Investigation on Partial Discharge of Power Cable Termination Defects using High Frequency Current Transformer

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ABSTRACT

This paper presents partial discharge (PD) investigation of different cable termination defects. The medium voltage power cables as rated of 3.6/6(7.2) kV are applied. Finite Element Method Magnetic (FEMM) program is used as a simulation tool for electric field stress investigation. The partial discharges patterns are detected by using a commercial High Frequency Current Transformer (HFCT). The simple cases for internal, surface and corona discharge are firstly observed in order to investigate the performance of the HFCT. Then eight different case studies of cable termination defects are further investigated, which includes non-terminator, voids between XLPE and stress control, 20 mm. overlaps between semiconductor and stress control, particles on XLPE, non-smooth XLPE, needle tip on insulation screen, impropriate cable bending, and proper termination. The results are then compared with the results from a conventional PD diagnosis tool according to IEC 60270 standard. The results of PD detection show that the commercial product can detect the PD waveform and measure the electric charge when it is highly enough. The test can also identify trends toward breakdown and there severity due to improper cable termination defects.

Keywords: Cable termination, PD measurement, electric charge, high frequency current transformer, inception voltage, partial discharge.

1. INTRODUCTION

In Thailand, electric distribution system in metropolitan area is significantly expanding to serve the increasing of power demand. Not only new distribution facilities need to be constructed but also existing ones must be renovated. The underground cable is introduced to distribution system with the reasons of reducing engineering problems such as maintenance cost, electric field emission, system reliability and security as well as creating less visual and environmental impact. The previous study revealed that although underground distribution system is presumably reliable comparing to overhead counterpart, but failures of underground cable system cause considerably longer repair time. Proper cable termination and joint are vital for reliable delivery of electricity.

Therefore, in this paper, the partial discharge (PD) measurement using commercial High Frequency Current Transformer (HFCT) is performed to investigate discharge pattern and PD inception voltage of various cases of cable defects due to human error. The FEMM program is used as a simulation tool in order to investigate electric field stress in cable termination. The trend toward breakdown of different defects is additionally analysed. Consequently, the human error during cable terminator installation leading to termination defects result in faster degradation of terminator due to high electric stress in the detected area.

2. PARTIAL DISCHARGE INVESTIGATION

A. Type of Partial Discharge

Partial discharge consists of internal discharge, surface discharge, and air corona [1]. Internal discharges occur at dielectric with a number of cavities of various sizes inserted between two carbon or metal electrodes. The discharge occurs when the supply voltage is higher than the inception voltage of cavities. Surface discharge takes place externally along the insulation surface between two metalic or carbon electrodes. External corona discharge occurs at a sharp metalic point. If the discharges occur on the negative half cycle of the sinusoidal test waveform, the location of sharp edge is at high voltage side. On the other hand, if the discharges occur on the positive half cycle of the sinusoidal test waveform, the location of sharp edge is at the earth potential.

B. Partial Discharge Detection

Partial discharge detection for HV equipment such as power transformer, power cable, and etc. can be classified into two types that are on-line monitoring and off-line monitoring. The on-line testing techniques [2]-[3] are such as ultrasonic PD detection [4], acoustic sensor [5]-[6] and HFCT [7]-[10] while the off-

Manuscript received on November 19, 2013 ; revised on January 6, 2014.
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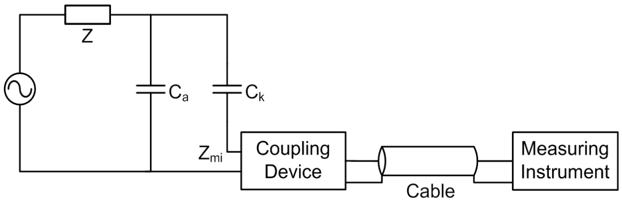
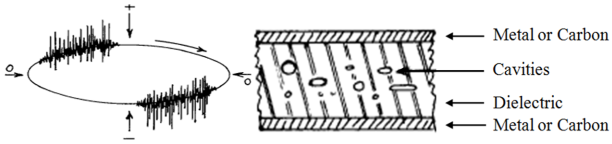


