial discharge detection methods (TEV, AE, UHF) that have been widely used in recent years, and introduces the current research status of partial discharge pattern recognition and PD source localization of switch cabinets. The partial discharge detection technology of the cabinet is proposed.

2. Transient earth voltage (TEV) detection technology

2.1. Transient earth voltage (TEV)
When a partial discharge occurs in a high-voltage electrical device, the discharge amount tends to first gather on the grounded metal part adjacent to the ground point, so that the ground current spreads on the surface metal of the device. For internal discharge, the discharge volume is concentrated on the inner
surface of the ground shield. The discharge signal cannot be detected outside the device when the shield is continuous, but the shield layer is usually discontinuous at the insulation part, gasket connection, cable insulation terminal, etc. The signal is transmitted to the shielded enclosure of the device. Therefore, the electromagnetic waves generated by the partial discharge are transmitted through the joints of the metal box or the gasket of the gas-insulated switch, and continue to propagate along the outer surface of the metal box of the device, while generating a certain transient voltage pulse signal to the ground. The phenomenon was first discovered by Dr. John Reeves in 1974 and named it transient-to-ground voltage (TEV) [3].

2.2. Basic principles of TEV technology
The internal discharge of the switch cabinet mainly includes surface discharge, internal discharge, and tip discharge of high-voltage electrodes. During the discharge process, the frequency of the electromagnetic wave excited by the partial discharge pulse can reach several GHz, and a transient voltage to ground is generated on the metal case of the device. By installing a special capacitive sensor on the outer surface of the device, this TEV signal can be detected and the partial discharge inside the switchgear can be obtained. The detection principle of TEV is shown in Figure 1.

![Figure 1. Detection principle of partial discharge (TEV) in switchgear](image)

2.3. Status of TEV research
Researchers have done some research on TEV detection technology for partial discharge in switch cabinets. Reference [4] pointed out the feasibility of using TEV method to identify the type of partial discharge of switchgear. Reference [5] pointed out that the amplitude of the TEV signal is proportional to the amplitude of the local power source. The higher the frequency of the local power source, the stronger the TEV signal.

Literature [6] pointed out that: in the same compartment of the switch cabinet, the TEV signal amplitude of the detection point decreases with increasing distance; the TEV signal amplitude decreases faster between different compartments due to the influence of the metal partition; TEV The signal uses the communication path between the switch cabinets as the propagation channel. In addition, reference [7] pointed out that the TEV amplitude decreases with the distance between the measurement point and the PD power source.

Literature [8] pointed out that the frequency of the TEV signal is closely related to the resonant frequency of the switchgear itself; the gap size of the switchgear and the direction of the partial discharge current will affect the intensity of the TEV signal spectrum. Reference [9] based on the empirical cumulative distribution function of the geoelectric wave amplitude, proposed more flexible, better technical and economic benefits and reliability, more in line with the region's high-voltage switchgear state judgment principles and operation and maintenance strategies. Huang Shilong and others have measured that the original signal amplitude of TEV is less than 100mV, and the energy distribution is between 3-200MHz [10]. In addition, reference [11] introduced a method for localizing transformers based on transient voltage to ground and ultrasonic array signals.
3. Ultrasonic (AE) Detection Technology

3.1. Basic principles of Ultrasound (AE) technology

When a partial discharge signal is generated inside a power device, shock vibration and sound are generated. The ultrasonic method (AE or ultrasonic, also known as acoustic emission method) measures the partial discharge signal by installing a contact ultrasonic sensor on the outer wall of the device cavity or by an open ultrasonic sensor. The schematic diagram and schematic diagram of the ultrasonic detection are shown in Figures 2 and 3 respectively. The method is characterized in that the sensor has no connection with the electrical circuit of the electrical equipment and is not subject to electrical interference, but is susceptible to ambient noise or mechanical vibration of the equipment when used in the field.

![Figure 2. Detection principle of partial discharge (AE) in switchgear](image1)

![Figure 3. Schematic diagram of AE detection for local discharge of switch cabinet](image2)

3.2. Status of AE research

The ultrasonic AE research has also accumulated a lot of successful experience in field applications. Literature [12] proposed a blind source separation method based on the similarity matrix to pre-process the original ultrasonic signal and effectively extract the feature quantity of partial discharge. Reference [13] combined with optical fiber transmission technology, digital signal processing technology, and ultrasonic detection technology to design a GIS partial discharge ultrasonic detection system, which can effectively detect GIS partial discharge.

