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Diagnosis of Medium Voltage Cables for Nuclear Power Plant

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Abstract – Most accidents of medium-voltage cables installed in nuclear power plants result from the initial defect of internal insulators or the initial failure due to poor construction. However, as the service years of plants increase, the possibility of cable accidents is also rapidly increases. This is primarily caused by electric, mechanical, thermal, and radiation stresses. Recently, much attention is paid to the study of cable diagnoses. To date, partial discharge and Tanδ measurements are known as reliable methods to diagnose the aging of medium-voltage cables. High frequency partial discharge measurement techniques have been widely used to diagnose cables in transmission and distribution systems. However, the on-line high frequency partial discharge technique has not been used in the nuclear power plants because of the plant shutdown risk, degraded measurement sensitivity, and application problems. In this paper, the partial discharge measurement with a portable device was tried to evaluate the integrity of the 4.16kV and 13.8kV cable lines. The test results show that the high detection sensitivity can be achieved by the high frequency partial discharge technique. The present technique is highly attractive to diagnose medium voltage cables in nuclear power plants.

Keywords: High frequency partial discharge, Medium voltage cable, Nuclear power plant

1. Introduction

The operating experience reveals that a defect of the insulator or poor construction causes the initial failure of a cable. However, the number of cable failures increases with plant aging within the plants' licensed period [1, 6]. These cable failures have resulted in plant transients, shutdown, loss of safety functions or redundancy, entries into limiting conditions for operation, and challenges for plant operators. Therefore, the diagnosis of MV (Medium Voltage) cables installed in the Nuclear Power Plants (NPPs) has become one of the most urgent issues in recent years. In accordance with periodic safety review, the condition monitoring and maintenance for cables is also continuously required [2-4].

In the case of MV cables, the PD (Partial Discharge) measurement is one of the recommended techniques to diagnose deterioration of a cable. Recently, the PD tests have been widely performed to diagnose cable in the transmission and distribution system. However, on-line PD has not been used in NPPs due to the risk of plant shut-downs, measurement sensitivity and application problems.

Recently, the measurement sensitivity of the partial discharge measurement technique has been innovatively improved by applying the high frequency signal processing and detecting techniques. From a number to hundreds MHz band, this techniques is called the HFPD (High Frequency Partial Discharge). In many countries as well as in Korea, the HFPD technique is applied to the high or extra-high voltage cables in use. It has been successfully applied to transmission and distribution lines, but not applied to the medium voltage lines.

In this paper, the HFPD technique is introduced, which was applied to diagnose the status of 13.8 and 4.1kV MV cables installed in nuclear power plants.

2. Aging Management of MV Cable

2.1 Aging mechanism of MV cable in nuclear power plant

The damage that can occur in nuclear power plants can be classified into the cause of damage related to the design based accident and the general cause of damage. The cause of damage related to the design based accident is from the loss of coolant accident, main steam line break, flooding and fire. The general cause of damage related to environmental factors, such as temperature, radiation, and humidity, depends on the installed location of equipment. It can induce the facility degradation and can be accelerated by twisting pressure and installation errors.

The principal aging factors of MV cables in nuclear power plants are described as follows:

a. Temperature: If a cable is exposed to high temperature for a long time, its insulation and jacket experience aging, which means that mechanical characteristics are deteriorated due to the polymer oxidation. During

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Table 1. Diagnostic technology for cable in NPPs

