On-site Portable Partial Discharge Detection Applied to Power Cables Using HFCT and UHF methods

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Abstract: - Partial discharge (PD) events happen inside the power cables and cable terminations with the insulation degradation. The PD detection can effectively supply the information of cable status. According to the electrical and electromagnetic emission of PD activities, high-frequency transformer (HFCT) and ultra-high-frequency (UHF) methods are employed to detect the PD signals. Besides, a portable PD monitoring device is developed for on-site PD testing. The device consists of signal conditioning, high-speed data acquisition system and data processing unit. The comparison between HFCT and UHF results discriminates the real PD signals from interference remarkably, and contributes to PD source location. Additionally, advanced phase-resolved PD analysis is used to recognize the defect pattern. The on-site experiments show that the combination of HFCT and UHF methods is successful and abstractive in the power cables condition diagnosis.

Key-Words: - Partial discharge, HFCT, UHF, Potable PD monitoring device, High-speed data acquisition, Interference discrimination, Pattern recognition

1 Introduction

Partial discharge activity is normally the early indication of insulation degradation inside high-voltage (HV) and medium-voltage (MV) power cables [1, 2]. Though the cables can still be in service even with some insulation defects, it tends to fail or break down in the near future. So effectively detecting the PD signals is useful and essential in the asset maintenance of power cables. One distinct advantage of PD method is its non-destructive feature, which means that the detection procedure does not require power apparatus to be off service. Accurate PD detection and location contribute to finding out the defects in the early stage, and then proper maintenance can be arranged.

The PD events emit acoustic, electrical and electromagnetic energy. According to different PDs emission patterns and signals bandwidth, many detection methods are developed, including AE sensors, HFCT and UHF antenna [3, 4]. The acoustic emission (AE) signals attenuation characteristics was investigated through different cable and joint insulation materials and the AE detection sensitivity is found up to 10pC [5]. The use of HFCT around metallic earthing strap was described to couple PD electrical currents in power cables, and improved wavelet transform techniques was implemented to reject noise from on-line PD measurements [6]. The UHF sensor was introduced to diagnose the cable terminations in service, and compares the detective PD levels with conventional IEC method [7].

Due to the complexity of on-site cable network interconnections, it is not effective enough to use only one detection method to distinguish the PD signals from ambient interferences. There are many kinds of inferences in field environment, e.g., discrete spectral interference from communication and radio emissions, stochastic noise from power electronics, white noise from ambient, and so on [8]. The PD signals have wide-band feature, and thus one type sensor can only detect signals within certain bandwidth. But in some cases, sensors of different detective bandwidth can acquire PD signals simultaneously, and it implies a real PD event with highly probability. This paper proposes the use of hybrid detection methods of HFCT and UHF sensors to distinguish the real PD signals from ambient noise. The result comparison between these two-type sensors provides more effective and reliable detection methods and results.

Furthermore, on-site PD tests are normally carried out using oscilloscope. It intends to obtain the original waveform from HFCT and UHF sensors as introduced [9]. However, the sample rate of oscilloscope needs to be above 10 GHz to satisfy the requirement of UHF signals observation. This scope observation method is not convenient in on-site testing. Besides, only the waveform cannot supply sufficient information to recognize PD signals. To overcome the above weak points, a portable PD monitoring device is developed. The input channels consist of up to three HFCTs and one UHF sensor. Self-designed signal conditioning circuit is presented. The integrated data acquisition system is based on DSP (digital signal processor) and CPLD (complex programmable logic device). The developed software supplies with instant digital signal processing, waveform analysis and statistical spectrum display. All these contribute to more effective on-site PD testing on power cables.

2 PD Detection

Among the available PD detection techniques, HFCT and UHF methods are most popular and achieve best performance. And the PD detection mechanism using HFCT and UHF methods is illustrated in Fig. 1.

