On-site partial discharge measurements on GIS cable terminations

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Abstract: Up to now, partial discharge measurement is an effective diagnosis assessing the insulation condition, especially for defect detecting. Due to the in-field installation, cable termination is easily damaged by improper workmanship. Hence, partial discharge measurement is suitable for acceptance test and routine test. However, on-site off-line partial discharge measurement on GIS cable termination is hardly done because of the high level of background noise. The background noise is usually in wide frequency range and high amplitude resulting from the antenna-like long cable. The alternative method is on-line partial discharge measurement. The advantage of on-line partial discharge measurement is the high signal to noise ratio. Therefore, operator can use higher measuring frequency to avoid the interference of background noise. A set of 161 kV GIS terminations with 3 km-long cables is taken as the test objective. Authors utilize the on-line partial discharge measurement as acceptance test, and the test result is compared with off-line partial discharge measurement. The measurement shows that on-line partial discharge measurement has better performance as an on-site diagnosis. As a routine test, on-line partial discharge measurement on GIS cable termination has some problems needed to be solved. One of the problems is to locate the partial discharge source. The partial discharge signals coming from GIS and cable termination both can be detected at the cable termination, and both have similar properties. A GIS system with partial discharge activities is taken as an example. Authors successfully locate partial discharge source by means of waveform analysis and phase-resolved-pattern identification. The cable termination with partial discharge activities was dissection after test, and the dissection result coincides with measurement result. Through the test result, on-line partial discharge measurement is suitable for on-site test on GIS cable termination, especially for dirty electric environment.

1 INTRODUCTION

Partial discharge is a discharge that occurs within the insulation media without bridging the system electrodes. Partial discharge is caused by the locally high electric field exceeding the breakdown electric field, and the high electric filed are usually resulted from the defects such as voids, contaminants, and cracks. There are several transient phenomena complying with partial discharges (PDs), such as the electric field disturbance, pressure wave, light, and etc. Hence, the partial discharge measurement (PDM) utilized these phenomena to detect PDs[1-6]. Among these phenomena, there are more restrictions on the detection of non-electrical phenomena. Therefore, most PDM is electrical method. Because PDMs are more sensitive to defects than other insulation diagnostics, PDM becomes an effective diagnosis assessing the insulation condition, especially for defect detecting.

Due to the in-field installation, cable termination is easily damaged by improper workmanship[4-5]. Experiences show that the poorly installed terminations are usually the causes of cable system failure. These poorly installed terminations usually generate PDs leading into insulation breakdown. Hence, PDM is suitable for acceptance test and routine test to assess the insulation of cable system. However, on-site off-line PDM is hardly carried out because of the high level of background noise. The background noise is usually in wide frequency range and high amplitude resulting from the antenna-like long cable. The alternative method is on-line PDM, which has wide frequency range. The advantage of on-line PDM is the high signal-to-noise ratio (SNR) by utilizing filters to suppress noise or the selected frequency range. Therefore, tester can use higher measuring frequency to avoid the interference of background noise.

As mentioned above, PDM is an efficient diagnostics of insulation condition, and the majority failure of cable system is caused by the PDs inside cable terminations. Therefore, there are standards for PDM on cable system derived from IEC 60270, and is so-called conventional PDM. These standards are treated as off-line PDM in factory/laboratory. Complying with the adoption of condition-based maintenance, however, more and more on-line PDM methods, which are so-called non-conventional PDM, are developed. Hence, the draft of IEC 62478 is in progress, defining the measuring system, sensors, frequency range, reading quantity, and etc. The main differences between IEC 60270 and IEC 62478 are measuring frequencies and measured quantities.

In order to comparing the performance of conventional PDM and non-conventional PDM, a set of 161 kV GIS terminations with 3 km-long cables is taken as the test objective. Authors utilize the on-line PDM as acceptance test, and the test result is compared with on-site off-line partial discharge measurement. Because of adequate filters suppressing background noise, on-line PDM has better sensitivity than off-line PDM in the field. The measurements show that on-line PDM has better performance as an on-site diagnosis.

On-line PDM on in-service system is also necessary because of the existence of time-consumed-formation defects, which may not be detected in acceptance test.