Fig.1: *Basic IEC 60270 Discharge Detection Circuit.*

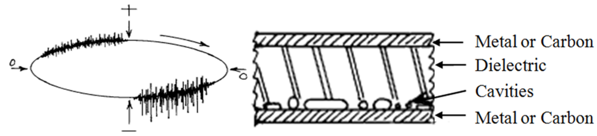
line testing techniques [11] are as high potential testing, IEC60270 [12] conventional PD detector, power factor/dissipation factor testing, radio frequency testing [13]. Those PD detection tools help to detect the abnormal condition at the beginnings of either small partial discharge, mechanic problems, arcing, surface contact of HV equipment. Moreover, these tools can identify the problem's causes and severity. Then the maintenance can be properly acted.

Partial discharge detection tecniques according to IEC 60270 standard [13], known as conventional method, is widely accepted with the highest accuracy. This technique can describe the phenomena of internal discharge, surface discharge, and air corona. The test circuit is represented in Fig. 1.

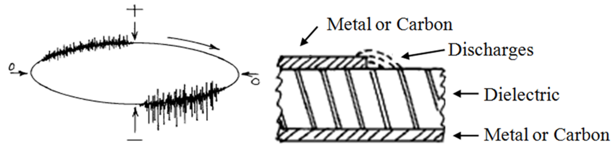
The circuit consists of coupling capacitor (C_k), filter (Z), input impedance of measuring system (Z_{mi}), connecting cable, coupling device, measuring instrument and test object (C_a). Then, the discharge patterns can be observed. Some examples on discharge patterns in [1] are given in Fig. 2.



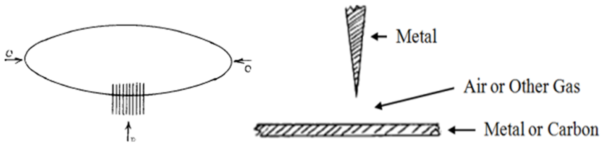
(a) Internal Discharge in Dielectric Voids



(b) Internal Discharge in Voids between Dielectric and Carbon



(c) Surface Discharge between Dielectric and Carbon



(d) Corona Discharge

Fig.2: *Examples on Discharge Patterns [1].*

3. EXPERIMENT SETUP

In this paper, the off-line partial discharge detection in cable termination defects is proposed by using conventional diagnostic tool. The test circuit in the HV laboratory is shown in Fig. 3 and Fig. 4. It consists of 100kV test transformer, capacitive voltage divider, conventional PD detector using the IEC 60270 standard (ICMsystem), and test object as cable. Additionally, the commercial HFCT is installed and used to measure the PD patterns. The HFCT results will be compared with the conventional diagnostic tool.

A. Simple Test Cases

The four simple test objects for internal discharge, surface discharge, HV needle and earth needle are firstly applied as presented in Fig. 5.

B. Power Cable Defects

Eight different simulated cable defects are modeled in this paper as given in Fig. 6 in order to investigate the partial discharge phenomena as well as breakdown trend and severity of each type of terminator defects due to human error during cable terminator installation.

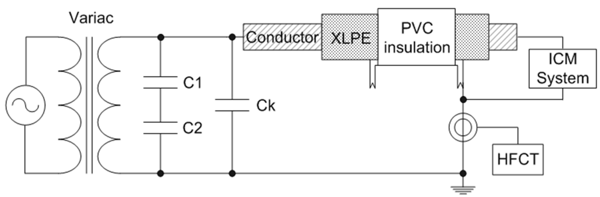


Fig.3: *PD Testing Circuit Equivalent.*

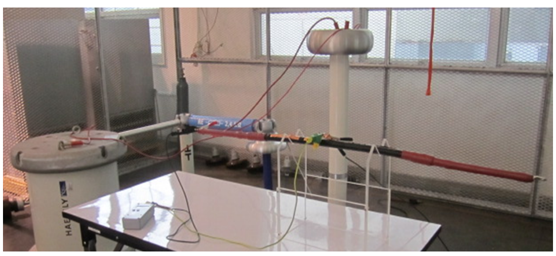
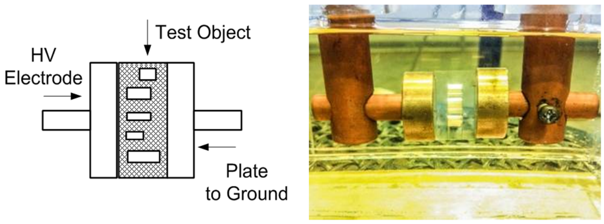
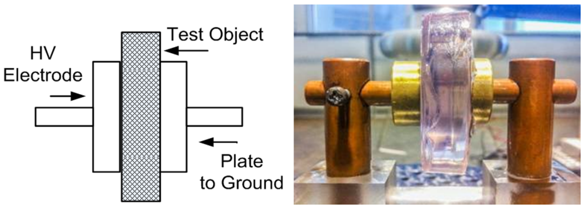