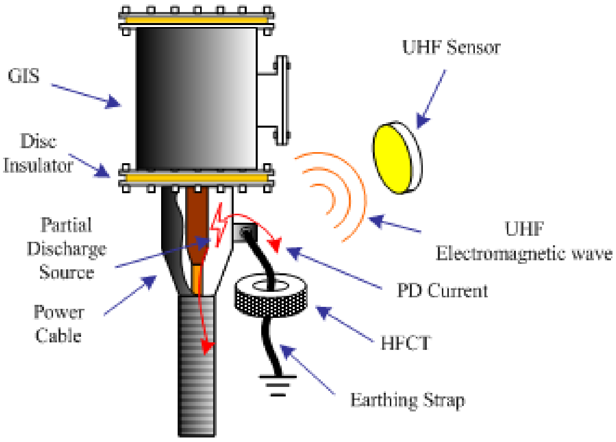


Fig. 1 PD detection mechanism using HFCT and UHF sensors.

2.1 HFCT Method

Once a PD event happens in the cable termination, some electric charges accumulate and form a high frequency PD current. Two current streams of different polarity flow towards opposite directions. One current flows to the other far end of the cable through the cable core conductor. The other flows through the earthing strap, which supplies with a low impedance path to the ground. Thus it is possible to pick up the PD current information by placing HFCT appropriately. The HFCT is made of ferrite core enwind with several rounds of electric wire, which is referred as rogowski coil [8]. Any change in the central current of the HFCT will induce voltage on the output port of electric wire, and this can be interpreted as the PD events. The detection bandwidth up to 10MHz is adequate in power cables [10]. On the other hand, the discrete spectral interference (DSI), especially the amplitude modulation (AM) radio broadcasting with bandwidth from some hundred kilo Hz to 2MHz, is the dominant interference in on-site power cable detection. So the developed HFCT sensor is designed to cover the bandwidth of 2MHz to 10MHz.

As shown in Fig. 1, the HFCT is placed around the earthing strap of cable termination or the insulation surface without shielded screen. Generally, the later can obtain signals of better SNR (signal-to-noise). However, it is not always easy to place the sensor here for on-site testing. On the contrary, clamping HFCT on the earthing strap is more feasible.

2.2 UHF Method

The PD events inside power cable or cable terminations will excite UHF EM (electromagnetic) wave to surrounding environments as introduced [11]. The frequency range of UHF signals reaches as high as 1.5GHz. The developed UHF sensor is composed of planar equiangular spiral antenna, which can cover the bandwidth from 300MHz to 1.5GHz to satisfy the detection of UHF signals.

The cable terminations are almost shielded by metallic sheath. But there still exists some ways without complete shielding for the UHF signals to transmit outwards. As illustrated in Fig. 1, for example, the disc insulator of epoxy resin between the cable termination and adjacent GIS can be a path for EM wave transmission. Another way is through the earthing strap, which plays the role of transmitting antenna for excited EM wave.

The UHF EM wave attenuates heavily in air, and it is not sensitive enough for detecting the signals far from the PD source. The fast attenuation characteristics of UHF method contribute to PD source location. The point of largest coupled signals probably implies that the PD source is nearby.

3 Portable PD Monitoring Device Development

As to detect the partial discharge phenomenon of on-line power cables, a portable PD monitoring device is developed. As shown in Fig. 2, the device consists of three main components, i.e. signal conditioning circuit, data acquisition system and signal processing unit. They are all assembled in a case with rolling wheels and pull handle for portable purpose. Three-channel HFCT and one-channel UHF sensors are equipped. Adapting to dedicated on-site testing conditions, a combination of these sensors can be chosen. For example, the earthing strap of each phase in 220kV high-voltage cable termination system is connected to ground separately. Whereas, the shielded screen of the three-phase 35kV medium-voltage cables is twisted together and connects to ground by one earthing strap. Additionally, the HFCT sensor is made of split-core structure to clamp or remove around the earthing strap more conveniently.

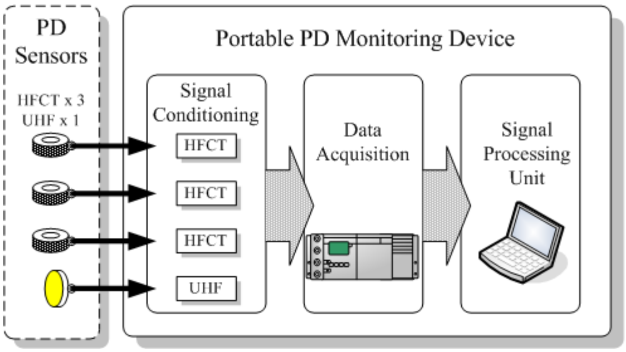


Fig. 2 Structure of developed portable PD monitoring device.