As a routine test, on-line PDM on GIS cable termination has some problems needing to be solved. One of problems is to locate the PD source. The PD signals coming from GIS and cable termination will be both detectable at the cable termination, and have similar properties. A set of GIS cable terminations with PDs is taken as an example. Authors successfully locate PD source by means of waveform analysis and phase-resolved-pattern identification. The cable termination with PDs was dissection after test, and the dissection result coincides with measurement result.

Generally speaking, conventional PDM has poor performance on-site because of high background noise suppression. Under the aid of oscilloscope and spectrum, on-line PDM on GIS cable termination can locate the PDs.

2 TEST METHODLOGY

(1) PDM on cable system

i. Conventional PDM[1,3]

PDM described in IEC 60885-3 is derived from IEC 60270. The basic test circuit is shown in fig. 1. Test apparatus consist of a high voltage power supply (W), a voltmeter (V), filter (Z), coupling capacitor (C_K), input impedance (Z_A), test object (C_X), and discharge calibrators (C_{cal}). The required sensitivity is better than 10 pC.

The applied voltage is gradually raised to 2 U_0 and is held for 10 seconds. Then the voltage is slowly reduced to 1.73 U_0, and the acceptance level of PD is below 10 pC at 1.73 U_0.

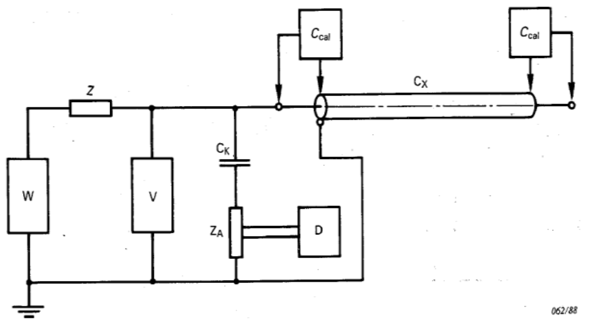


Figure 1 basic partial discharge measurement diagram[1]

ii. Non-conventional PDM

As the condition-based maintenance (CBM) becomes popular, the on-line PDM becomes necessary. Hence, more and more so-called non-conventional PDM are developed. Because the PDs comply with different phenomena as shown in fig. 2, PDs can be detected by various detection methods. However, various methods show different sensitivities and the relation between reading qualities and apparent discharge also differs[7]. There is no specific definition of the measuring system, yet. Therefore, the results measured by different instruments usually cannot be compared between each other. This may confuse customers when they need a thirty party to confirm the measured result.

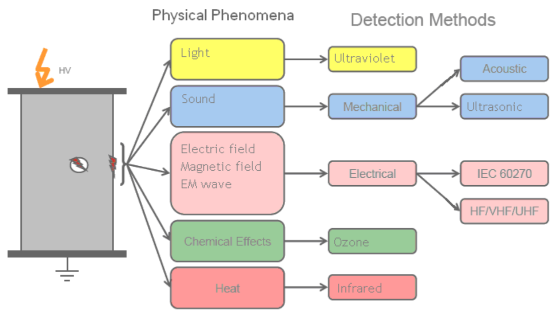


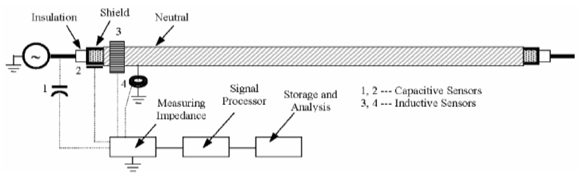
Figure 2 different phenomena complied with PDs

Because of the inconsistent sensitivities and frequency range utilized by different detection methods, IEC TC42 has drafted IEC 62478 to clarify the measuring system, including types of sensors, frequency ranges, frequency and time domain signal processing, and reading quantities.