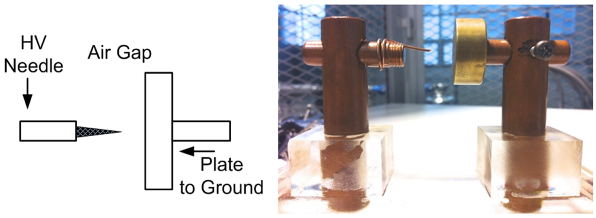
Fig.4: *PD Test Circuit Set Up in HV Laboratory.*



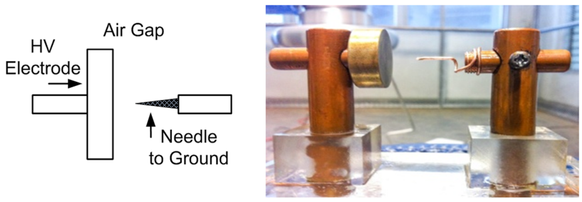
(a) Case 1: Internal Discharge



(b) Case 2: Surface Discharge

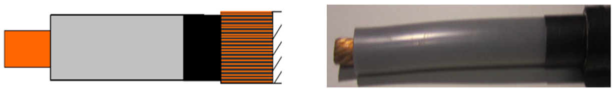


(c) Case 3: HV Needle Corona



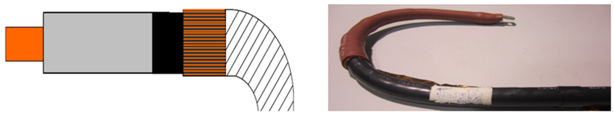
(d) Case 4 : Earth Needle Corona

Fig.5: *Simple Test Objects.*

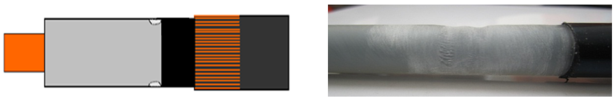


1. Non-stress Control

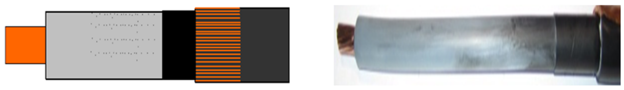
2. Stress Control Position



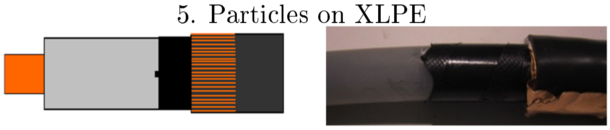
3. Bending Radius



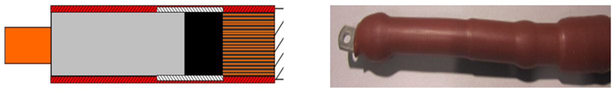
4. Sandpaper Insulation



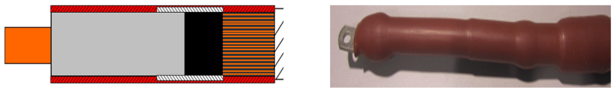
5. Particles on XLPE



6. Needle Tips at Screen



7. Insulation Roughness



8. Proper Termination

Fig.6: *Eight Different Cable Termination Defects.*

*Case*1 : *Non − stress control* : This case is modelled without stress control for reducing electric field stress.

*Case*2 : *Improper stress control position* : Improper installed position by sliding 20 mm. out from installation standard due to viciousness of worker.

*Case*3 : *Small bending radius* : In some place, the sharp bending of power cable is inevitably required that causes air gap inside in terminator.