The monitoring device obtains the signals from HFCT and UHF sensor, digitizes them and stores in the memory. The signal processing unit extracts the PD pulse and calculates the characteristic parameters. The PD pulses of HFCT and UHF sensors are compared to discriminate the real PD events from environmental noise. More advanced analysis technique is used to recognize the insulation defect pattern. The results are then displayed on the screen. The on-site sensors installation and portable PD monitoring device is shown in Fig. 3.

(a) (b)

Fig. 3 Structure of developed portable PD monitoring device, (a) on-site sensors installation; (b) developed portable PD monitoring device.

3.1 HFCT Signal Conditioning

Because of the severe interference in on-site test environment, some essential signal conditioning procedures must be considered for the design of HFCT and its corresponding amplifier. The magnetic core with surrounding wires is installed in a metallic shield using aluminium to avoid outside noise as much as possible. Meanwhile, it is necessary to leave a non-shielded slot at the inside the centre of the shield to couple the high frequency pulse through the HFCT. The connection between HFCT and signal conditioning circuit is displayed in Fig. 4.

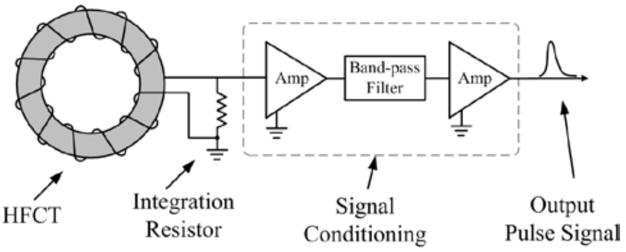


Fig. 4 Connection between HFCT and corresponded signal conditioning circuit.

The signal produced by HFCT is transmitted to the portable PD monitoring device by coaxial cables. The amplitude is so weak within the range of some millivolts, that the subsequent amplification and filtering are employed. The coupled signal is amplified firstly. As to avoid narrow band interference, a pair of 2-order band-pass filter is used, with frequency range from 2MHz to 10MHz. Then the signal needs to be amplified again. After the signal conditioning including amplification and filtering, the signal achieves better SNR effect for subsequent data acquisition.

3.2 UHF Conditioning

The frequency bandwidth of UHF signal arose by PD phenomenon is about 300M~1.5GHz, which exceeds the detection range of normal acquisition device. The sample rate of oscilloscope is enough to sample UHF signals. However, the oscilloscope is not convenient to move on-site. And it cannot be used to diagnose the PD defects because it just records time series samples. Thus the peak-hold detection technique is employed in the signal conditioning procedure to realize the sampling of

UHF signals at a sample rate probably of some mega-hertz. The circuit sketch is shown in Fig. 5, and the acquired waveform is illustrated in Fig. 6.