Literature [14] pointed out that the ultrasonic detection technology has better sensitivity when detecting GIS partial discharge signals. The research by Niu Bo et al. pointed out that the combination of pumping ozone concentration detection method and ultrasonic method has certain effectiveness in qualitative and localization of abnormal discharge inside the switchgear wall bushing [15].

In addition, when performing ultrasonic partial discharge detection, there are three typical disturbances, namely mechanical vibration, external corona interference, and magnetically induced noise, will be encountered at the scene. These three kinds of interference are similar to the discharge characteristic map, which can easily cause misjudgment to the inspector. Literature [16] identified the mechanical vibration interference signals on the switchgear by the spectral characteristic method and the frequency method.

4. UHF Detection Method

4.1. Basic principles of UHF technology

The basic principle of ultra-high frequency (UHF) is to detect signals of ultra-high frequency electromagnetic waves (300MHz ~ 3GHz) generated during partial discharge in power equipment through UHF transmitters, so as to obtain relevant information about partial discharge and realize partial discharge monitoring [17]. The schematic diagram of UHF partial discharge detection is shown in Figure 4.
4.2. Status of UHF research
The UHF method has been widely used in the field and has accumulated more successful detection experience. Li Junhao et al. used the UHF method to detect the floating potential discharge caused by loose connection bolts in the PT chamber [18]; Tang Ju et al. used complex wavelet transform technology to extract UHF PD signals from white noise [19]. Figure 4. Detection principle of partial discharge (UHF) in switchgear

Reference [20] designed a new type of multi-band omnidirectional UHF sensor, which can detect various types of discharge signals well, and meet the requirements of partial discharge detection and positioning in substations. There is a delay phenomenon in the propagation process of UHF electromagnetic waves, which is beneficial to the location of partial discharge points [21]. Literature [22] pointed out that the noise contained in the UHF PD signal is mainly white noise, and the wavelet transform filtering algorithm has a good suppression effect on white noise. Reference [23] found that the time domain characteristics of the partial discharge envelope signals generated by the same defect model were roughly the same, and the envelope shapes of different defect models were different. Zhang Xiaoxing et al. found that there is a linear relationship between the UHF signal energy and the square of the discharge volume [24]. Sun Shuguang and other studies found that there are some differences between different types of discharge waveforms and the phase mode in which they occur [25]. Reference [26] pointed out that the current sensor (TA) and the bus bar have a strong attenuation effect on the electromagnetic wave signal; the insulator will cause obvious waveform distortion; the circuit breaker has a limited influence on the electromagnetic wave signal. Literature [27] established a transformer oil-paper insulation partial discharge model, studied the correspondence between UHF electromagnetic wave signals and pulsed currents, and the relationship between UHF electromagnetic wave signals and propagation distance.

5. Comprehensive Detection Method
There are many interference sources in the substation site, and a single detection method can not reflect the operation status of the tested equipment comprehensively, objectively and truly. Only by comprehensively using different detection methods and analyzing the detection data comprehensively and comprehensively can an objective and reasonable decision be made. The UHF method is suitable for finding the suspected partial discharge phenomenon in GIS equipment and positioning it preliminarily; the ultrasonic method is suitable for determining the partial discharge and its accurate positioning [28]. The sensitivity of the combined acoustic and electrical detection technology to detect PD signal is high [29]. The basic principle of detecting partial discharge of GIS by combined acoustic and electric method is shown in Figure 5.

In reference [30], the sensitivity of three PD detection techniques to PD mode is studied. Quzhou Electric Power Bureau actively explores the promotion and application of comprehensive detection technology for local discharge of switchgear based on detection of ultrasonic, TEV and UHF according to the development needs and characteristics of its own power grid, shifting the focus of maintenance to the detection analysis and pre control of equipment status to grasp the status information of switchgear equipment in real time [31]. In reference [32], the pulse current detection method and UHF detection
method are combined to realize more accurate location and diagnosis of partial discharge, and the phase of partial discharge is determined.