*Case*4 : *Effect of sandpaper* : Sandpaper for scrubbing insulation screen causes small insulation damage and voids.

*Case*5 : *Particle on XLPE* : Unclean XLPE skin causes dust and semiconductor particles contaminated on XLPE.

*Case*6 : *Needle tip on screen* : Improper removing of outer-semiconductor screen causes needle tip.

*Case*7 : *Insulation roughness* : Using machine for removing outer-semiconductor produces non-smooth XLPE skin.

*Case*8 : *Proper termination* : According to installation standard and practice.

Using the test circuit in Fig. 4, the voltage from test transformer is raised until the PD occurs. The acquisition period is 10 seconds for any test. The test voltage is applied in sinusoidal waveform. Then, the discharge is detected by ICMsystem and displayed in form of dots as well as charge intensity whereas the discharge detected by HFCT is displayed in form of voltage spite with respect to sinusoidal waveform.

4. SIMULATION RESULTS BY FEMM

The electric field stresses of eight simulated defects of cable terminators were observed by using Finite Element Method Magnetic (FEMM) program in order to investigate electric field stress, voltage distribution as well as the critical point in cable termination, which is expected to be the initial cause of partial discharge and breakdown. Fig. 7 on the left shows the recommended dimension of each layers of the power

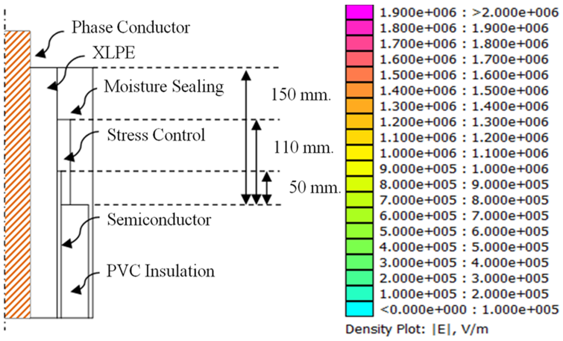


Fig.7: *Layers of Cable Termination and EFD.*

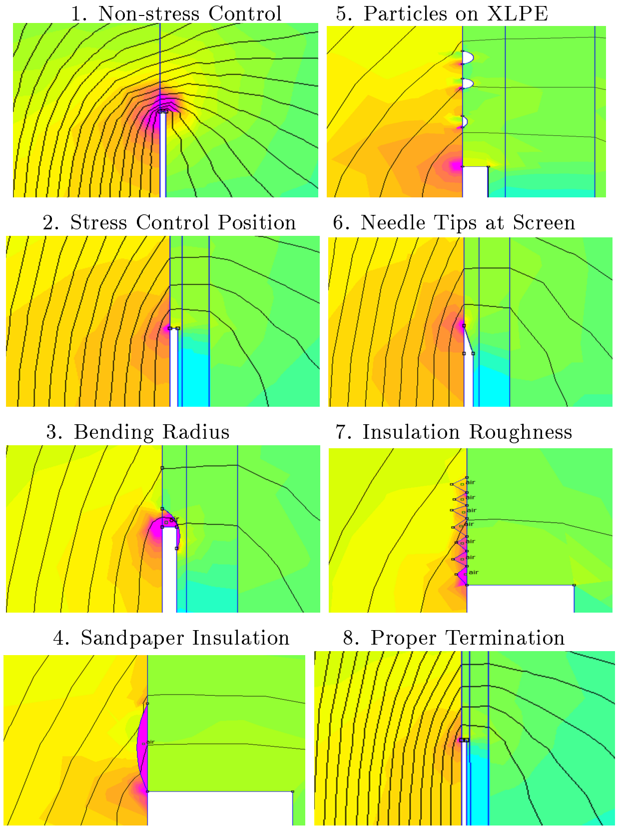


Fig.8: *Electric Field Patterns by FEMM.*

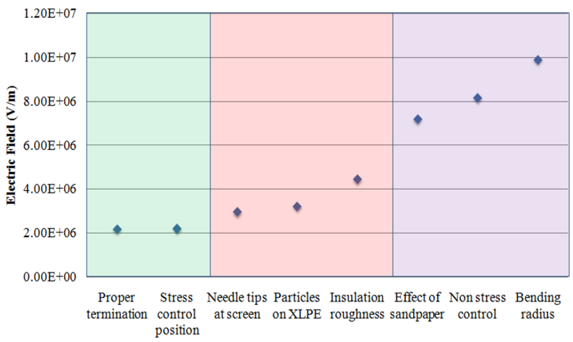


Fig.9: *Highest Electric Field Stresses of Different Termination Defects Observed by FEMM.*

cable rating 3.6/6(7.2) kV, which should be prepared before cable termination installation.

