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Partial Discharge Ultrasonic Analysis for Generator Stator Windings

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Abstract – The objective of this research is to utilize the ultrasonic method to analyze the property of partial discharge (PD) which is generated by the winding of the insulation stator in the generator. Therefore, a PD measurement system is built based on ultrasonic and virtual instruments. Three types of PD models (internal PD model, surface PD model and slot PD model) have been constructed. With the analysis of these experimental results, this research has identified the ultrasonic signals of the discharges which were produced by three types of PD models. This analysis shows the different features among these PD types. Both the time domain and frequency domain of the ultrasonic signals are obviously different. In addition, an experiment based on a large rotating machine has been done to analyze ultrasonic noises. The result indicates that the ultrasonic noises can be wiped off by the filters and algorithms. The application of this system is convenient for the detection of early signs of insulation failure, which is an effective method for diagnosis of insulation faults.

Keywords: Partial discharge (PD), Ultrasonic, Stator windings, Insulation, Generator, Motor

1. Introduction

At present, there are some gas-filled voids inside the dielectric in the system of high voltage, due to the influence of different materials and manufactured factors. The voids can cause partial discharge, the same as for the insulating surface. The partial discharge of insulating materials is always caused by gas-filled voids. As long as the gas-filled voids cause partial discharge, the accelerating of dielectric deterioration will come with that at the same time. It will lead to electrical breakdown failure as this situation keep on broadening out and developing [1].

Therefore, if PD happens in a large generator, the electrical stator windings will be the significant symptom for the deterioration of the insulation system. Experience indicates that the partial discharge activity was an important indicator for the electrical insulation problem. It is propitious to evaluate the quality of high voltage windings by measuring PD frequently, which is also an effective diagnostic approach for insulating malfunction. The results of this analysis and measurement can be used as an important data for the electrical equipment which needs to be replaced or repaired.

PD testing has been utilized to determine electrical insulation condition since the middle 1950's [2]. In last few decades, the technique of PD measurement and diagnostic for electrical insulation has become a hot researched subject [3-4]. A number of papers have been published which have been introducing insulation diagnosis and insulation condition assessments [5]. Also, there are various types of PD testing systems that are available [6]. They are accompanied by several physical manifestations such as electrical impulse, frequency impulse, ultrasonic impulse, light impulse and chemical reaction, etc.

The electrical method and ultrasonic method are the two main techniques to detect PD for transformer. On the other hand, there still are many other different techniques available for PD measurement in rotating machines, single winding, spool and the entire stator winding. The earliest method has been used to measure PD pulse current by means of a high-frequency current transformer which has been built in the neutral point. However, some others use the lead of RTD temperature sensors to serve as an antenna to measure the PD [7]. Today, the online routine of PD test for the majority machines is found to be using high-voltage capacitors as PD sensors [8].

However, these PD testing systems are only applicable for a certain insulation system or rotating machines, and insofar these are still debating topics among researchers [1]. At present, there are few studies using the ultrasonic method to measure PD from stator windings. Therefore, it is necessary to develop some new testing methods that are truly capable in indicating the deteriorating condition. A new system has been developed to detect the acoustic signal which is emitted from the partial discharge due to a material defect in the insulation system of the stator winding.

2. Materials and Methods

The PDs are accompanied with several physical manifestations: electrical pulses, radio frequency (RF) pulses, acoustic pulses, light, and chemical reactions like air or hydrogen which will happen in the course of cooling

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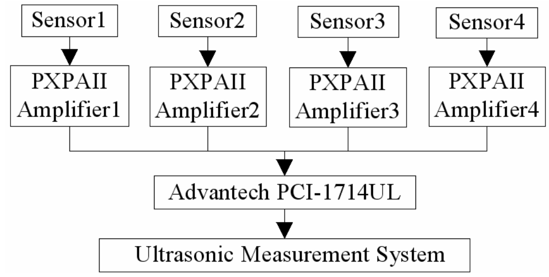


Fig.1. System framework

Table 1. Operating specifications of the AE sensor

item	parameter
Operating frequency range	30-140kHz
Resonant frequency	95kHz
Sensitivity	>80dB

these gases. These manifestations can be measured as a means of quantifying the PD activity in a stator winding and in each individual coil or bar. In this study, the ultrasonic signal generated by the PD was investigated via the ultrasonic monitoring system. It is based on case studies of three types of dominant PD activity for generator stator winding models, and then analyzes their experimental results.