In reference [33], TEV, AE and UHF are used to determine the existence of PD and locate the PD power supply. In reference [34], aiming at a typical partial discharge defect of GIS, ultra-high frequency, ultrasonic detection and time difference method are adopted to accurately locate the discharge position.

Figure 5. Combine acoustic and electrical detect GIS partial discharge schematic diagram

Experiments on different PD defect models were carried out in literature [35][36], and the results showed that the joint detection method of TEV and AE was a very effective way to detect PD phenomenon in switchgear.

6. Identification of Partial Discharge Mode and Localization of Partial Discharge Source

6.1. Study on Partial Discharge Pattern Recognition

The pattern recognition method of partial discharge (Figure 6) has made great progress in recent years. At present, the most widely used method is neural network (NN) recognition method [37-39]. In reference [40], a new Gustafson Kessel (GK) fuzzy classification method is introduced, which classifies four kinds of defects according to characteristic fingerprint. Ren Xianwen et al. proposed a method of PD pattern recognition based on LS-SVM [41].

Figure 6. Diagram of PD mode

Li Xin et al. identified the PD type in GIS by the distribution characteristics of detection pulse with phase [42]. Hao Yingshuai applied the logistic model tree to the type discrimination of partial discharge in switchgear [43], which has a good classification effect. In reference [44], based on the support vector
machine (SVM) algorithm, a 4-class SVM model is designed and constructed to identify the discharge type by voting. In reference [45], the energy of partial discharge in frequency division is taken as the eigenvector, and the Markov distance algorithm is used for clustering analysis, which can effectively identify the partial discharge mode of switchgear. In reference [46], a pattern recognition model of PD PRPD map based on CNN-LSTM deep learning was constructed.

6.2. Study on PD Source Localization

In the power grid, a substation usually operates several switch cabinets in parallel, forming a row of cabinets. The scale of a row of cabinets can reach dozens of switch cabinets. Therefore, the positioning of the local discharge power of the switch cabinet can effectively improve the maintenance efficiency. However, compared with large-scale equipment such as GIS and transformer, the positioning requirements of the switchgear are different, because GIS and transformer can be considered as single cavity equipment in structure, so the specific discharge coordinates need to be determined for positioning, which usually requires three or more sensors [47].

Based on the method of combining TEV and AE, literature [48-49] realized the localization of partial discharge power, which has a certain practical value for partial discharge detection. The initial magnitude and sequence of TEV signals received by multiple detection probes can realize the positioning of local discharge power [9]. Zheng Jiankang et al. used four channel sensor, hyperboloid method and space grid search method to realize the accurate positioning of PD power [50]. Xiong Jun and others put forward the algorithm of PD waveform comprehensive processing and time delay location based on multiple weighted average, and established the method of PD defect auxiliary confirmation based on X-ray excitation [51].

7. Conclusion

There are three kinds of partial discharge detection technology in high voltage switchgear: transient to ground voltage (TEV), ultrasonic (AE) and UHF. The three detection methods have their own advantages: TEV method has the largest signal amplitude under the same conditions, while UHF method has a better signal-to-noise ratio under the condition of better detection environment; ultrasonic method has the best positioning effect under the method of spatial geometric positioning using signal difference. The combined acoustic and electrical detection method can detect the partial discharge in the switch cabinet well, and has higher accuracy than the single detection method in the identification of the partial discharge model and the location of the partial discharge power supply.

As an important enterprise in the power and energy industry, State Grid Corporation of China proposes the strategic goal of "three types and two networks". In order to achieve this goal, we need a large number of high-precision sensors, as well as more intelligent algorithms (deep learning, migration learning, etc.). For the detection of partial discharge in switchgear, it is the future trend to develop new sensors, improve the measurement accuracy of existing sensors, and use more comprehensive detection methods and in-depth learning and other intelligent algorithms.