Cable rated 3.6/6(7.2) kV are specified as $U_0/U(U_m)$, where U_0 is cable nominal voltage between conductor and metal covering or earth, U is cable nominal voltage between the phase conductors for 3-phase and U_m is the maximum permissible voltage.

The edge of outer semiconducting shield, which is at ground potential, is expected to be the weakest point due to the highest electric field stress. Therefore, it should be covered by the stress control is used in order to reduce the electric filed stress at that point. Similarly, Fig. 7 on the right hand shows the relationship between the colour shades and the range of electric field density (EFD) from FEMM simulation. By applying the FEMM to eight termination defects, the simulated results are shown in Fig. 8.

The result in Fig. 8(1) shows that the edge of outer semiconducting shield is the weakest point due to the highest electric field stress as displayed by pink colour with the stress more than 1.9 MV/m. In Fig. 8(2) the stress control can reduce the magnitude of electric field stress at the edge of semiconducting shield. For bending radius, sand paper, particles on insulation and insulation roughness, the electric field stress in void is greater than that in the insulation as shown in Fig. 8(3), 8(4), 8(5) and 8(7) due to its lower permittivity. Then the highest electric field stress occurs in void and at the edge of outer semiconducting shield. The needle tip at screen or outer semiconducting shield has the highest electric field stress as expected due to its smaller surface area. The proper installation of cable terminator can reduce the high electric field stress at the edge of semiconducting shield as shown in Fig. 8(8).

Fig. 9 presents the highest electric field stress of all defects from the FEMM. The results show that highest stresses occur at the end of semiconductor in cases of cable bending and non-stress control. In addition, whenever there are voids in cable termination, they certainly produce the stress in termination due to voids, especially the bigger voids caused from sandpaper during semiconductor cutting and XLPE insulation roughness as well as some particles remain in between insulation and stress control. Cases of 20 mm. stress control overlap and semiconductor in curve shape produce lower electric field stress than other cases whereas the cable bended more than standard produce the highest stress.

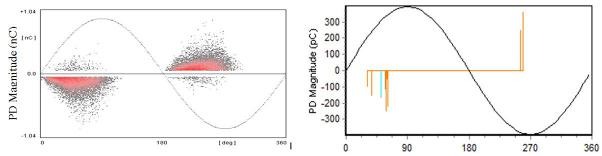
5. EXPERIMENTAL RESULTS

A. PD Detection of Simple Test Objects

The results of PD detection using HFCT are compared with the results from the conventional diagnostic tool according to IEC60270 standard. The results of four simple test cases; internal discharge, sur-

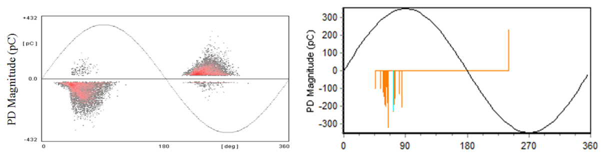
Table 1: *Initial PD Detection Voltage and Electric Charge.*

Case	Defects	Detection Voltage (kV)	Electric Charge (pC) by ICMsystem	Electric Charge (pC) by HFCT
1	Internal	10.62	380.00	356.91
2	Surface	8.35	235.56	226.45
3	HV needle	4.36	500.00	501.31
4	GND needle	4.88	710.00	843.45



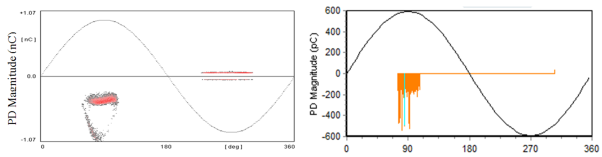
(a) Detected by ICM system (b) Detected by HFCT