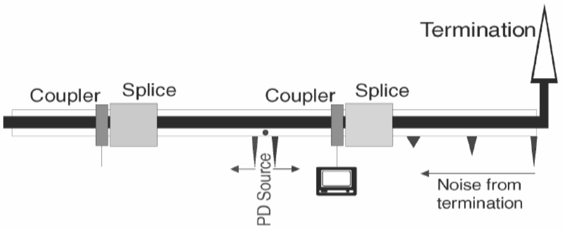
(2) On-site PDM on power cable systems

Most experience shows that the failures of power cable systems usually result from defects inside cable accessories, and PDM is an effective diagnostics to assess the insulation condition[4,6]. These defects are usually formed during the installation in field. Hence, on-site off-line PDM on power cable system is necessary to be added into acceptance test. However, there are time-consumed-formation defects not detected by acceptance test, and on-site on-line PDM is requested for the routine test to complement the lack of acceptance test.

IEEE Std. 400.3 describes the application of on-site PDM, including off-line PDM and on-line PDM, as shown in fig. 3. The main difference between on-line and off-line PDM is their voltage sources. One is system voltage source and the other one additional voltage source separately. Coupling device of type 2, 3, 4 in fig. 3(a) can also be used as the coupler in fig. 3(b). This implies that the measuring system of on-line/off-line PDM can be the same. In such way, on-site off-line/on-line PDM can both have good sensitivity.



(a) off-line PDM[4]



(b) on-line PDM[4]
Figure 3 Typical test setup for on-site PDM

(3) Comparison between conventional/non-conventional PDM

Conventional PDM is an off-line PDM in factory/laboratory. The applied voltage is adjustable and the background noise can be reduced to acceptable level by means of a shielding room. Therefore, the PDIV and PDEV can be both measured and the sensitivity can be good. In these advantages, conventional PDM has the ability to detect small defects, to classify the types of defects. However, the sensitivity of conventional PDM will become poor at dirty electric environment due to the limited frequency range. Moreover, some time-consumed-formation defects cannot be detected by conventional PDM due to the short duration of voltage applied[4,5].

Non-conventional PDM is an on-line PDM on-site, opposite to conventional PDM. The test condition is the operating condition, so the PDs won't disappear. Hence, the time-consumed-formation defects can remain and is detectable. Besides, filters can be used to reduce the high background noise, and a better signal-to-noise ratio (SNR) can then be achieved. But, the types of partial discharge sometimes become difficult to be recognized due to the unchangeable operating voltage.

Time-consumed-formation defect is one reason why non-conventional PDM is important. Another reason is the high SNR. Because of the adjustable frequency range, operator can choose a clear frequency band to do PDM.

Based on authors' experiences, the common background noise usually spreads at the frequency range up to 30~40 MHz[6], as shown in fig. 4. Fig. 5 is an example explaining the benefit of on-site on-line PDM. Fig. 5(a) is the phase-resolved-pattern measured by on-site conventional PDM, and it shows nothing except high background noise level. Fig. 5(b) is the phase-resolved-pattern measured by on-site non-conventional PDM, and a high pass filter is utilized to suppress the noise. The pattern of fig. 5(b) shows obvious PDs.

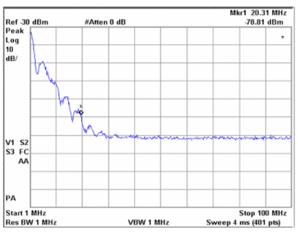
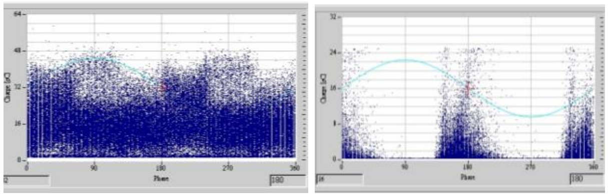


Figure 4 Typical background noises in field


(a) without filter (b) with 150 MHz high-pass filter
Figure 5 phase-resolved-pattern measured by on-line PDM

3 ON-SITE PDM FOR ACCEPTANCE TEST

In June 20th 2007, one extra-high voltage new-installed cable was prepared to join into the system. Before energized, a high voltage test was needed as the acceptance test. Hence, an on-site PDM was integrated into the high voltage test, and the test circuit was modified.

