Investigation of the Evaluation of the PD Severity and Verification of the Sensitivity of Partial-Discharge Detection Using the UHF Method in GIS

Wensheng Gao, Dengwei Ding, Weidong Liu, and Xinhong Huang, Member, IEEE

Abstract—The measurement of partial discharge (PD) using ultra-high frequency (UHF) method is considered an effective approach to monitor the online condition of the equipment, which is used to facilitate the detection of incipient defects in gas-insulated switchgear (GIS). In this paper, in order to assess the severity of PD defects using UHF method, the actual 220-kV GIS were subjected to experimentation. The PD was measured simultaneously by using the UHF method and the IEC60270 measurement technique. The combined measurement has been carried out on different defects in PD test cells, including the floating metal, metallic protrusion, and void in epoxy resin. The inner coupler installed in the GIS tank, and the outer coupler placed outside the spacer, are used to measure the UHF signal. The relationship of the apparent amplitude and the time-of-flight, and the integral energy from 300 MHz to 1.6 GHz of the signal induced by PD in GIS are analyzed thoroughly. In this way, the severity of PD can be quantified using the UHF signal. In addition, to verify the sensitivity of the UHF detection method, a pulse generator with a rise time of about 500 ps is designed. The CIGRE method for the verification of sensitivity, which is used worldwide, is applied in the experiment. The results of the pulse generator experiment are compared to the results produced by the actual discharge sources, and several possible approaches of improving this method are proposed.

Index Terms—Evaluation of severity, gas-insulated switchgear (GIS), IEC60270, partial discharge (PD), ultra-high frequency (UHF) method, verification of sensitivity.

I. INTRODUCTION

PARTIAL-DISCHARGE (PD) detection is a popular means of monitoring insulation conditions. PD detection can reveal incipient faults and provide real-time diagnostic information to maintenance personnel. Therefore, the detection of PD is an effective way of preventing insulation failure [1]–[3]. The ultra-high-frequency method (UHF), which is highly sensitive and almost immune to the noise, has become well recognized as a means of measuring the energy radiated from PD. Compared with the UHF method, the IEC60270 measurement technique, an international standard PD detection technique, is a conventional method of testing electrical equipment [4]–[6].

When PD occurs in GIS, a small current pulse is generated in the circuit. The IEC60270 measurement technique can be used to detect this current pulse. It details the technique for the quantification of apparent charge of the PD pulses. The definitions and descriptions, which relate to the measurement circuits as well as to the calibration and test procedures, are provided in the standard. Since many lab technicians worldwide are already skilled in its use, the IEC60270 measurement technique is preferred in the manufacturer testing of electrical equipment. However, it is not suitable for monitoring the online conditions of the equipment, such as gas-insulated switchgear (GIS) [7]–[9].

Electromagnetic waves are generated from the protrusion and short gap discharge in GIS. The frequency spectrum of the electromagnetic waves can extend beyond gigahertz, because the rising edge of the PD signal is very steep [10]. The UHF sensors are used in UHF detection to detect electromagnetic waves over 300 MHz. Therefore, the potential interference caused by public broadcasts and other sources can be avoided. The excitation of the UHF signal changes in response to the change of the rising edge of the PD pulse and the measurement circuit is independent of the discharge circuit. In this case, it is difficult to quantify the PD magnitude in terms of pC. For this reason, even though the UHF detection method is adopted widely, it has not yet been recognized as a common method of quantifying PD magnitude [11]–[15].

The factual standard adopted by many engineers is used to verify the sensitivity of the UHF method. This method is described in a paper, which covers the CIGRE Electra test procedure [16]. The upper limit of output voltage of the pulse generator referred to in [16] is 20 V, which is the subject of some controversy among the users of the UHF PD monitoring systems. In addition, the method can only verify the highest sensitivity of the PD monitoring system. It cannot be used to examine the linearity of the system. This makes it suitable only as a temporary approach. The international standard for implementing the UHF method is currently under discussion [17]–[20].