No.	Technique	Applied cable and materials	Descriptions
1	Direct current High-Potential test	- High voltage and low voltage cables - Insulation and jacket materials	- Whole cables are not required - Insulation cables can be damaged
2	Step voltage test (Dc high voltage)	- High voltage and low voltage cables - Insulation and jacket materials	- Whole cables are not required - Progress analysis data are provided - Insulation cables can be damaged
3	Illuminated borescope	- Cables difficult to be accessible - Insulation and jacket materials	- Able to diagnose cables that are difficult to access - Progress analysis data are not provided
4	Visual inspection	- All cables to be accessible - Insulation and jacket materials	- Simple analysis is able for damage about cable jacket - Depends on experiences and knowledge without providing quantitative data
5	Compressive modulus	- Low voltage cables - EPR, PVC, CSP, SR materials	- Accessible to cables at test - Difficult to detect deterioration point - Difficult to diagnose in case of shielded or XLPE insulation cables
6	Tanδ test	- High voltage and low voltage cables - Insulation and jacket materials	- Progress analysis data are provided - Applicable to shielded cables
7	Insulation resistance	- High voltage and low voltage cables - Insulation and jacket materials	- Able to correct depending on environmental main cause at test - Progress analysis data are provided - Unable to measure Insulation deterioration accuracy decline at special condition
8	Partial discharge test	- High voltage and low voltage cables - Insulation and jacket materials	- Able to diagnose deterioration point of cables - Skidded experiences and knowledge are required
9	Time domain reflectometry	- High voltage and low voltage cables - Insulation and jacket materials	- Deterioration point of cables and information for confirmation are required - Non-destructive test
10	Line resonance analysis	-High voltage and low voltage cables - Insulation and jacket materials	- Able to diagnose cables that are difficult to access - Skilled experiences and knowledge are required
11	Infrared imaging thermography	-High voltage and low voltage cables - Insulation and jacket materials	- Non-destructive test, able to test at operation - Data storage and able to analyze the progress - Have to be able to access to cables at test

the operation, ohmic heating may cause a temperature rise in certain areas. This kind of problem may take place in densely layered cables within a cable tray or cables used at upper limits of the rated current. If cracks exist on the degraded insulation and jacket, then conductors become exposed to the atmosphere and damaged by chloride and sulfide that are produced in the aging process of polymer.

b. Radiation: Some cables in the reactor containment building are affected by the radiation. Therefore, another layer of insulation is covered on the surface of jacket in order to reduce the effect of the radiation on those cables. Cables exposed to irradiation environment show similar characteristics in many aspects with those cables that are degraded by heat. The typical irradiation damage includes decreased mechanical characteristics and the alteration of surface conditions. The effects of aging by irradiation include treeing, craze marks, discoloration, stickiness, bubbling, and drooping.

c. Moisture: Moisture does not cause damage to cable insulation by itself, but it may accelerate the aging process if combined with other aging stressors. Moisture existing for a continued period of time may deteriorate the mechanical characteristics of already degraded cables and cause bubbling or stickiness on the surface of the insulation material.

If cracks exist on the cables, the current may flow to the ground through such cracks due to moisture. In the case of contaminated cable insulation materials, the current may also flow to the ground through such contamination, resulting in occasional short circuits.

2.2 1 Diagnostic method for cable in NPP

Because the MV cable unlike the high or EHV (extra-high voltage) cable has the metal shield layer, the penetration of water is easy and the water tree can be generated by the cable insulation and conductor. In addition, because applied voltage is lower than that in the high-voltage cable system, if there is the same type and size of defects as in high voltage cables, deterioration may not be developed there. Table 1 shows 11 kinds of diagnosis techniques for nuclear power plants are presented in the DG-1240 [9].

3. MV Cable PD Measurement in Plant

Given that the electrical equipment is not fully short circuited, if the applied voltage slowly increases to the electrodes with the unequal distribution of electric field, PD is occurring where the electrical field is concentrated in the void or the crack of insulation.

Specially, defects such as the void or contaminants in the composite insulation may be caused by PD. When applying a voltage to the dielectric of MV cable, a number of PD cause aging and eventually gives rise to the breakdown of insulating materials. The number of discharge occurrence, size, shape, and location information on the electrical breakdown are very important to evaluate the integrity of cables.