2.1 Ultrasonic measurement system

The objective of this research is to detect the ultrasonic signals emitted from PD, and then a special measuring system has been established. Fig.1 shows the measurement system that can detect and analyze the ultrasonic signals. The ultrasound generated by PD is detected with the four ultrasonic sensors (PX04, the characteristic of which was shown in Table 1). The tested signals will pass through the wideband amplifiers (PXPAII), and input into an analog input cards (PCI-1714UL, Advantech) which has simultaneous 4-channel. PCI-1714UL is a kind of fast-speed synchronization data acquisition cards. The signals acquired from PCI-1714UL will be transmitted to the personal computer (sampling frequency is up to 10 MHz).

An ultrasonic measuring system has been developed based on LabVIEW. This system will record the signals acquired from the data acquisition cards. Only one channel of this system was used for the data reported in this study.

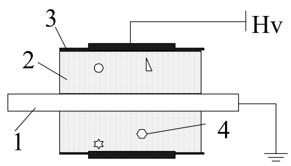
2.2 PD model

In order to obtain a correct explanation for ultrasonic PD measurements, it needs to know how the actual electrical activity in a cavity can be transferred into the measurement system. As we know, PD occurs in different types and in various areas of the stator winding. They are assorted as four types according to where the PD occurs. In the operation of the generator or large motor, PD could occur as internal discharge, surface discharge, end-winding discharge and slot discharge among different phases, such as copper conductor interfaces and inter-turn discharge [9].

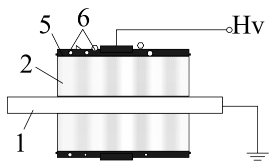
In this article, the PD models for generator/motor were designed for simulating PD occurring in the insulation of the stator windings in the generator/motor. They can be divided into three types of models [10]. These three different types of PD models which had been made by bars of the stator windings were designed to simulate those PD phenomena mentioned above. All these models were made according to the same real winding bars under the same industrial manufacturing technology conditions.

2.2.1 Internal PD model

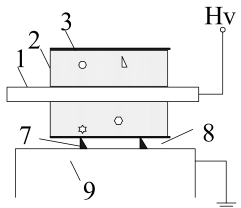
There are always some cavities in the insulation of stator winding bars due to industrial manufacturing technology or something else. Under the processing of generator/motor running, with the high voltage and hot stress, the cavities would be broken, and then they would produce the internal PD. Then internal PD model has artificial cavities in its insulation, and its insulation surface is also covered by aluminum foil. It's shown in Fig. 2 (a). Once the experiment began, aluminum foil would be connected to the high voltage, and copper conductor would be connected to the ground electrode.



(a) Experiment model of internal PD



(b) Experiment model of surface PD



(c) Experiment model of slot PD

Fig. 2. Experiment PD model. 1-copper conductor; 2-main insulation layer; 3-low resistance corona-preventing layer; 4-cavity; 5-High resistance corona-preventing layer; 6-oil contamination or damaged corona-preventing; 7-point-contact; 8-gap; 9-stator core

2.2.2 Surface PD model

The surface PD models for end-winding were simulated by the winding bar models which can protect itself being damaged by semiconductor layer or oil contamination. Its surface has aluminum foil covered as well. Once the experiment began, the same as internal PD model, aluminum foil would be connected to the high voltage, and copper conductor would be severed as ground electrode. It's shown in Fig. 2 (b).

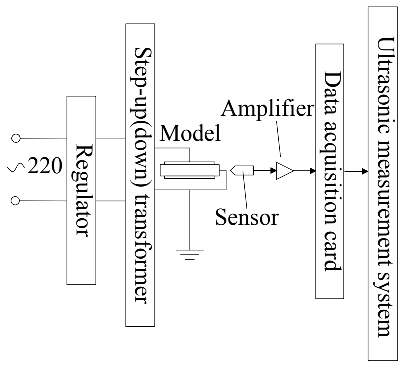
2.2.3 Slot PD model

In view of slot PD occurring at the interface between winding and slot, we simulate the slot PD existing in the untouched part of stator bar in the slot. A very thin gap was set between a whole bar model and copper board which has been connected by two insulation shims. Therefore, a slot PD model was formed. It's shown in Fig. 2 (c). Once the experiment began, copper conductor would be connected to the high voltage, and the slot would be severed as ground electrode.