In this paper, three types of typical defects in GIS are tested. Both the IEC60270 measurement technique and UHF detection
method are used simultaneously to record the PD signal. The relationship between the apparent charge and the UHF signal is analyzed in detail. In addition, a pulse generator is designed to verify the sensitivity of the UHF detection method, and some proposals are put forward to complement the GIGRE method.

II. EXPERIMENT ARRANGEMENT

A. Experiment Measurement Circuit

In order to investigate the evaluation of the PD severity in GIS, a special experimental platform is arranged. An actual 220-kV GIS with a spacer is used in the experiment, as shown in Fig. 1. The diameters of the inner conductor and the enclosure are 90 and 320 mm, respectively. The PD test cell is placed at the leftmost port of GIS. The disk coupler 1 in the GIS is 25 cm from the PD test cell and 120 cm from the spacer. The distance from disk coupler 2 to the spacer and to the rightmost port is 30 cm in both cases. The outer coupler is located outside of the spacer. The IEC60270 instrumentation is composed of the coupling capacitor, the measuring impedance, and amplifier 1. The system is calibrated according to IEC60270 standards before the experiment. A Tektronix DPO4104 oscilloscope is used to record the amplitude of the current pulse which is, in turn, used to calculate the apparent charge. The demodulated wave of the UHF signal is detected through amplifier 2 and chosen as the trigger signal. An Agilent DSO9254A digital oscilloscope (2.5 GHz in bandwidth, 10-GSample/s sample rate) is used to record the original UHF signal. The Agilent oscilloscope is triggered by the signal from the Tektronix oscilloscope, ensuring that the current pulse and the UHF signal acquired by the oscilloscope will be excited by the same PD pulse. The tee cable connector connects the inner coupler 2 to the Agilent oscilloscope and amplifier 2 through two 10-m cables. The output of amplifier 2 is the demodulated wave. The connection is kept similar to that of the outer coupler. The PD test cell is connected to a high-voltage (HV) power supply, rated up to 100 kV.

In this apparatus, three types of typical defects in GIS are tested, including floating metal, metallic protrusion, and the void in the epoxy resin. Especially, the floating metal PD model is achieved by fastening a brass wire with a certain distance to the HV electrode. Moreover, there are three different structure sizes and an arrangement for each defect, as shown in Fig. 2. The typical PD source is placed in the PD test cell, which is filled with SF\textsubscript{6} and maintained at a pressure of 0.4 MPa. The disk coupler is installed in the GIS, and the dipole antenna is placed closely outside the spacer. The attenuation characteristics of the frequency from 10 MHz to 1.6 GHz, as measured by spectrum analyzer, are illustrated in Fig. 3. The smaller
Fig. 3. Attenuation characteristics of the inner and outer coupler from 10 MHz to 1.6 GHz.

Fig. 4. The measurement made by the two oscilloscopes.

the attenuation, the better the performance will be. Frequency responses lower than 500 MHz of the disk coupler in GIS are found to be better than those of the dipole antenna outside the GIS. However, the frequency responses over 300 MHz are sufficient for the acquisition of UHF signals induced by the PD in GIS.

B. Experimental Procedure for the Evaluation of PD Severity

When the applied voltage reaches the inception voltage of PD, the pulse signal from the measurement impedance and the UHF signal can be acquired stably. The measurements made by the two oscilloscopes are presented in Fig. 4. The amplitude of the pulse is recorded and transformed to the apparent charge according to the previous calibration. The original UHF signal lasts for less than 200 ns and is saved by the oscilloscope. Three types of defects are tested in succession, and the inner coupler and the outer coupler are used to acquire the PD signal. The ranges of applied voltages and the apparent charge of the defects are shown in Table I. The apparent charge (pC) in Table I is for a specific single discharge pulse.