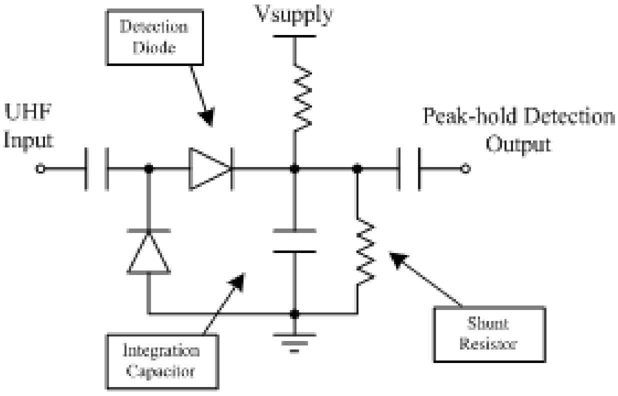


Fig. 5 Peak-hold detection circuit applied to UHF signals

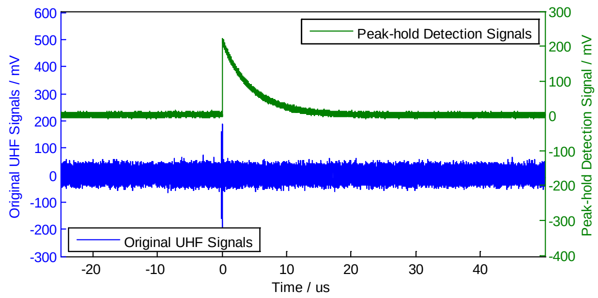


Fig. 6 Waveform comparison between original UHF signals and peak-hold detection

The UHF signal is amplified by 40dB firstly. Then the signal will go through a high frequency diode and integrated by a capacitor. The voltage over the integrated capacitor will rise when the polarity of UHF signal is positive, and that voltage will drop by leakage current of the shunt resistor. Because of the hysteresis reaction of the integration circuit, the peak-hold envelope of the positive pulse shape is recorded on the capacitor, which can be sampled by data acquisition part subsequently.

Compared to the detail waveform of pulse shape, the amplitude and phase position related to AC power voltage are more valuable. Thus, reserving the peak-hold waveform is adequate to supply the diagnosis with enough PD information. And what is more important, the peak-hold detection lowers the requirements of sampling rate to a large extent.

3.3 DSP-CPLD Based Data Acquisition System

To acquire the PD signals for 3-channel HFCT and 1-channel UHF sensors, a data acquisition system is developed. The system is designed based on the combination of DSP and CPLD as shown in Fig. 7.

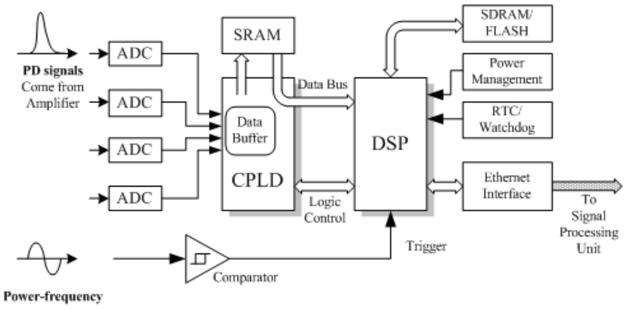


Fig. 7 Structure of DSP-CPLD based data acquisition system

The high performance DSP chip from Texas Instruments (TI), i.e. TMS320C6713B, is chosen as the control and processing core of the developed data acquisition system. As running at the operation frequency of 300MHz, the system provides high control efficiency and data-bus bandwidth for PD signals acquisition and processing. The CPLD chip xc95288 from Xilinx is also essential in the acquisition design. Due to the pipeline sampling strategy of selected ADC chip ADS807, CPLD is more effective to supply with the control logic between the ADC and memory storage buffer.

The PD signals are transmitted to the data acquisition part after amplification and hardware filtering. The four ADCs, which are controlled by CPLD, sample the PD signals at a sample rate up to 50MHz. CPLD supplies ADCs with the read/write time sequence and sampling clock.

The sampling results come from the ADCs are transferred to SRAM memory mounted on the virtual data-bus of CPLD. Due to the compact interconnection among the ADCs, CPLD and SRAM, the one-shot continuous sampling procedure runs up to several tens of AC power voltage cycles. The SRAM acts as a data buffer, and then the data are fetched by DSP. It performs some necessary data pre-processing like data aligning and so on. An ethernet interface is attached to the peripheral of DSP. All the sampling result data are transmitted to the signal processing unit via ethernet for further data analysis.

Because of the high correlation between PD phenomenon and the energized power phase position, it is necessary to trigger the PD sampling process by the fixed power phase angle. The AC supply voltage enters to a comparator, and a square waveform with the same frequency is formed consequently. The rising edge of the square waveform is used to start the PD signals sampling, which helps to synchronize the results with energized power phase angle.

3.4 Software Implementation

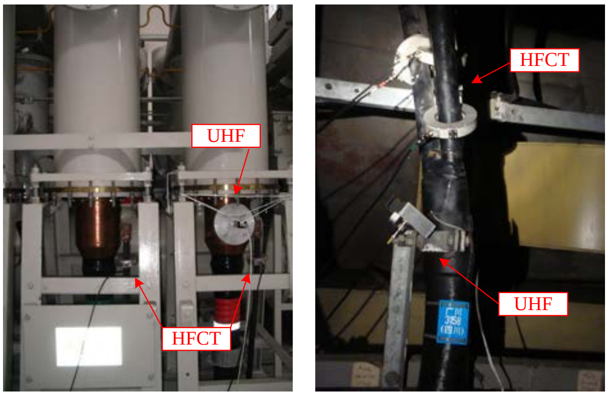
The main work of the DSP consists of two parts, i.e. the necessary pre-processing algorithm for the sample data and communication with the signal processing unit.