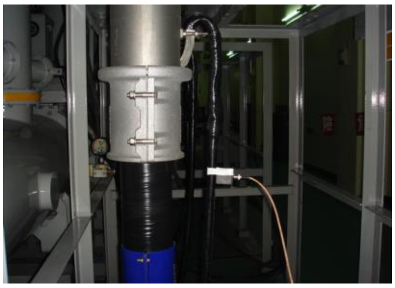
The rated voltage of the cable is 161 kV, and the length of the cable is 3 km. Both ends of the cable are terminated at GIS bushings, and relative CBs and DSs are all opened. In order to apply test voltage, a set of test bushings is installed as shown in fig. 6. As shown in fig. 6, an additional blocking impedance and a coupling capacitor are installed to do on-site PDM.

On-site PDM can be divided into two parts by the different coupling paths. One is conventional PDM as shown in fig. 7(a), and its frequency range is between 100 kHz to 500 kHz with a bandstop filter. Another is non-conventional PDM equipped with UHF sensor as shown in fig. 7(b), and its frequency range is up to 1.7 GHz with varies bandpass/highpass filters.

The measuring systems of these two PDMs are shown in fig. 8, and are similar to fig. 3.


Figure 6


(a) Coupling capacitor



(b) UHF sensor
Figure 7

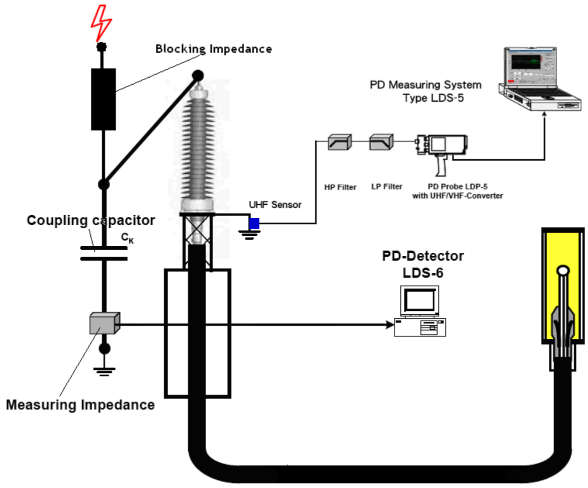


Figure 8 measuring system of on-site PDM

Before test, a pulse generator injects calibration signals into the tested cable for the calibration of measuring systems.

Fig. 9 is the calibration of conventional PDM. Because the cable length is long, the cable gets a lot of noise and the 2000-pC calibration signal is chosen to calibrate the measuring system of conventional PDM. This means that the partial discharge activities smaller than 500 pC will not be detected as shown in fig. 9.

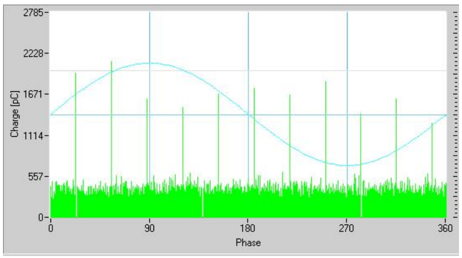


Figure 9 Calibration of conventional PDM

Before the adoption of filters, non-conventional PDM also measures a lot of noise. Fortunately, unlike conventional PDM, the frequency range of non-conventional PDM is wide. Therefore, non-conventional PDM can suppress background noise by utilization of bandpass/highpass filters.

Fig. 10 is the calibration of non-conventional PDM with adequate filtering. As shown in fig. 10, the 50 pC calibration signal is big enough to be distinguished from background noise. The background noise is about 2 pC, and any partial discharge signal larger than 2 pC will be detected.

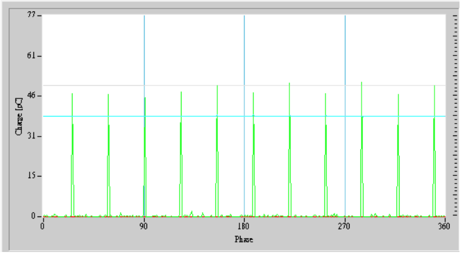


Figure 10 Calibration of non-conventional PDM

After calibration of measuring systems, the test voltage is applied to the cable. The test voltage is slowly raised to 2 U_0, and holds for ten seconds. Then, the test voltage is gradually reduced to 1.73 U_0, and hold for ten minutes. Both PDMs are carried out as the test voltage is held at 1.73 U_0.