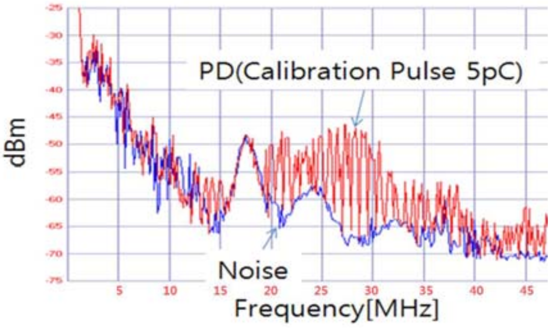
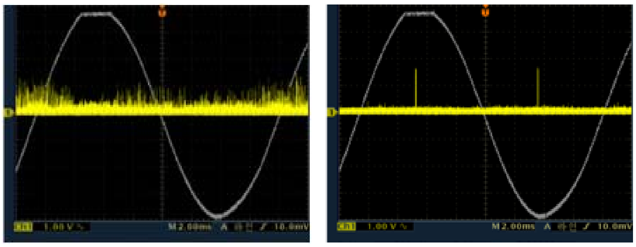


Fig. 1. Frequency spectrum of the background noise and PD pulse



(a) Low-frequency band (12MHz)

(b) High-frequency band (27MHz)

Fig. 2. Detection of partial discharge pulses by varying the frequency bands

3.1 HFPD testing

The HFPD testing is a diagnostic technique applied to electric power cables at high frequency bands(1~several hundred MHz).

The partial discharge current pulses, generated from various power equipment including power cables, have pulse rise times starting from hundreds of p-sec and pulse durations of tens of n-sec. Their frequency spectrum shows that the partial discharge signals are distributed from hundreds of MHz frequency bands. In addition, a large external noise signal at the low-frequency band (400~800kHz) is generated and must be measured in the shield room, but it is reduced toward higher frequency bands (1~100MHz).

Fig. 1 shows the measured spectrum of the partial discharge and the noise for 13.8kV power cable installed in an NPP. The 5pC of the partial discharge pulse signal exists up to 30MHz, but the noise is only present at the band of 20MHz or less. Note that, in Fig. 1, the frequency (X axis) has a 5MHz band width.

Fig. 2 shows the detection results according to the variation of measurement frequencies for a 13.8 kV cable of a condensate pump motor in an NPP. When measured in the 12 MHz band, the partial discharge cannot be distinguished because of the noise, but in the 27 MHz band, it can be detected clearly.

Therefore, in the case that the partial discharge signal is measured at the optimized partial discharge signal/noise (S/N) ratio, it is possible to measure partial discharge at on-line and to increase the sensitivity significantly.

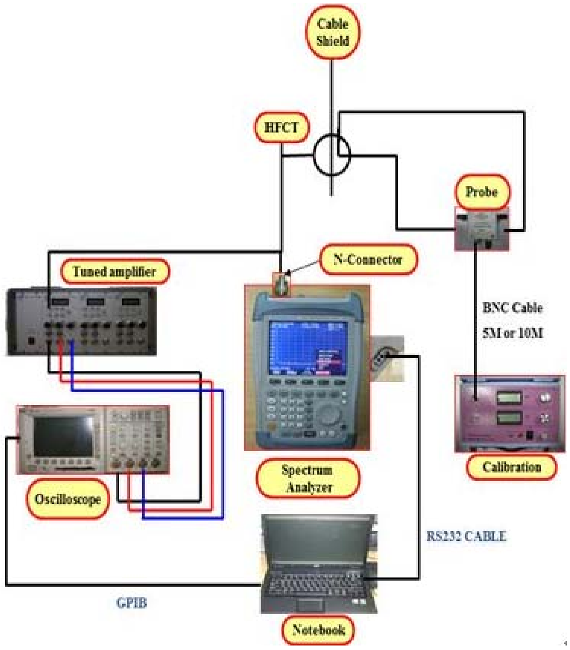


Fig. 3. Partial discharge diagnosis system configuration

3.2 Partial discharge diagnosis system configuration

To diagnose the partial discharge of the cable, an HFCT (High Frequency Current Transformer) is installed to the shield of the cable. The broadband signal detected from the HFCT is input to the meter body through the tuned amplifier. With the meter, the user can detect the high frequency band of a signal as shown in Fig. 2 (b). The amount of discharge and the status of discharge are measured using oscilloscope. By using the software for partial discharge pattern analysis, the Φ-q-n (Phase-Discharge-Pulse) pattern is analyzed to determine whether a partial discharge has occurred or not [5]. The Fig. 3 shows a portable diagnostic system configuration.