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References

[1] IEC 270 standard
[2] Qiu Changrong, Wang naiping. Partial discharge and test technology of electrical equipment [M]. Beijing: Mechanical Industry Press, 1994
[3] Neil Davies, Joe Chung Yin TANG, Paul Shiel. Benefits and experiences of non-intrusive partial discharge measurements on MV switchgear[C]//CIGRED 19th International Conference on Electricity Distribution. Vienna, Austria: CIGRED, 2007:0475.
[4] Ye Haifeng, Qian Yong, man Yuyan, Yan Wei, Wei Jufang, Sheng Gefu, Jiang Xiuchen. Partial discharge simulation of switchgear based on transient ground voltage [J]. High voltage apparatus, 2013,49 (07): 13-17 + 24
[5] Wu Ji, LU Hong, Wang Liuhuo, Hu Bing. Experimental study on propagation characteristics of partial discharge transient earth wave (TEV) in switchgear [J]. High voltage apparatus, 2014,50 (11): 115-121
[6] Yu Ying, Li ruipeng, Huang Chao, Zhang Wei, Zhang long, Yang Yuqi. Study on the distribution characteristics of TeV on the surface of switchgear based on FDTD method [J]. Insulation materials, 2015,48 (04): 45-51
[7] Ye Haifeng, Qian Yong, Wang Hongbin, Man Yuyan, Sheng Gefu, Jiang Xiuchen. Spectrum characteristics of transient ground voltage signal on the surface of switchgear [J]. High voltage technology, 2015,41 (11): 3849-3857
[8] Xiong Jun, Lu Guojun, Wang Yong, Wang Youyuan, Wang Wei, Yang Yuan. State judgment and operation and maintenance strategy of high voltage switchgear based on the empirical cumulative distribution characteristics of ground wave amplitude [J]. China Southern Power Grid technology, 2016,10 (02): 38-43
[9] Huang Shilong, Wang Xiaohui, Guo xumin, Li Yansong, Zhao Tao, Liu Yunpeng. Research and implementation of partial discharge detection technology of switch cabinet using TEV sensor [J]. High voltage electrical appliances, 2016,52 (10): 19-26
[10] Ning Yu, Xiong Jun. Empirical cumulative distribution characteristics of partial discharge ground wave amplitude of high-voltage switchgear [J]. High voltage apparatus, 2019,55 (02): 77-84
[11] Cheng Shuyi, Lu Fangcheng, Xie Qing, Wang Zijian, Li Yanqing, Yang Haitao. Localization method of Transformer PD based on transient to ground voltage and ultrasonic array signal [J]. Journal of electrical technology, 2012,27 (04): 255-262
[12] Zhang Chongyuan, Yue Haotian, Wang Bowen, Liu Yunpeng, Luo Shihao. Deep learning pattern recognition method of partial discharge ultrasonic signal based on similar matrix blind source separation and convolution neural network [J]. Power grid technology, 2019,43 (06): 1900-1907
[13] Liu Yunpeng, Li Yansong, Huang Shilong, Zhao Tao. Partial discharge ultrasonic detection system for gas insulated switchgear based on optical fiber transmission [J]. High voltage technology, 2016,42 (01): 186-191
[14] Li Dajian, Liang Jizhong, bu Kewei, Yang Jinggang, Li Yanming. Ultrasonic detection of typical defects in GIS [J]. High voltage electrical appliances, 2009,45 (01): 72-75
[15] Niu Bo, Ma Fei, Ding Pei, Chen Lei, Tian Lu, Liu Weifeng, Wei Ying. Application of ozone concentration detection technology in partial discharge detection of switchgear [J]. Insulating materials, 2018,51 (08): 69-74
[16] Feng Xinyan, Zhao Tingzhi, Yang Chenglong, Xu Yongpeng. Typical interference analysis of GIS ultrasonic partial discharge detection site [J]. High voltage electrical appliances, 2018,54 (10): 241-245
[17] Sun Caixin, Xu Gaofeng, Tang Ju, et al. Study on the model and performance of built-in sensor for detecting partial discharge in GIS [J]. Chinese Journal of electrical engineering, 2004, 24 (8): 89 - 94
[18] Li Junhao, Hou Xinyu, Li Haitao, et al. Detection and analysis of discharge defects in a 110 kV GIS Pt gas chamber [J]. High voltage apparatus, 2013, 49 (12): 141 - 144
[19] Tang Ju, Zhou Qian, Xu Zhongrong, Liu Mingjun, Sun Caixin. Mathematical modeling of UHF PD signal in GIS [J]. Chinese Journal of electrical engineering, 2005 (19): 106-110
[20] Ye Haifeng, Qian Yong, Wang Hongbin, Dong Yue, Sheng Geyun, Jiang Xiuchen. Development of Multi Band UHF sensor based on meander technology [J]. High voltage technology, 2014,40 (08): 2389-2397
[21] Huang Xingquan, Kang Shuying, Li Hongzhi, Zhang Yuxiao. Study on propagation characteristics of UHF electromagnetic wave of partial discharge in GIS [J]. High voltage technology, 2006 (10): 32-35