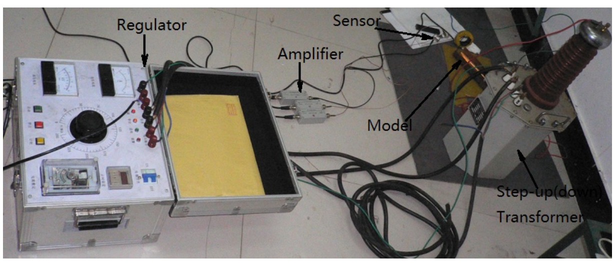
The sizes of all models were made big enough to obtain a good effect. Several models based on winding bars were made for each type of PD to get more samples for following experiments and analysis.

2.3 Experiment setup

The experimental device for PD is shown in Fig. 3. All the measuring instruments are placed in a shielding room. The regulator is connected to 220V power supply. Step-up (down) transformer is controlled by the regulator to exert high voltage on PD models. By changing PD models, ultrasonic measurement system would acquire ultrasonic signals from different PD models. Then the characteristics of different ultrasonic signals would be analyzed. In the experiment, PD models are made of 36MW/10kV generator bars. For all types of experimental PD models, the distance between ultrasonic sensor and PD models is around 20cm, which it's shown in Fig. 3 (b).



(a) Hardware structure of the experiment



(b) Photograph of the experiment

Fig. 3. Experimental apparatus

3. Results and Discussion

Because the propagation velocity for ultrasonic is not the same in different space. In different phases, the propagation time for the PD ultrasonic by different PD models from the models to sensor may not be the same. The PD ultrasonic signals were generated and propagated in different conditions. So they have no comparability. In view of this, the paper only discusses the spectrum of ultrasonic signal for the PD.

3.1 Ultrasonic signals by internal PD model

The voltage which was given from the step-up (down) transformer increases gradually by adjusting the regulator. During the voltage increasing to 10kV, amplitudes of the received ultrasonic signal from ultrasonic sensors amplitudes were growing constantly, and the density of that was increasing densely. This phenomenon indicates that the internal PD model continues to discharge, and the discharges are more frequently and the strength of the discharges is more intensely.

When the internal PD model was applied at 10.5kV, some amplitudes of the PD will be larger than the trigger value of the ultrasonic measurement system. Fig.4 shows the spectrogram of this ultrasonic signal detected by the ultrasonic sensor. As shown in Fig.4, the typical ultrasonic signal generated by the partial discharge in the internal PD model lasted about 100 to 300μs and decreased as an exponential rate. At 10.5 kV, the apparent discharge level was larger than others. Therefore, the results show increase of the detected signals' amplitudes with increase of the applied voltage.

The frequency spectrum of the internal PD ultrasonic signal is shown below in Fig. 4. The frequency range of the acoustic signal in the internal PD model covers from 5 kHz to 200 kHz. The peak of resonant frequency was around 96 kHz. There is a strong value of the spectrum in the range of 20 kHz frequency. To obtain the feature for the acoustic signals, there is a possible extension of the method to identification the type sources for PDs.