Fig.10: *Internal Discharge.*



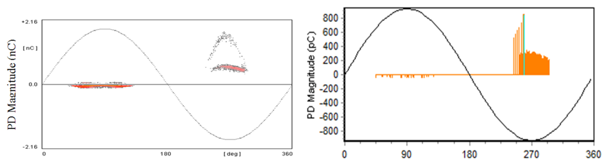
(a) Detected by ICM system (b) Detected by HFCT

Fig.11: *Surface Discharge.*



(a) Detected by ICM system (b) Detected by HFCT

Fig.12: *HV Needle Corona.*



(a) Detected by ICM system (b) Detected by HFCT

Fig.13: *Earth Needle Corona.*

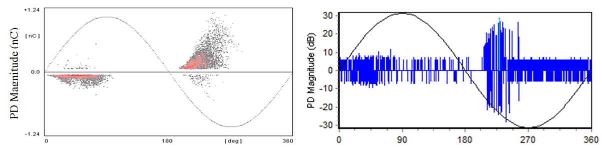
face discharge, HV needle, and earth needle cases, are given in Table 1. The results show that the HFCT can detect the PD patterns and electric charge that are confirmed by the results from the conventional diagnostic tool as shown in Fig. 10 to Fig. 13. However, the HFCT can clearly detect only when the number of electric charge in pC. is high enough while the conventional tool can sensitively detect the inception voltage and electric charge.

B. PD Detection of Cable Termination Defects

For eight cases of cable termination defects, the accurate inception voltage and electric charge of all cases can be detected only by using the conventional tool. The results are given in Table 2. After that the measurement using HFCT has been performed and its result is presented in Table 3.

Table 2: *PD Inception Voltage and Electric Charge of Cable Termination Defects by Conventional Tool.*

Case	Termination Defects	Inception Voltage (kV)	Electric Charge (pC)
1	Non-stress control	4.06	44.00
2	Stress control position	14.65	33.00
3	Bending radius	12.64	11.80
4	Using sandpaper	16.18	15.00
5	Particles on XLPE	15.10	37.25
6	Needle tips at screen	9.70	37.00
7	Insulation roughness	8.13	41.18
8	Proper cable termination	16.02	29.40



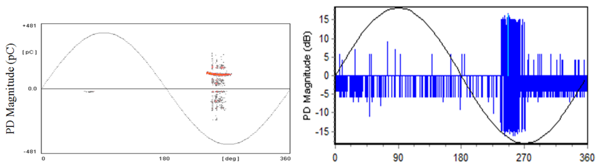
(a) Detected by ICM system (b) Detected by HFCT

Fig.14: *Effect of Non Stress Control.*

However the comparison of electric charge measured by both tools is not possible due to the difference in detection principle. This shows that the conventional tool has better sensitivity than the HFCT. Moreover, the phase resolved measurement results from both tools for 8 cases are presented from Fig. 14 to Fig. 21 in order to compare the discharge pattern. It is clearly seen that the detected PD patterns from both tools are similar and imply the combination of internal and surface discharge phenomena.

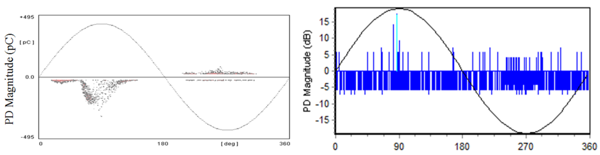
Table 3: *PD Voltage and Electric Charge of Cable Termination by HFCT.*

Case	Termination Defects	Detection Voltage (kV)	Electric Charge (pC)
1	Non-stress control	5.50	10.00
2	Stress control position	17.75	22.97
3	Bending radius	16.60	15.59
4	Using sandpaper	17.60	13.95
5	Particles on XLPE	17.27	33.64
6	Needle tips at screen	12.24	10.67
7	Insulation roughness	15.30	14.77
8	Proper cable termination	18.36	19.69



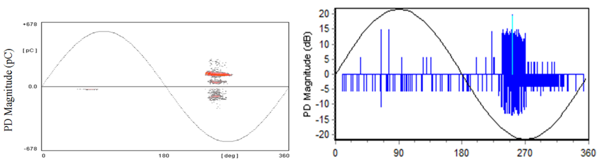
(a) Detected by ICM system (b) Detected by HFCT