Fig. 11 and Fig. 12 are the phase-resolved-patterns measured by conventional/non-conventional PDMs separately. There are no PDs measured in both pictures. However, the background noises measured by these two PDM are quite different. The risk of conventional PDM is the unrecognized defects because of the high background noise confusing the identification of partial discharge smaller than 500 pC. According to the measurements, non-conventional PDM shows the better performance than conventional PDM in the field.

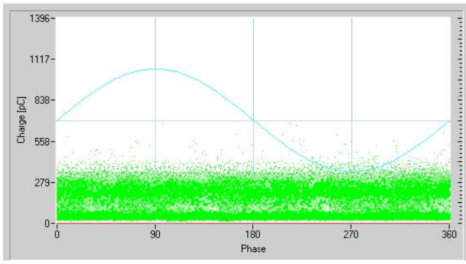


Figure 11 phase-resolved-pattern of conventional PDM

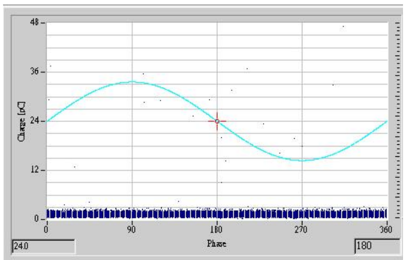


Figure 12 phase-resolved-pattern of non-conventional PDM

Generally speaking, while the background noise is intensive in the field, the sensitivity of on-site conventional PDM will have relatively poor sensitivity. The risk of failure caused by partial discharge remains. In opposite, on-site non-conventional PDM can maintain high sensitivity due to the noise suppression by filters. Hence, on-site non-conventional PDM can have similar performance as in laboratory, and the failure caused by partial discharge can be prevented.

4 ON-SITE ON-LINE PDM

Experiences show that some equipment is PD free in acceptance test, but PDs are detected by on-line PDM after a period of operation. The main reason is the time-consumed-formation defect, which cannot be detected at acceptance test. Hence, on-line PDM is an effective diagnostics as a routine test. However, the disadvantage of on-line PDM on GIS termination is the location of PD source. Authors took a set of 161 kV GIS cable terminations as example. The on-line PDM is illustrated, and location of PD source was also carried out

The feeder of the GIS is bundle conductor, which means that there are two GIS cable terminations per phase. One end of the cables is terminated in GIS, and the other end of the cables is terminated in oil-immersed transformer. The on-line PDM on the 161 kV cable terminations utilizes UHF sensors attaching to grounding wire, as shown in fig. 13. Because of the high background noise from ground wire, several filters are adapted to suppress background noise. The waveforms, phase-resolved-patterns, and spectrums of PDs are all monitored and compared among six cable terminations, as shown in fig. 14.


Figure 13 Sensor position


Figure 14 Arrangement of measuring device

There are PDs measured in all cable terminations, and the phase-resolved-patterns are all similar as shown in fig. 15. The phase-resolved-patterns show the internal partial discharge rather than noise. By comparing all the phase-resolved-patterns, the strongest one is the #1 S-phase cable termination. Therefore, the signal source is considered inside #1 S-phase cable termination.

Moreover, oscilloscope and frequency spectrum are used to confirm the PD source. Arriving time analysis (ATA) is used to identify which cable terminations has the PD source, by comparing waveforms in oscilloscope, as shown in fig. 16. Fig. 16 also shows that the PD signal recorded at #1 S-phase cable termination is the first one among all termination.

Fig. 17 is the spectrum analysis of the partial discharge signal. The signal has wide frequency range instead of a narrow frequency range, and this implies the signal is internal partial discharge signal instead of resonance caused by outside partial discharge.