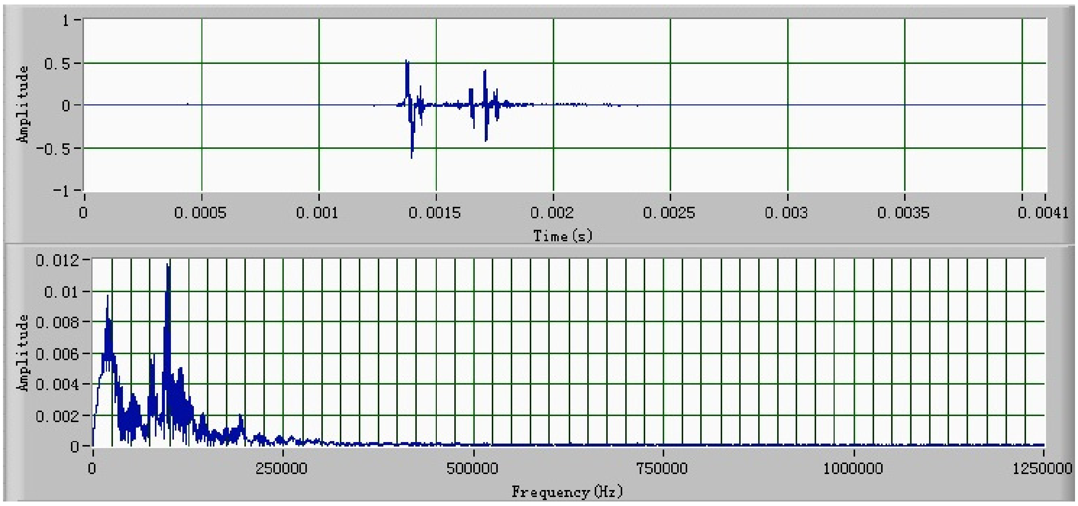


Fig.4. The ultrasonic spectrogram of internal partial discharge

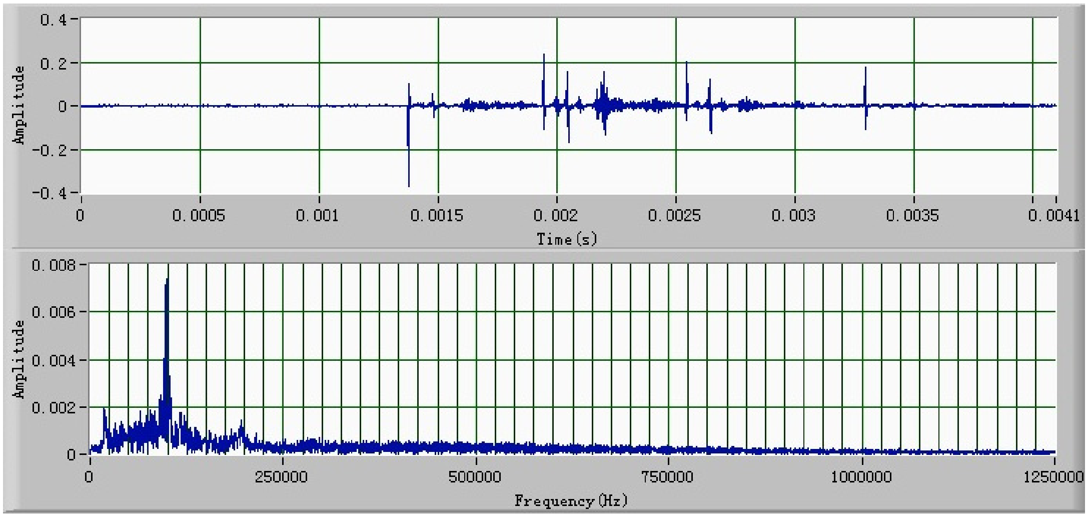


Fig. 5. The ultrasonic spectrogram of surface partial discharge

3.2 Ultrasonic signals by surface PD model

Moreover, under the same experimental conditions and using the same method to adjust the regulator, the voltage which was obtained from step-up (down) transformer was increased gradually. When the voltage was increased to 28kV, the amplitudes of the discharges were noticed to be relatively larger, and the discharges appeared more strongly.

Fig.5 shows the spectrogram of an ultrasonic signal detected by surface PD model. The apparent discharge level at 28 kV was larger than others which voltage was less than 28 kV. Moreover, the PD signals came with ultrasonic noise. This noise decreased faster than the signal generated by the partial discharge. The figure for frequency spectrum of the surface PD ultrasonic signal is shown below in Fig.5. The frequency range of the PD ultrasonic signal generated by the surface PD model was 20-200 kHz, and its peak frequency was about 96 kHz. The 96 kHz peak frequency is similar to that of the internal PD model because of the resonant frequency of the ultrasonic sensor. There are strong values of the spectrum between 20 and 110 kHz.

The characteristics for the surface PD ultrasonic signal in Fig. 5 are different from the signals of Fig. 4, due to the model structure. This can be of a vital importance for the correct interpretation of the measurement results obtained from the ultrasonic sensor generated by different PDs. Moreover, obtaining varied results for the different type's model under study can be useful for recognizing PDs measured by the ultrasonic sensor method for stator windings of appliance operating in generator.