The peak-to-peak value can be determined from the original UHF signal. Since the component that is lower than 300 MHz is easily influenced by the reflection from the structure of GIS and the component over 1.6 GHz becomes seriously attenuated, a bandpass filter from 300 MHz to 1.6 GHz is used to process the original signal. The power \( P \) is calculated to describe the integral energy of the signal from 300 MHz to 1.6 GHz [7]. Its expression is shown in the following formula, in dBm:

\[
P^* = \frac{\sum_{n=0}^{N} u(n)^2 \Delta T}{N \times \Delta T} P = 10 \times \log \frac{P^*}{1mW}
\]

where \( u(n) \) is the UHF signal from 300 MHz to 1.6 GHz, and its record length is 200 ns. The sample rate is 10 GSamples/s, so the sample interval \( \Delta T \) is equal to 0.1 ns. \( N = 2000 \) is the record length of data. \( R \) is the impedance of the measurement circuit with the value of 50 \( \Omega \).

III. EVALUATION OF SEVERITY

A. Floating Metal

The floating metal model contains an epoxy resin stand, which holds the brass wire that serves as the floating metal. When the applied voltage exceeds the inception voltage, PD occurs in the gap between the upper electrode and the floating metal.

In the experiment, the diameter of the floating metal ranges from 0.5 to 1 mm, and the distance from the floating metal to the upper electrode increases from 0.5 to 1 mm, as shown in Fig. 2. As a result of the variations in the structure, the apparent charge varies from 18 to 382 pC, as presented in Table I. For the inner coupler, the correlations between the apparent charge and the acquired UHF signal, including the peak-to-peak value and the power \( P \) of the signal from 300 MHz to 1.6 GHz, are presented in Fig. 5, while the correlations between the apparent charge and the acquired UHF signal for the outer coupler are shown in Fig. 6.

This illustrates that the larger the radius of the floating metal and the longer the distance from the floating metal to the upper electrode, the bigger the apparent charge of PD. The peak-to-
Fig. 5. Correlation between the apparent charge of the floating metal and the UHF signal as measured by the inner coupler. The diameter of floating metal and the distance between the floating metal and the upper electrode: (1) 0.5 mm, 0.5 mm; (2) 1 mm, 0.5 mm; (3) 1 mm, 1 mm.

Fig. 6. Correlation between the apparent charge of the floating metal and the UHF signal as measured by the outer coupler. The diameter of floating metal and the distance between the floating metal and the upper electrode: (1) 0.5 mm, 0.5 mm; (2) 1 mm, 0.5 mm; (3) 1 mm, 1 mm.

peak value ranges from a few mV to almost 1800 mV, and the power $P$ is from $-55$ dBm to almost $-5$ dBm. The cluster separation is quite noticeable. This demonstrates that when the apparent charge increases, the peak-to-peak value grows in a linear fashion and the power of the signal from 300 MHz to 1.6 GHz grows in a logarithmic fashion. The larger the apparent charge, the smaller the increases of the power.

The experiment result shows that the signal acquired from the outer coupler is smaller than the one from the inner coupler. The largest peak-to-peak value is almost 1400 mV, and the maximum of the power is nearly $-10$ dBm. Even so, the correlations between the apparent charge and the acquired UHF signal are similar to those of the inner coupler.

For the floating metal, once the inception voltage has been reached, PD magnitude does not vary with the applied voltage. The UHF signal and the apparent charge are influenced by the structure of the PD model, such as the diameter of the floating metal and the distance between the floating metal and the upper electrode. The larger the radius of the floating metal and the longer the distance from the floating metal to the electrode, the longer the discharge path and the larger the charge accumulating on the floating metal will be. Hence the discharge of floating metal model 3 is the most serious.

B. Metallic Protrusion

In the test cell of the metallic protrusion in the SF$_6$, corona discharge is observed at the tip of the electrode when it is energized by the inception voltage. In the experiment, the tip radius is changed and the distance from the tip electrode to the plane electrode is varied from 3 mm to 5 mm. The apparent charge in the metallic protrusion is less than 60 pC and changes with the applied voltage. The correlation between the apparent charge and the UHF signal acquired by the inner coupler and outer coupler are shown in Figs. 7 and 8, respectively. First, it indicates that when the tip radius of the electrode becomes smaller, the apparent charge increases. The distance from the tip electrode to the plane electrode is found to have little impact on the apparent charge.