4. Measurement of PD Diagnosis for Energized MV Cable in Operated NPP

For the first time in Korea, the PD diagnosis was performed for energized 13.8kV and 4.16 kV MV cables installed in an operating NPP. By using the LS-SPD50 equipment (LS cable company), PD-Base I equipment (Techimp company), and MPD 600 equipment (Omicron company) with the measuring instrument, the applicability of the technique to NPPs was examined. As shown in Fig. 4, the measuring sensor is used together with the HFCT (High Frequency Current Transformer). Most of the noise signal was removed by applying filters in the analysis phase.

(a) LS-SPD50 (b) PD-Base I (c) MPD 600

Fig. 4. Measurement field of partial discharge

4.1 Measurement result of PD using LS-SPD50

By using LS-SPD50 equipment, the PD of 13.8kV 3 circuit and 4.16kV 4 circuit cables were measured. Fig. 5 shows the PD diagnosis results obtained from the cable shield layer of circulating water pump motors (1). The signal was measured from the HFCT sensor that was installed to the cable shield. With frequency tuning, the PD was acquired at the largest S/N ratio band. In Fig. 5 (b), X-axis is a 5MHz per division, and therefore the largest band was found about 31MHz. Fig. 5 (c) shows measured result of 5pC calibration signal at 31MHz band. Finally, the pattern analysis result of PD at 31MHz band is shown in Fig. 5 (d).

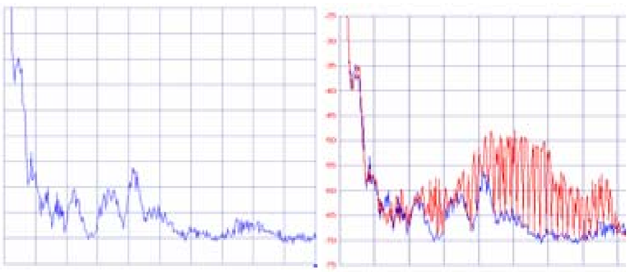
4.2 Measurement result of PD using PD-Base I

By using the PD-Base I equipment, the PD of two 13.8kV circuit cables for a circulating water pump electric motor (3) was measured as shown Fig. 6. The PD signal was divided into two patterns as shown in Fig. 6 (b). When dividing into A and B patterns, it was analyzed like Fig. 7 and 8. In this study, the pattern A was an external high-frequency noise and the pattern B was determined as an internal discharge. The value was approximately 9pC. The measured MV cable was connected to circulating water pump motor; therefore, to know the exact PD occurring position and further diagnosis could be performed.

For the reference, PRPDA (Phase Resolved Partial Discharge Analysis) is used to detect the types of defects shown in the phase of electric source.

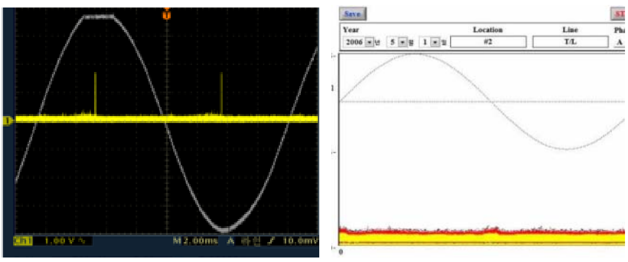
4.3 Measurement result of PD using MPD 600

By using the MPD 600 equipment, PD with A, B, C phase of MV cable for circulating water pump motor (4) was measured at the same time and 3PARD techniques were applied to diagnose the PD. 3PARD technical concept is used so that the noise occurs equally in each phase of the cable. Assuming that the vector sum of the noise converges to zero, then PD can be measured clearly. Just by focusing



(a) measuring the cable noise (Circulating water pump motor cable)