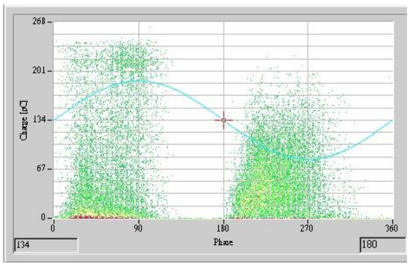


Figure 15 Phase-resolved-pattern of #1 S-phase cable termination

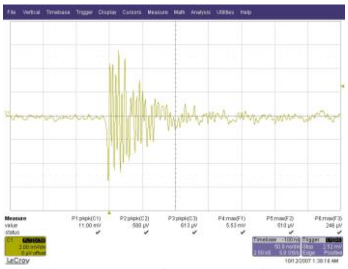


Figure 16 Waveforms used for ATA
(50.0 ns/div, 2.0 mV/div, Input resistance: 50 Ω)

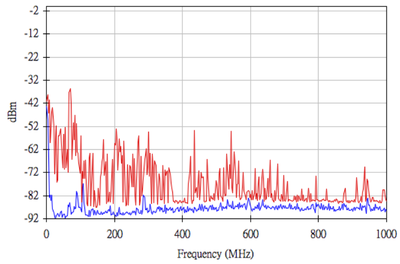


Figure 17 PDs' spectrum of #1 S-phase cable termination
(Blue line: background noise, Red line: max. hold of measured signal)

Because cable terminations are directly connected to GIS, it is possible that the PD signal comes from GIS itself. Hence, on-line PDM on GIS is carried out. All spacers are all covered by metal rings, so no electric field disturbance caused by partial discharge can be detected by external sensors. In such case, only the pressure wave can be detected, and the acoustic emission (AE) sensor is utilized. Fig. 18 shows the results measured by AE sensor, and no partial discharge activities are detected.

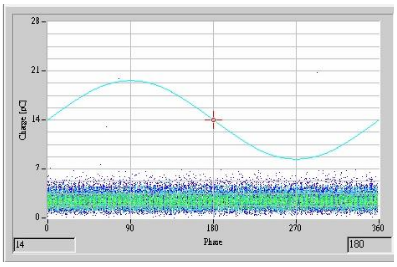


Figure 18 PDM on GIS with AE sensor

Among aforementioned results, it is verified that the partial discharge source is inside the #1 S-phase cable termination instead of GIS. Hence, a suggestion of replacement is proposed.

After dissection, the partial discharge source of the 161 kV cable termination is shown in fig. 19. Comparing with the standard installation illustrated in fig. 20, there is no tape wrapped in the junction of terminal and XLPE. Therefore, the insulated oil inside termination infiltrated into the interspace between conductor and inner-semiconductor. The partial discharge activities finally happen.


Figure 19 PDs caused by poor installed cable termination

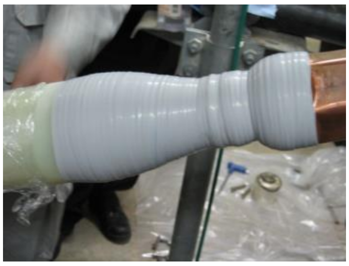


Figure 20 well installed cable termination

As mentioned above, the conclusions of on-site non-conventional PDM and dissection coincide with each other. This implies that non-conventional PDM can effectively assess the insulation condition, and the location of PD source can be carried out by the aid of other analysis.

5 CONCLUSION

As illustrated above, conventional PDM on long cable usually has poor sensitivity on-site due to the high background noise even though it has good performance in factory/laboratory. Hence, the risk of PD caused breakdown cannot be avoided by on-site conventional PDM. Non-conventional PDM usually has wide frequency range, and the SNR can be enhanced by selected frequency range and the adoption of filters. Therefore, non-conventional PDM on long cable has similar sensitivity whether the sensed background is high or low.

Non-conventional PDM usually has better immunity against noise, and is usually treated as routine test. Because PDs originated from GIS and GIS cable terminations have similar properties, however, on-site non-conventional PDM on GIS cable terminations may have a location problem. A set of 161kV GIS cable termination is taken as example. By combining pattern recognition with ATA and spectrum analysis, non-conventional PDM not only can detect PDs, but also can locate the PD source. The non-conventional PDM also coincides with dissection result.

Consequently, non-conventional PDM on long cable is an effective diagnostics of insulation material by the ability of noise suppression. Besides, the location problem of on-line non-conventional PDM on GIS cable termination is overcame by the aid of ATA and spectrum.

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