[22] Li Lixue, Huang Chengjun, Zeng Yi, Qian Yong, Li Dejun, Jiang Xiuchen. Wavelet method for noise suppression of GIS Partial Discharge envelope signal [J]. High voltage electrical appliances, 2009,45 (01): 33-35

[23] Li Lixue, Teng Letian, Huang Chengjun, Zeng Yi, Jiang Xiuchen. Envelope analysis and defect identification of UHF PD signals in GIS [J]. High voltage technology, 2009,35 (02): 260-265

[24] Zhang Xiaoxing, Tang Junzhong, Tang Ju, Luo Yang, Xie Yanbin. Correlation analysis of UHF signal and discharge capacity of typical PD defects in GIS [J]. High voltage technology, 2012,38 (01): 59-65

[25] Sun Shuang, Lu Jianguo, Yu Huizhong, Shen Jianwei, Jin Shaohua. PD detection of typical GIS based on UHF method [J]. High voltage apparatus, 2012,48 (04): 7-12

[26] Li Lixue, Teng Letian, Huang Chengjun, Zeng Yi, Jiang Xiuchen. Envelope analysis and defect identification of UHF PD signals in GIS [J]. High voltage technology, 2009,35 (02): 260-265

[27] Peng Chao, Lei Qingquan. Relationship between time-frequency characteristics and propagation distance of partial discharge UHF signal [J]. High voltage technology, 2013,39 (02): 272-279

[28] Hu Weitao. Test of partial discharge detection in GIS by combined acoustic and electric technology [J]. Journal of electric power science and technology, 2012,27 (02): 57-64

[29] Tian Yan, Zhang Ruiyan, Dong Zhiwen, Bai Yu, Liao Chen. Location analysis of partial discharge defects in GIS [J]. High voltage apparatus, 2017,53 (06): 182-185 + 190

[30] Li Yongxiang, Wang Tianzheng, Jin Tao, Chen Yutong, Wang Zhipeng, Li Yanpeng. Detection and analysis of partial discharge in high voltage switchgear based on various detection technologies [J]. High voltage electrical appliances, 2017,55 (03): 220-225

[31] Ma Fuqi, Wang Bo, Dong Xuzhu, Wang Hongxia, Luo Peng, Zhou Yinyu. Power Vision edge Intelligence: power depth vision acceleration technology driven by edge computing [J]. Grid technology: 1-10 [2020-01-17]. https://doi.org/10.13335/j.1000-3673.pst.2019.2382

[32] Guo Wenqiang, Dong Yao, Li Qinghua, Zhang Mengmeng, Wang Lixian. Application of PSO-BP neural network in temperature prediction of switchgear equipment [J]. Journal of Shaanxi University of science and technology, 2020,38 (01): 149-153

[33] Liu Shaohui. Joint location of pulse current and UHF signal of GIS Partial Discharge [J]. High voltage electrical appliances, 2015,51 (12): 126-129 + 135

[34] Li Yongxiang, Wang Tianzheng, Jin Tao, Chen Yutong, Wang Zhipeng, Li Yanpeng. Detection and analysis of partial discharge in high voltage switchgear based on various detection technologies [J]. High voltage electrical appliances, 2017,53 (01): 45-50

[35] Tian Yan, Zhang Ruiyan, Dong Zhiwen, Bai Yu, Liao Chen. Location analysis of partial discharge defects in GIS [J]. High voltage apparatus, 2017,55 (03): 182-185 + 190

[36] Zhao Changwei, Ding Guocheng, Yang Wei, Yang Haitao, Cheng Dongfeng, Li Binbin. Comparative study on PD detection methods based on switchgear defect model [J]. High voltage apparatus, 2019,55 (03): 220-225