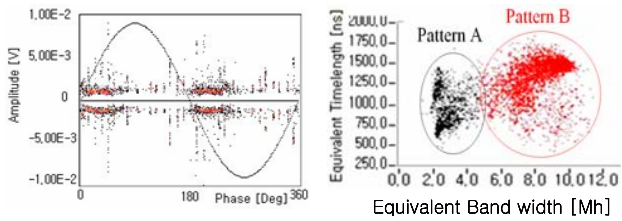
(b) frequency spectrum analysis of online cable after the addition of the calibration signal



(c) 31MHz band signal addition results of 5pC

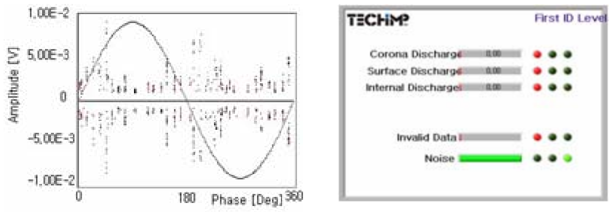
(d) 31MHz bandwidth results of a PD pattern analysis

Fig. 5. Measurement results using LS-SPD50 equipment



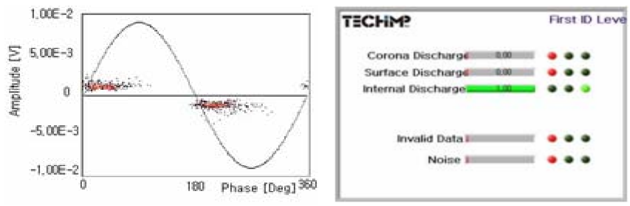
(a) the entire PD pattern (b) Classification map