As the chosen of high performance DSP from TI, the program of the DSP is debugged and executed on the Code Composer Studio (CCS) development platform. The program written in C language can be synthesized, and then an executable file is generated. The file is burned into the flash in the data acquisition system for the auto boot-loader implementation of DSP.

The signal processing unit consists of a laptop computer, which is embedded into the portable PD monitoring device. Application software with graphic user interface is developed on the Visual Studio platform using C# language. The acquired PD signals are analysed and the results are shown by the developed software.

4 On-site Experiments

Many on-site experiments were carried out to evaluate the efficiency and performance of the PD monitoring technique combined with HFCT and UHF method. The experiment equipment is set up differently according to the on-site situation as shown in Fig. 8. Some insulation defects are found out through these tests to prevent further degradation.



(a) (b)

Fig. 8 On-site PD testing sensors installation on HV and MV cable terminations, (a) 220kV cable termination; (b) 35kV cable termination.

4.1 Case Study A

Because of the high insulation requirement of high voltage cable, the three phases of 220kV power cables are normally laid separately. In the test shown in Fig. 8 (a), two HFCTs are placed around the earthing strap of phase B and C respectively. One UHF sensor is placed near the disc insulator between cable termination and GIS chamber. The experimental set-up of the portable PD monitoring device, HFCT and UHF sensors are depicted in Fig. 9.

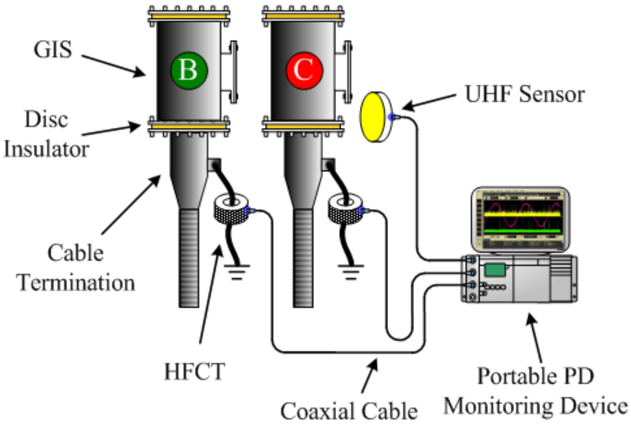
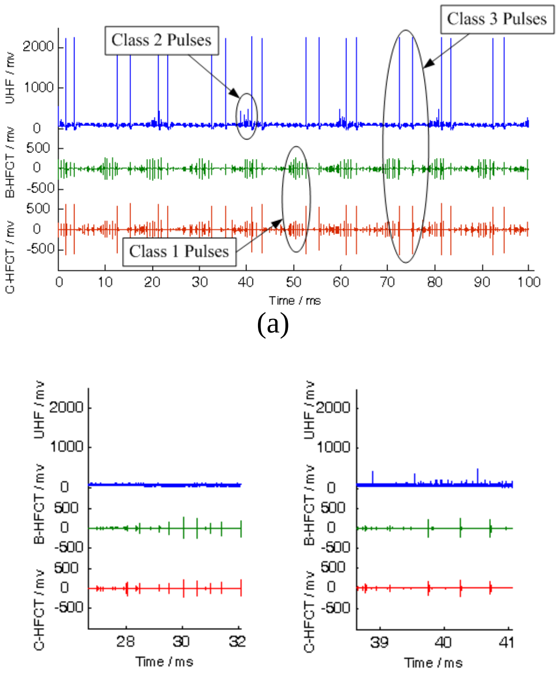


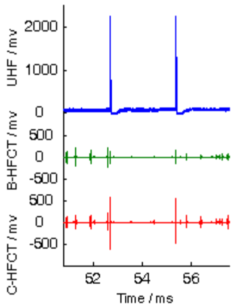
Fig. 9 Experiment set-up of PD detection on 220kV GIS cable termination.