[37] Ma Fuqi, Wang Bo, Dong Xuzhu, Wang Hongxia, Luo Peng, Zhou Yinyu. Power Vision edge Intelligence: power depth vision acceleration technology driven by edge computing [J]. Grid technology: 1-10 [2020-01-17]. https://doi.org/10.13335/j.1000-3673.pst.2019.2382

[38] Guo Wenqiang, Dong Yao, Li Qinghua, Zhang Mengmeng, Wang Lixian. Application of PSO-BP neural network in temperature prediction of switchgear equipment [J]. Journal of Shaanxi University of science and technology, 2020,38 (01): 149-153

[39] Huang Xinbo, Zhang Xiaoling, Zhang Ye, Yang Luya, Liu Cheng, Li Wenjing. Defect state identification of transmission line based on radial basis probabilistic neural network [J/O]. Automation of power system: 1-15 [2020-01-17]. http://kns.cnki.net/kcms/detail/32.1180.TP.20191219.1042.008.html
[40] Wang Hui, Zheng Wendong, Huang Chengjun, et al. Application of GK fuzzy classification algorithm in GIS PD pattern recognition [J]. Power system protection and control, 2011, 39 (17): 50-54

[41] Ren Xianwen, Xue Lei, Song Yang, et al. PD pattern recognition based on least square support vector machine based on fractal characteristics [J]. Power system protection and control, 2011, 39 (14): 143-147

[42] Li Xin, Li Chengrong, Ding Lijian, Ding Yansheng, He Peng, Jiang Jianling, Yang Jing. PD pattern recognition based on UHF signal detection GIS [J]. High voltage technology, 2003 (11): 26-30

[43] Hao Yingshuai, Xu Liyang, Yin Yijie, Chen Zhihong, Zheng Wendong, Huang Chengjun. Partial discharge identification method of switch cabinet based on logistic model tree [J]. High voltage electrical appliances, 2014,50 (02): 80-85

[44] Si Liangqi, Qian Yong, Bai wanjian, Ye Haifeng, Hu Yue, Sheng Gefu, Jiang Xiuchen. Pattern recognition of GIS UHF Partial Discharge Based on support vector machine [J]. High voltage apparatus, 2014,50 (11): 1-6

[45] Chen Pan, Yao Chengu, Liao Ruijin, Chen Yu, Mi Yan. Application of frequency division energy spectrum and Markov clustering algorithm in partial discharge pattern recognition of switchgear [J]. High voltage technology, 2015,41 (10): 3332-3341

[46] Zhou Xiu, Zhu Hongbo, Ma Yunlong, Liu Weifeng, Gao Bo, Tian Tian, Luo Yan, Li xiuguang, he Ninghui. Research on PD pattern recognition of transformer based on deep learning [J]. High voltage electrical appliances, 2019,55 (12): 98-105

[47] Li Dajian, Li Junhao, Yan Ming. Research on UHF PD location method of transformer based on multi-sensor [J]. Insulation materials, 2013,46 (2): 53-56

[48] Lu Fangcheng, Li Haide, Wang Zijian, Cheng Yifeng. Research on partial discharge detection and location of switchgear based on TEV and ultrasonic [J]. Electrical measurement and instrumentation, 2013,50 (11): 73-78

[49] Niu Bo, Ma Fei, Zhou Xiu, Fang Yi, Ma Yunlong, Tian Tian, Xu Yuhua, Luo Yan. Study on the location of partial discharge power source based on the joint acoustic and electric method [J]. High voltage apparatus, 2019,55 (08): 108-115 + 122

[50] Zheng Jiankang, Yang Xiaoyu, sun Haojie, Li Hongjie, Zhu Mengxin, Zhu Chunyang, Wei Bo. Study on partial discharge location and discharge signal parameter evaluation of switchgear [J]. High voltage electrical appliances, 2016,52 (04): 139-144 + 151

[51] Xiong Jun, Mo Wenxiong, Zhang Qiang, Li Chengrong, Zhu Lu. Location method and engineering application of GIS Partial Discharge Based on UHF / SHF and X-ray excitation [J]. High voltage electrical appliances, 2018,54 (05): 106-113