Fig.15: *Effects of Stress Control Position.*



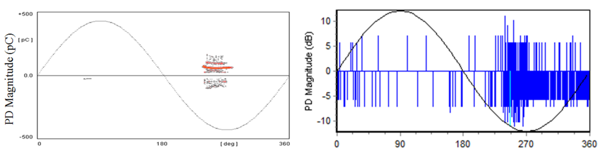
(a) Detected by ICM system (b) Detected by HFCT

Fig.16: *Effect of Bending Radius.*



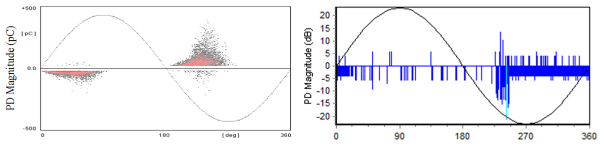
(a) Detected by ICM system (b) Detected by HFCT

Fig.17: *Effect of Using Sandpaper.*



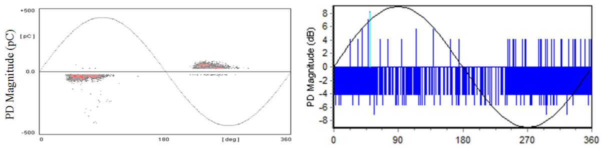
(a) Detected by ICM system (b) Detected by HFCT

Fig.18: *Effect of Particle on XLPE.*



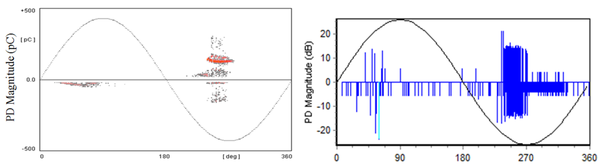
(a) Detected by ICM system (b) Detected by HFCT

Fig.19: *PD Effects of Needle Tips at screen.*



(a) Detected by ICM system (b) Detected by HFCT

Fig.20: *Effect of Insulation Roughness.*



(a) Detected by ICM system (b) Detected by HFCT

Fig.21: *Proper Cable Termination.*

The trend of breakdown voltage is presented in Fig. 22 by plotting the relationship between the discharge voltages and electric charge of all cases. The trends are differentiated into three groups. The most severe group is case of non-terminator. The partial discharges occurred around the range of rated voltage and increased significantly with the slight increasing of the supply voltage. The second group consists of needle tip on insulation screen and insulation roughness. In this group, the partial discharges occurred when the supply voltage was increased between two to three times of the rated voltage. The last group includes the cases of 20 mm. overlaps between semiconductor and stress control, particles on XLPE, impropriate cable bending, non-smooth XLPE, and voids between XLPE and stress control. The good cable termination can withstand the highest voltage up to 16.02 kV. Thereafter, the partial discharge occurred.

6. CONCLUSIONS

The medium voltage power cables as rated of 3.6/6 (7.2) kV are used in the measurement. Eight different case studies of cable termination defects are investigated. The voltage partial discharge pattern and electric charge in different cases obtained from HFCT measurement are compared with that from conventional tool. The results of partial discharge measurements show that the HFCT can detect the discharge pattern and electric charge when the supply voltage was raised highly enough. Comparing to conventional

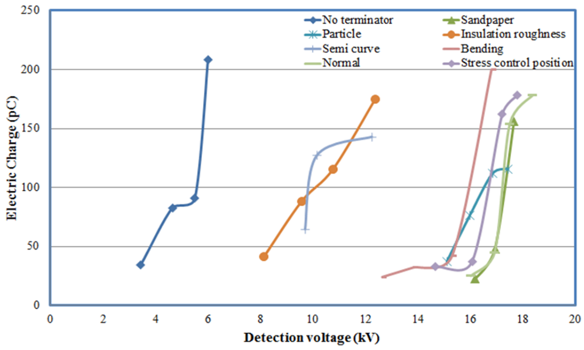


Fig.22: *Trend of Breakdown Voltage of Cable Termination Defects.*

tool, the commercial HFCT cannot detect due to its poor sensitivity the inception voltage. The severity of the terminator defects, subsequently causing the future power outage, can be differentiated into three groups. Non-terminator case is the most severe. The cases of particles on XLPE and insulation roughness are in the second severe group, whereas cases of needle tip on insulation screen, impropriate cable bending, voids between XLPE and stress control, 20 mm. overlaps between semiconductor and stress control as well as effect of using sandpaper third severe group. The FEMM simulation results also show the severities of cable termination defects.