For the inner coupler, the peak-to-peak value of the UHF signal induced by the metallic protrusion is less than 25 mV, and the power is less than $-40$ dBm. There is no obvious correlation between the apparent charge and the peak-to-peak value because of the randomicity of the PD excited by the metallic protrusion. Even though, the correlation plot is characterized by two distinct clusters due to the difference of the tip radius. The tip radius of metallic protrusions 2 and 3 remained the same and
remained bigger than that of metallic protrusion 1. The correlation between the apparent charge and the power is similar in pattern to that between the apparent charge and the peak-to-peak value.

Compared with the inner coupler, there is no obvious difference for the correlation between the apparent charge and the UHF signal acquired by the outer coupler.

The electric field around the tip electrode is quite nonuniform and influenced seriously by the tip radius. Hence, the corona discharge is induced easily by the protrusion. While the tip radius increases, the electric field around the tip electrode gets weaken, so the incepted voltage will increase with the tip radius, but the corona discharge may become more serious. For the metallic protrusion model, the distance from the tip electrode to the plane electrode has an impact on the incepted voltage. Compared with the tip radius, the effect of the distance between the tip electrode and the plane electrode on the severity of corona discharge is much smaller.

C. Void in the Epoxy Resin

A small air bubble is intentionally allowed to remain in the epoxy-resin throughout the casting process. The dielectric constant of the air is much smaller than that of epoxy-resin, so when sufficient voltage is applied, there are discharges in the void. Voids of different sizes are used so that the intensity of the discharge will range from 380 to 520 pC. The correlation plots between the apparent charge and the UHF signal acquired by the inner coupler and outer coupler are shown in Figs. 9 and 10, respectively.

The peak-to-peak value of the UHF signal acquired by the inner coupler is from a few mV to almost 200 mV. The power ranges from $-55$ to $-25$ dBm. The peak-to-peak value is found to correlate with the apparent charge in a quadratic fashion. However, while the apparent charge increases to a certain point which is near 500 pC, the peak-to-peak value decreases with the increase of the size of the void as shown in Fig. 9. When the diameter of the void increases, the path of the PD may be easily changed, and the excited UHF signal begins to vary. Hence the green dots have a very distinct behavior in Fig. 9 because of the special characteristics of the discharge in the void. The correlation between the power and the size of the void is similar to that between the peak-to-peak value and the size of the void. However, its quadratic envelope is not so obvious.

Compared with the inner coupler, there is no significant difference in the correlation between the apparent charge and the UHF signal acquired by the outer coupler.
Fig. 9. Correlation between the apparent charge of the void in the epoxy resin and the UHF signal as measured by the inner coupler. The diameter of void in the epoxy resin: (1). 0.2 mm; (2). 0.5 mm; (3). 1 mm.

It can be seen that the characteristics of PD in the void are related closely with the discharge path. While the diameter of the void in the epoxy resin increases, the discharge path gets longer. Hence, the incepted voltage increases, and the apparent charge gets larger as the size of the void increases. Although the discharge is found to vary with the voltage, the effect of the size of the void on the PD is more remarkable.

IV. VERIFICATION OF SENSITIVITY

The procedures for the verification of the sensitivity of the PD detection in GIS are proposed in [16]. The waveform parameter related to the test pulse signal is presented in the article. In this study, a pulse generator is designed according to the reference standards presented in [16]. The output voltage of the designed pulse generator ranges from 1 V to 60 V, which is three times larger than the upper limit of output voltage (20 V) mentioned in [16], and the repetition rate is approximately 50 Hz. The wave of output single corresponding to an output voltage of 2 V is shown in Fig. 11. The rise time of the pulse is nearly 0.5 ns, and the pulselength is about 20 ns. The amplitude of the signal is 1.6 V, and it increases when the output voltage of the pulse generator increases. In the experiment, the pulse generator is connected to inner coupler 1 through a 10-m cable, and the outer coupler and inner coupler 2 are used for measurements as shown in Fig. 1. Before the experiment, the spectrum analyzer is used to assess insertion losses between both ports.