After comparing the signals of HFCT and UHF sensors, some summing-ups can be drawn based on the amplitude and occurrence timing characteristics of the pulses. Three different classes of pulses can be distinguished from each other as illustrated in Fig. 10 (a).



(a)

(b) (c)



(d)

Fig. 10 Signals comparison between HFCT and UHF sensor, (a) multi periods observation; (b) type 1 pulses; (c) type 2 pulses; (d) type 3 pulses.

Detail of type 1 is shown in Fig. 10 (b). These pulses just exist in HFCT coupled signals, while no pulses appear at the same time in UHF signals. Moreover, the pulses present its repetition rate in accordance with energized power frequency about 50Hz. This kind of pulses should be judged as outer interference from other power apparatus in the station through grounding bar.

Detail of type 2 is shown in Fig. 10 (c). In contrast to type 1, the pulses in type 2 just exist in signals of UHF channel and none in that of HFCT. No pulse appears in HFCT implies that the source has no electrical contact with the cable termination. Thus, the pulses coupled by UHF sensor should be judged as outer EM wave interference through ambient air. One cluster of pulses occurs in one AC power cycle. After all, it is found to be the interference induced by daylight lamp.

Detail of type 3 is shown in Fig. 10 (d). There are pulses exist at the same moment in all the channels. The signals from HFCT mean that the discharge source has electrical contact with the cable termination. Because of the fast attenuation feature of EM wave transmission in air, those pulses from UHF sensor imply that the source locates close to the sensor position, and not far away from the cable termination.

More details can be inferred to reveal the PD source location from Fig. 10 (d). Firstly, all of the class 3 pulses detected by the UHF sensor, two HFCTs of phase B and C happen at the same moment, so it can be presumed that the PDs are of the same source. Secondly, the pulses amplitude of phase C is larger than that of phase B, which means that the PD source is closer to the cable termination of phase C. The pulse signals from phase B HFCT are supposed to originate from the cross-linked grounding box, where all the earthing strap of three phases joint together to ground. Finally, the pulses distribute in great relation with the phase angle of energized voltage, and the defect point should locate inside the cable termination.

Based on the above discussion of type 3 pulses, it is possible to locate the PD source more accurately. The UHF sensor moves around the cable, cable termination and connected GIS chamber. After the amplitude comparison of detected pulses from different position, the PD source is located at the cable termination.

4.2 Case Study B

The three-phase cables rated 35kV are normally assembled together to reduce occupation space. There is only one earthing strap coming from the cable termination, twisted with all shielded screen of three cables. The PD current from three phases is mixed through the only strap. So as to distinguish the PD current phase from phase, it is more effective to place the HFCTs around the branch cables. Moreover, a UHF sensor is placed nearby the termination to compare with signals from HFCT as shown in Fig. 8 (b).

The portable PD monitoring device acquired signals of 3-channel HFCTs and 1-channel UHF sensor, and the testing installation is shown in Fig. 11.

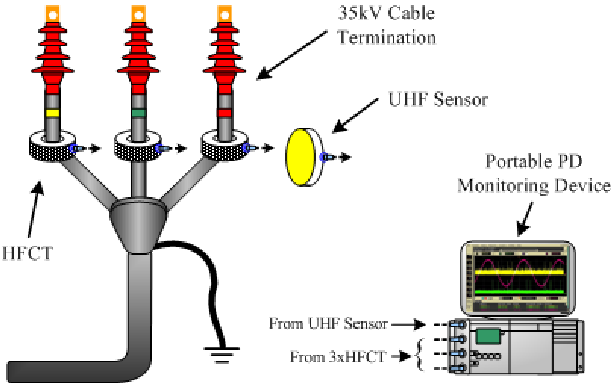


Fig. 11 Experiment set-up of PD detection on 35kV cable termination.

The comparison between UHF sensor and phase C HFCT is depicted in Fig. 12. It is clearly that most of the pulses of these two sensors correspond exactly at the same time. Because The EM wave cannot transmit for a long distance, Fig. 12 confirms that the PD source is not far away from the termination.