Fig. 6. Circulating water pump electric motor (3) cable result of measurement



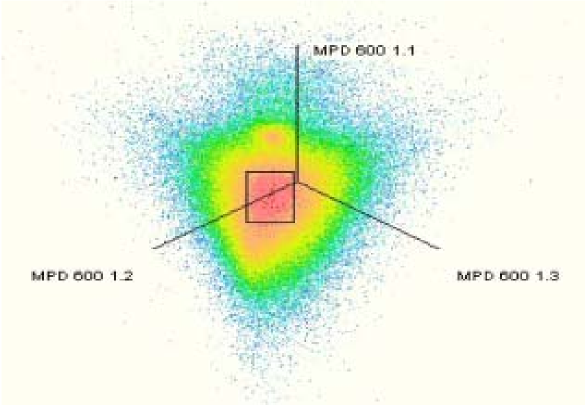
(a) PRPDA (b) Diagnosis result

Fig. 7. Pattern A analyzed result

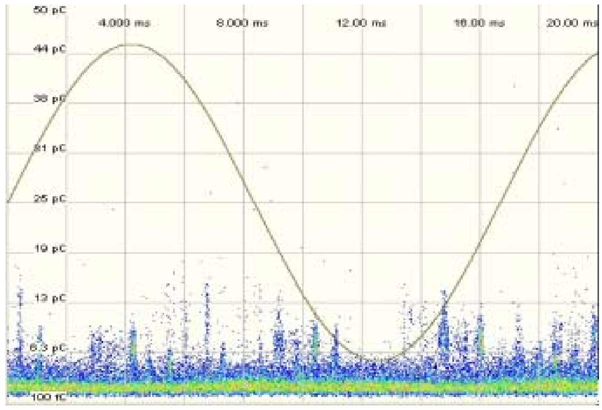


(a) PRPDA (b) Diagnosis result

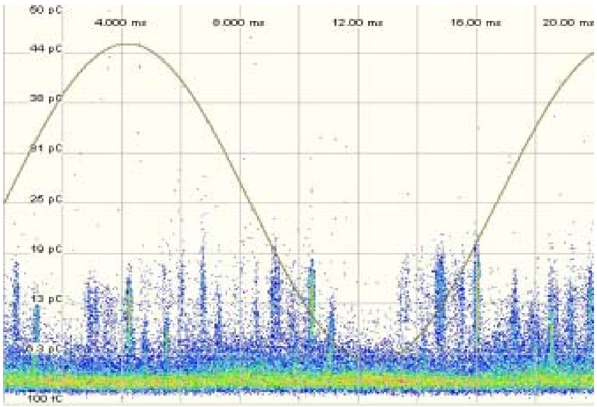
Fig. 8. Pattern B analyzed result



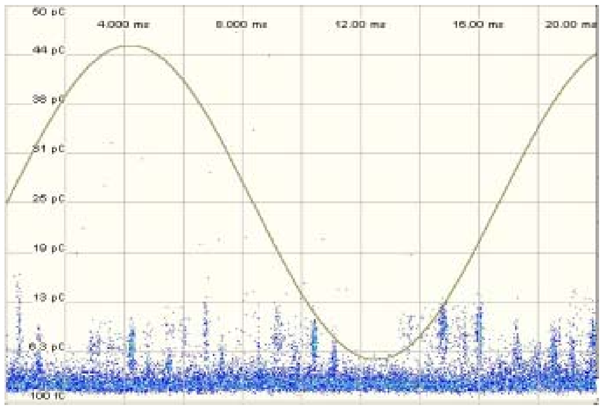
(a) 3 PARDA



(b) A Phase PRPDA



(c) B Phase PRPDA



(d) C Phase PRPDA

Fig. 9. Circulating water pump electric motor (4) cable result of measurement

on near zero, the PRPD analysis was performed on the specified area as Fig. 9 (a), and then the noise was measured as shown in Figs. 9 (b), (c), and (d).

Three bands (5, 7, and 10 MHz) were measured because measuring frequency changes the sensitivity of the signal to noise ratio in PD when the PDs were diagnosed for MV cables in an NPP.

Table 2. Diagnosis results of power cables

Sample Cable	Rating voltage (KV)	Operating current (A)	Measure-ment result of PD	Measure-ment equipment
Condensate pump motor 1	13.8	93	Normal	LS-SPD50
Circulating water pump motor 1	13.8	80	Normal	LS-SPD50
Circulating water pump motor 2	13.8	67	Normal	LS-SPD50
Circulating water pump motor 3	13.8	81	PD Measured	PD-Base I
			PD Measured	MPD 600
Circulating water pump motor 4	4.16	84	Normal	PD-Base I
			Normal	MPD 600
TPOCT pump motor	4.16	130	Normal	LS-SPD50
TPCCT pump motor	4.16	84	Normal	LS-SPD50
SW/GR-load center	4.16	25	Normal	LS-SPD50
Aux.-load center	4.16	25	Normal	LS-SPD50

4.4 Measurement of PD diagnosis for energized MV cable in an operating NPP

The PD diagnosis was performed for energized 4.16kV and 13.8kV MV cables in an operating NPP, using the PD test equipment. Test results are shown in Table 2.

As shown in the Table 2, the PD was caused from the circulating water pump motor (3). However, the measured cable was connected to the motor during that time. It was determined that cables were in a good condition according to VLF tanδ measurement results. From this fact, it is concluded that the PD was caused by motor connected to the cable. Additionally, PD criterion of motor is installed as a 10,000PC

5. Conclusion

The necessity of the fault diagnosis of medium voltage cables has been increased for the long term operation of NPPs. The management plan of medium voltage cables is requested for periodic safety review and continuous operation. In the U.S., the NRC recommends 11 kinds cable diagnosis techniques. Among them, the on-line PD diagnosis for 1.8kV and 4.16kV medium voltage cables can be applied to NPPs. In this paper, the PD measurement methods using the recent HFCT was applied. The diagnosis results give the measurement of the PD without shutdown of NPPs. The PD can be measurable because noises are generally caused by HFPD with measurement devices rather than transmission and distribution line.

The diagnostic results show that it is difficult to say one is better than others because three techniques used for measurement have each advantage and disadvantage. However, the measurement of PD has an advantage in the aspect that can be applied during the overhaul period without the shutdown of NPPs. The detection of cable defects by the measurement of the PD helps for a stable operation of NPPs.

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