The two ports insertion loss curves of inner coupler 2 and the outer coupler are shown in Fig. 12. The losses are caused by the two 10-m cables, the two couplers, and the structure of GIS. For the inner coupler, the loss plot is characterized by three
Fig. 12. Two ports insertion loss between the output of the pulse generator and the input of the oscilloscope.

noticeable peaks that depend on the cutoff frequency of high-order mode in GIS, such as TE11, TE21, and TE31. The loss of the outer coupler is more serious than that of the inner coupler, and it is also influenced by the high-order mode. The loss around the cutoff frequency of the high-order mode is relatively small.

While the output voltage of the pulse generator is 2 V, the signal acquired by inner coupler 2 and its frequency spectrum are shown in Fig. 13. The measurements of the outer coupler are shown in Fig. 14. The amplitude of the signal acquired by the inner coupler is much larger than that acquired by the outer coupler, and the duration is also longer. The characteristics of the frequency spectrum of the signal are consistent with those of the two port insertion loss plots. The increase in the frequency component occurs around the cutoff frequency of the high-order mode. The frequency spectrum of the injection pulse is known, so if the two port insertion losses are measured in advance using the spectrum analyzer, the frequency distribution of the acquired signal can be predicted accurately for the actual measurement in various conditions. This can be very useful in verifying the sensitivity of UHF PD detection.

Fig. 13. Signal acquired by the inner coupler and its frequency spectrum.

The output voltage of the pulse generator increases from 1 to 60 V over the course of the experiment. The variation of the signal acquired by the inner coupler and that acquired by the outer coupler is focused. As shown in Fig. 15, the peak-to-peak value of the inner coupler is larger than that of the outer coupler. When the output voltage of the pulse generator is 60 V, the maximum value of the inner coupler is almost 250 mV and that of the outer coupler is only 125 mV. A distinct linear trend can be observed. The linear fitting curves are found and plotted in Fig. 15.

The variation of the power of the signal acquired by the inner and outer couplers is shown in Fig. 16. The power of the inner coupler is still larger than that of the outer coupler. For the inner coupler, the maximum value is about 20 dBm and that of the outer coupler is nearly 30 dBm. It can be seen that the relationship between the power and the output voltage of the pulse generator is nonlinear. The power in the unit of decibel-meters is similar in logarithmic function to the output voltage.

While the output voltage of the pulse generator increases from 1 V to 60 V, the amplitude of the pulse, which is injected into GIS by the pulse generator, increases linearly with the output voltage. Hence the amplitude of the signal acquired by the inner coupler 2 and the outer coupler also gets larger linearly correspondingly. Even though, the relation between
V. DISCUSSION

The correlation between the apparent charge in the typical defects and the peak-to-peak value of the UHF signal acquired by the inner coupler is shown in Fig. 17. It shows that the PD sources can be separated easily due to the particular characteristics of the different defects. The correlation plot of the output voltage of the pulse generator and the peak-to-peak value is also presented in Fig. 17. The peak-to-peak range of the signal caused by the floating metal is far greater than that of the signal caused by the pulse generator. The correlation between the apparent charge and the power of the UHF signal acquired by the inner coupler is shown in Fig. 18. It indicates that when the power of the signal is small, under $-30$ dBm, the apparent charge of the discharge caused by the floating metal is similar to that of the metallic protrusion, but it is much lower than that of the void in the epoxy resin. The power range of the discharge caused by the floating metal remains greater than that of signal caused by the pulse generator. The case of the outer coupler is very similar to that of the inner coupler.

According to the previous investigation, the power of the signal from 300 MHz to 1.6 GHz, which lasts for 200 ns and contains the complete PD pulse, may be used to evaluate the severity of PD in GIS. The power is considered to describe the energy acquired from the PD source. For the same type of defect, the larger the power, the more serious the discharge. Regarding the different types of defect, the correlations between the power and the severity of PD are very different, as shown in Fig. 18. Although the power of discharge caused by the void in epoxy resin is small, the defect is quite serious. Though the power of discharge caused by the floating metal may be very large, the defect may be not very serious. Therefore, the PD must be classified before severity can be evaluated accurately. In addition, the location of the PD source must be identified, and the measurement position must be as close to the PD source as possible.