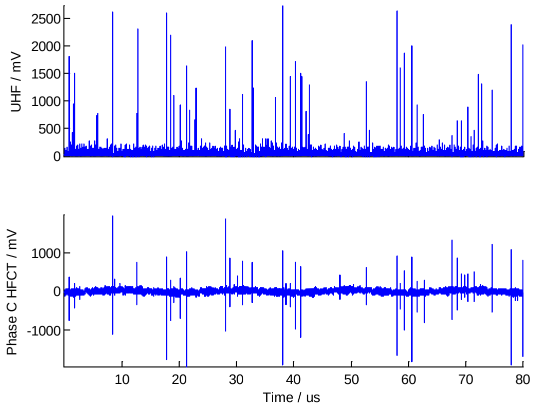


Fig. 12 Signals from the UHF sensor and HFCT of phase C.

Additionally, the signals of three-channel HFCTs are compared in Fig. 13. Firstly, the pulse magnitude of phase A and phase B are almost the same from 400 to -200 mV, while that of phase C is larger within the range from 2000 to -1000 mV. The onset pulse polarity of phase C is positive, which is different from the other two of negative.

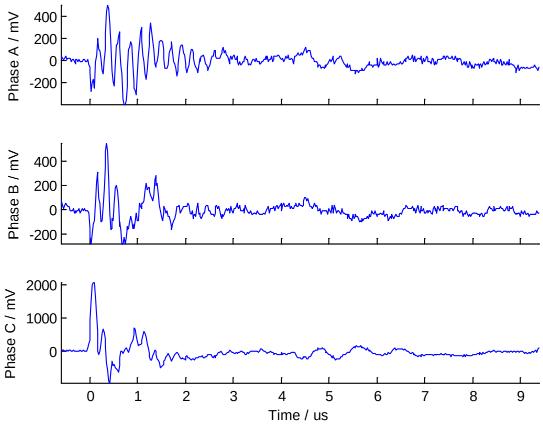
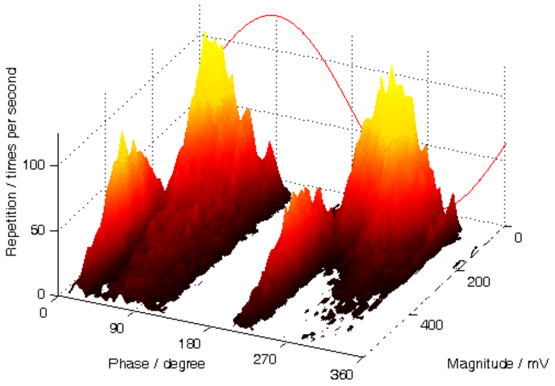


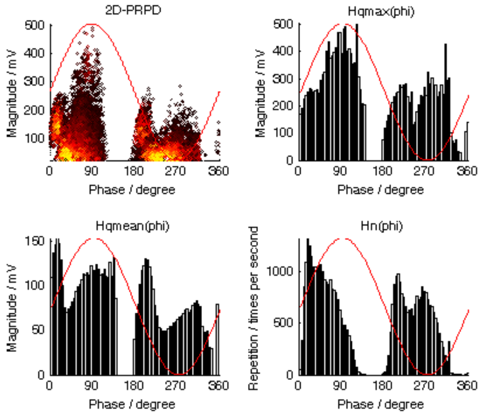
Fig. 13 Three HFCT signals of phase A, B and C.

These above points convinced that there is a PD source located insight the phase C cable termination. Moreover, the phase-resolved partial discharge (PRPD) analysis technique is employed to classify the insulation defect type. The PRPD is useful in the partial discharge pattern recognition. Plotted according to the Phi-Q-N matrix, PRPD spectrums illustrate the PD signals feature clearly. The portable PD monitoring device acquires PD signals from the HFCT of phase C, which is suspected having PD event. The acquisition procedure continues for a short duration of about several minutes to supply with abundant samples. Pulses are extracted from the signals after essential filtering. The Phi-Q-N matrix is calculated according to the phase angle and magnitude information. The deduced three-dimensional PRPD graph is plotted in Fig. 14 (a). Based on the Phi-Q-N matrix, several two-dimensional statistical distributions are deduced as follows,

- Hqmax ~ Phi, the maximum pulse magnitude - phase distribution.
- Hn ~ Phi, the pulse count - phase distribution.
- Hn ~ Q, the pulse count - magnitude distribution.