3.3 Ultrasonic Signals by Slot PD Model

Similarly, in the following the same method will be used to apply high voltage onto the slot PD model. When the

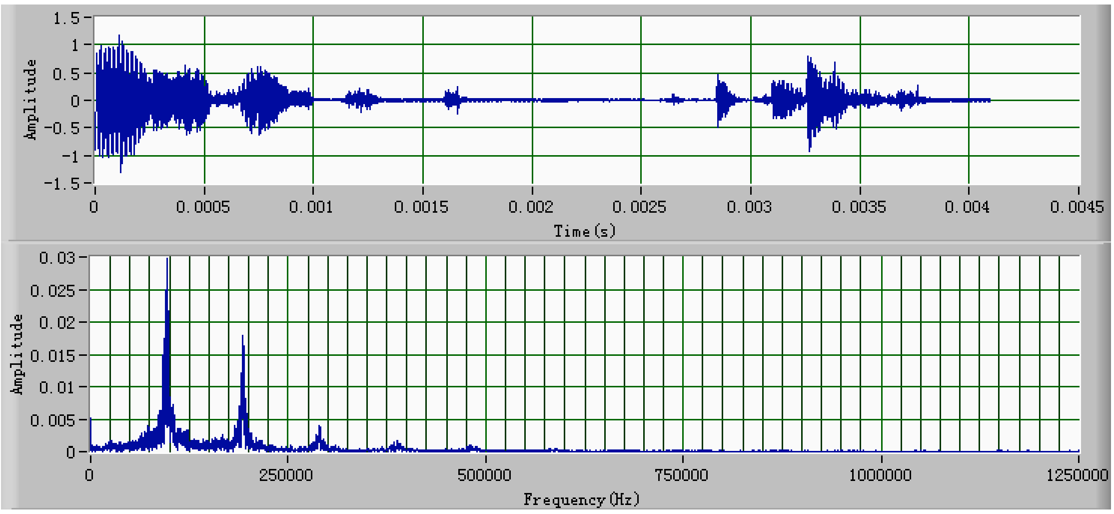


Fig.6. The ultrasonic spectrogram of slot partial discharge

Fig. 7. The photograph of the experimental setup

voltage was increased to 10.2 kV, the amplitudes of the discharges were found to be relatively larger, and the discharges appear more strongly. This can be clearly seen, the spectrogram of the ultrasonic signal shown in Fig. 6. It shows that two PDs are continuous, and decreased smoothly. From the frequency spectrum of the slot PD ultrasonic signal shown below in Fig.6, the frequency range of the PD ultrasonic signal generated by the slot PD model was 20-210 kHz, and its peak frequency was about 96 kHz and 190 kHz.

Moreover, more acoustic activity was recorded with progression of the delaminations. In Figure 6, there were much more acoustic activities than those of internal PD model or surface PD model, indicating most of the delaminations were occurring in the slot of generator. When the insulation begins to delaminate, the ultrasonic should be scattered and hence diffused by the delamination. Therefore, the intensity of the transmitted ultrasonic from slot PD model will be more than that from internal PD model or surface PD model. These characteristics will help distinguish slot discharge.

3.4 Comparisons and Results

The ultrasonic signals acquired from the above three types of PD models are repeated in the experiments. From the experimental results, many acquired ultrasonic signals are not the same from each other, and there are a lot of differences among each experimental ultrasonic signal. However, the ultrasonic PD signals generated by one type PD model are almost similar. The results analyzed above were based on the most same signals of a PD model, which were acquired from repeated experiments.

The experiments and analysis results show that the ultrasonic PD signals generated by each type of PD model are different, and they have individual characteristics. Therefore, the three types PD model utilized in this research work will be provided to extract these features. The identification algorithm will be used to discriminate the different types of PD sources.

3.5 Analysis of Ultrasonic Noise

In order to get the PD ultrasonic signals come from a large rotating machine which is under operating, an experiment should be done to analysis the ultrasonic noise to know whether the ultrasonic noise will be the same as the PD ultrasonic signal. There are many types of motors, but the mechanical noises generated by the running motors are almost similar. Therefore, a new three-phase synchronous generator (Chongqing Electric Machine Federation Co., Ltd.) was used to do an experiment.

Fig.7 shows the photograph of the experimental setup. Two ultrasonic sensors were used to detect the mechanical noises. Fig.8 shows the ultrasonic noises form the two sensors when the synchronous generator was under operation. And Fig.9 shows one of the ultrasonic noise signals and its frequency spectrum. The ultrasonic signal is a periodic signal. The frequency range appeared below 2.5 kHz. Therefore, this kind of ultrasonic noise is able to be removed by using an analog filter.