In the conclusion, human error during cable terminator installation leading to cable termination defects can cause the fast degradation of cable terminator because of high electric stress and partial discharge. Different case studies show the severity of defects aiming to create a good understanding and awareness of the problem to whom involving in the cable installation.

7. ACKNOWLEDGMENTS

The authors thank the Faculty of Engineering, King Mongkut's University of Technology North Bangkok, Thailand for financial support as well as the Construction Department and the Research and Development Department of Metropolitan Electricity Autholity (MEA) for supporting the commercial HFCT and test objects.

References

[1] CIGRE Working Group 21.03, "Recognition of discharges," *Electra*, no. 11, Dec. 1969, pp. 61-98.

[2] R.-N. Wu, and C.-K. Chang, "The use of partial discharges as an online monitoring system for underground cable joints," *IEEE Trans. Power Del.*, vol. 26, no. 3, pp. 1585-1591, Jul. 2011.

[3] X.J. Shen, and X.C. Jiang, "Development of online monitoring system for 1500 V ethylene-propylene-rubber DC feeder cable of Shanghai urban rail transit generation," *IET Transmission Distribution*, vol. 5, no. 7, pp. 720-728, Jul. 2011.

[4] L. Yongfen, J. Shengchang, and L. Yanming, "Phased-Ultrasonic Receiving-planar array transducer for partial discharge location in transformer," *IEEE Trans. Ultrason., Ferroelectrics Frequency Control*, vol. 53, no. 3, pp. 614-622, Mar. 2006.

[5] L.-J. Chen, T.-P. Tsao, and Y.-H. Lin, "New diagnosis approach to epoxy resin transformer partial discharge using acoustic technology," *IEEE Trans. Power Del.*, vol. 20, no. 4, pp. 2501-2508, Oct. 2005.

[6] W. Xiaodong, L. Baoqing, Roman H.T., O. L. Russo, K. Chin, and K. R. Farmer, "Acousto-Optical PD detection for transformers", *IEEE Trans. Power Del.*, vol. 21, no. 3, pp. 1068-1073, Jul. 2006.

[7] S. Birlasekaran, and W. H. Leong, "Comparison of known PD signals with the developed and commercial HFCT sensors," *IEEE Trans. Power Del.*, vol. 22, no. 3, pp. 1581-1590, Jul. 2007.

[8] A. Rodrigo, P. Llovera, V. Fuster, and A. Quijano, "Influence of high frequency current transformers bandwidth on charge evaluation in partial discharge measurements," *IEEE Trans. Dielectrics Elect. Insulation*, vol. 18, no. 5, pp. 1798-1802, Jun. 2011.

[9] F.P. Mohamed, W.H. Siew, J. J. Soraghan, S. M. Strachan, and J. Mcwilliam,"The use of power frequency current transformers as partial discharge sensors for underground cables," *IEEE Trans. Dielectrics Elect. Insulation*, vol. 20, no. 3, Oct. 2013.

[10] S. Birlasekaran, and W. H. Leong, "Comparison of known PD signals with the developed and commercial HFCT sensors," *IEEE Trans. Power Del.*, vol. 22, no. 3, pp. 1581-1590, Jul. 2007.

[11] G.C. Montanari, A. Cavallini, and F. Puletti,"A new approach to partial discharge testing of HV cable systems," *IEEE Elect. Insulation Mag.*, vol. 22, no. 1, pp. 14-23, Jan/Feb. 2006.

[12] A.J. Reid, M.D. Judd, R. A. Fouracre, B.G. Stewart, D. M. Hepburn,"Simultaneous measurement of partial discharges using IEC60270 and radio-frequency techniques," *IEEE Trans. Dielectrics Elect. Insulation*, vol. 18, no. 2, pp: 444-455, Apr. 2011.

[13] IEC Standard 60270, *High Voltage Test Techniques-Partial Discharge Measurements*, Ed. 3rd, 2000.

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