(a)



(b)

Fig. 14 PRPD spectrum of phase C PD events, (a) three dimensional PRPD; (b) two dimensional statistical distributions consist of two dimensional PRPD, Hqmax(Ph), Hn(Phi) and Hn(Q).

All these statistical spectrums are depicted in Fig. 14 (b), in which the phase-resolved characteristics can be observed. Firstly, the distributions are of strong relation with the energized power phase. Secondly, there is highly correlation between the positive half and negative half of sinusoidal voltage wave. And lastly, the PD events distributes mostly in the first and third quadrants, which indicate the rising slope of energized voltage. This kind of statistical features has typical PD characteristics. This PD should be aroused by void or cavity defect in the insulation materials.

5 Conclusion

To perform PD detection more precisely and improve test reliability, two different methods including HFCT and UHF sensors are utilized in this paper. A portable PD monitoring device is developed to meet the requirements of on-site PD tests. According to the different bandwidth and transmission paths, signal conditioning circuits are designed for HFCT and UHF acquired signals respectively. Proposed DSP-CPLD structure based high-speed data acquisition system is designed to obtain the PD signals continuously. Digital data processing unit applies filtering and pulses extraction, and employs further data analysis techniques.

On-site experiments are carried out to verify the performance of the developed portable PD monitoring device. Combination of selected HFCT and UHF channels is utilized to pick up the PD events inside HV and MV cable terminations. Two example cases are investigated. The field test results show that the proposed comparison method between HFCT and UHF signals affirms the PD happening and source location. Advanced PRPD analysis is also used to recognize the PD pattern.

References:

[1] Montanari, G. C., Partial discharge measurements: becoming a fundamental tool for quality control and risk assessment of electrical systems, *IEEE Int. Symp. on Electrical Insulation*, Toronto, Canada, 2006.

[2] Gulski, E., Cichecki, P., Wester, F., et al., On-site testing and PD diagnosis of high voltage power cables, *IEEE Trans. on Dielectrics and Electrical Insulation*, Vol.15, No.6, 2008, pp.1691-1700.

[3] Meijer, S., Agoris, P. D., Gulski, E., et al, Condition Assessment of Power Cable Accessories using Advanced VHF/UHF PD detection, *IEEE Int. Symp. on Electrical Insulation*, 2006.

[4] Markalous, S., Tenbohlen, S. and Feser, K., Detection and location of partial discharges in power transformers using acoustic and electromagnetic signals, *IEEE Trans. on Dielectrics and Electrical Insulation*, Vol.15, No.6, 2008, pp.1576-1583.

[5] Tian, Y., Lewin, P. L., Davies, A. E., et al, Acoustic Emission Techniques for Partial Discharge Detection within Cable Insulation, *IEE Eighth Int. Conf. on Dielectric Materials, Measurements and Applications*, 2000.

[6] Zhang, H., Blackburn, T. R., Phung, B. T., et al, A novel wavelet transform technique for on-line partial discharge measurements. 1. WT de-noising algorithm, *IEEE Trans. on Dielectrics and Electrical Insulation*, Vol.14, No.1, 2007, pp.3-14.

[7] Lemke, E., Strehl, T., Markalous, S., et al, Ultra-wide-band PD diagnostics of power cable terminations in service, *IEEE Trans. on Dielectrics and Electrical Insulation*, Vol.15, No.6, 2008, pp.1570-1575.

[8] Zhang, Z. S., Xiao, D. M. and Li, Y., Rogowski air coil sensor technique for on-line partial discharge measurement of power cables, *IET Science, Measurement & Technology*, Vol.3, No.3, 2009, pp.187-196.

[9] Zhou, Y., Qin, Y. and Chappell, P., Cost-effective on-line partial discharge of measurements for cables, *IEEE Electrical Insulation Magazine*, Vol.22, No.2, 2006, pp.31-38.

[10] Lemke, E., Gulski, E., Hauschild, W., et al, Practical aspects of the detection and location of PD in power cables, *CIGRE WG D1.33*, Paris, 2006.

[11] Tenbohlen, S., Denissov, D., Hoek, S., et al, Partial discharge measurement in the ultra high frequency (UHF) range, *IEEE Trans. on Dielectrics and Electrical Insulation*, Vol.15, No.6, 2008, pp.1544-1552.