By taking into account the different pulse shapes, PD can be distinguished from noise on a pulse-by-pulse basis,

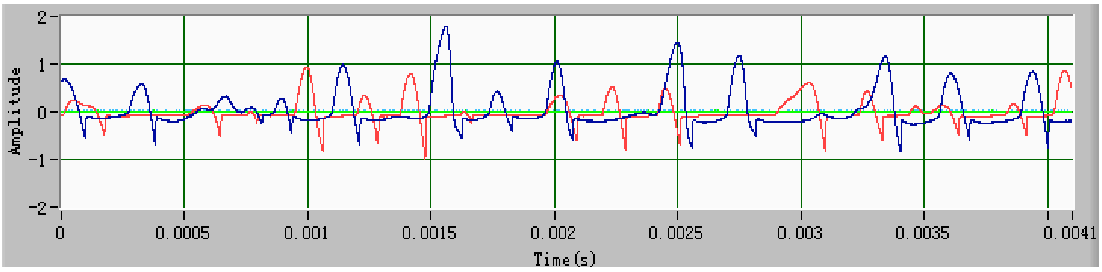


Fig. 8. Noises of two AE sensors by generator operation

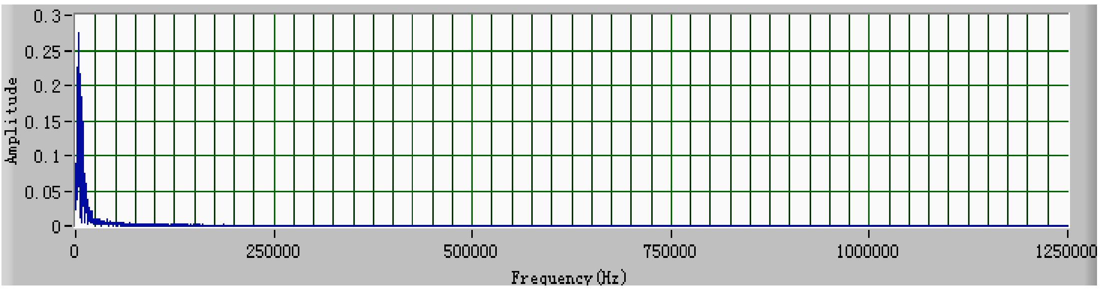


Fig. 9. Noise and its frequency spectrum of generator operation

and then the risk of false indications of stator winding problems caused by noise is greatly reduced.

The key result of these investigations is that PD can be distinguished from noise using a filter. In additional, they were based on pulse shape, amplitude, and characteristic. Furthermore, when PD does occur in medium voltage motors, the PD will exhibit the same pulse patterns as PD from high voltage motors. This information provided the scientific basis to develop a continuous PD monitoring system for medium or high voltage motors.

4. Conclusion

This study introduces the analysis of PD ultrasonic signal. Established three different PD models to simulate three different types of PDs, they are internal PD, surface PD and slot PD respectively. The frequency ranges of the ultrasonic signals were 5-200 kHz, and the peak resonant frequency was about 96 kHz for internal PD model, there are strong values of the spectrum near 20 kHz. The frequency range of surface PD model was 20-200 kHz, and its peak frequency was about 96 kHz. The peak frequency of slot PD model was about 96 kHz and 190 kHz.

This work would be helpful to extract and discriminate the features from the characteristic of the different types PD. This study provided a feasible basis for the future work which can extract the various features of the PD.

The investigations in this study based on three types PD models of stator winding bars under laboratory conditions, and the results might be without any noise. Therefore, an experiment under a large motor operating has been done to analyze the ultrasonic noise. As a result, it is possible to discriminate two kinds of ultrasonic signals–one is generated by PD in a motor and another one is generated by operating noise, using a proper analog filter to distinguish their lasting time and frequency range. Of course, when different large motor operates under different conditions, there are many types of noises. Many challenges still exist in interpreting generator PD data as a machine in operation may be subjected to multiple PD sources, or to one type of PD activity in multiple locations. So far, PD data interpretation still relies on the knowledge and expertise of a PD expert. To establishing a PD pattern recognition database based on field and laboratory case studies will aid in PD data interpretation. These are the work of our further study.

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