Some proposals based on the analysis of the pulse generator are presented to complement the GIGRE method. First, the PD source used in the experiment for the sensitivity verification must be placed very close to the enclosure of GIS and to the coupler used for the pulse injection. It has been verified that the characteristics of the high-order mode are more noticeable while the PD source is close to the enclosure. In this way, the frequency spectrum of the acquired signal will be consistent with the case to which the pulse generator is applied. Second, the peak-to-peak value may be used for sensitivity verification because of its linear correlation with the apparent charge. The measurement of floating metal model can ensure a linear correlation curve between the apparent charge and the peak-to-peak value. In this way, it is
possible to verify the UHF PD detection system in the different levels of apparent charge, such as 5, 20, 50, and 100 pC. The linearity of the system can be examined in a process similar to the calibration of IEC60270.

Even so, the pC level is still the generally accepted means of evaluating the conditions of the insulation system. Because of the fundamental principles behind the IEC and UHF detection techniques, the pC level is difficult to quantify using the UHF detection technique alone. More effort should be put into accurately evaluating the severity of PD in terms of pC.

VI. CONCLUSION

The evaluation of the PD severity and verification of sensitivity of PD detection using the UHF method in GIS are experimentally investigated and discussed. An actual 220-kV GIS is used to assess the severity of PD and verify the sensitivity of the UHF PD detection system. The inner and outer couplers are adopted to acquire the PD signal, respectively. Three types of defects are tested using the IEC60270 measurement technique and the UHF detection.

The experimental results are characterized in terms of the relationship between the apparent charge and the peak-to-peak value as well as the power of the signal from 300 MHz to 1.6 GHz. Power may be used for the evaluation of severity of PD in GIS. This indicates that the evaluation of the PD severity depends closely on the type of source of PD. The correlation pattern of floating metal between the apparent charge and the power is approximately logarithmic. The small power of the discharge caused by the void in the epoxy resin is found to correspond to a comparatively large apparent charge.

A pulse generator is designed, taking into account the GIGRE method of the sensitivity verification of PD for UHF detection. The rise time of the pulse is about 0.5 ns, the duration is about 20 ns, and the repetition rate is approximately 50 Hz. Since the output voltage of the pulse generator varies from 1 to 60 V, the peak-to-peak value of the acquired signal increases linearly with voltage, indicating that this system is suitable for the verification of sensitivity of PD in GIS. Because of the appearance of the characteristics of high-order mode, the PD source for the sensitivity verification experiment must be located close to the enclosure of GIS and to the coupler used for the pulse injection. In addition, the floating metal model is found to be more appropriate than other models in the sensitivity verification experiment due to the linear correlation curve between the apparent charge and the peak-to-peak value. Eventually, the highest sensitivity and the linearity of the UHF PD detection system are verified accurately.

REFERENCES


Dengwei Ding received the B.Sc. and M.Sc. degrees in electrical engineering from Tsinghua University, Beijing, China, in 2008 and 2010, respectively, where he is currently pursuing the Ph.D. degree in electrical engineering. His research interests include high-voltage switch equipment, the application of discrimination techniques, and the diagnosis of insulating systems by partial-discharge detection and analysis.

Weidong Liu received the B.Sc. degree in electrical engineering from the Shanghai Jiaotong University, Shanghai, China, in 1982 and the M.Sc. and Ph.D. degrees in electrical engineering from Tsinghua University, Beijing, China, in 1985 and 1989, respectively. During 1990–1992, he was a Visiting Scholar at the University of Liverpool, Liverpool, U.K. Currently, he is a Professor in the Department of Electrical Engineering, Tsinghua University. His research interests are high-voltage (HV) switch equipment, the online detection and fault diagnosis of HV equipment, signal processing, simulation analysis, and pattern recognition.

Xinhong Huang (M’04) received the B.Sc. and Ph.D. degrees in electrical engineering from Xi’an Jiaotong University, Xi’an, China, in 1992 and 1997, respectively. She began her academic career as a Lecturer with Xi’an Jiaotong University in 1997. Since 2004, she has been with the University of Western Ontario, London, ON, Canada, where she currently is a Research Engineer in the Department of Electrical and Computer Engineering.