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Characteristic Analysis and Origin Positioning of Acoustic Signals Produced by Partial Discharges in Insulation Oil

Dae-Won Park*, Hyang-Eun Jo*, Sun-Jae Kim* and Gyung-Suk Kil†

Abstract – This paper dealt with the propagation characteristics of acoustic signals produced by partial discharges and the positioning of PD origin in insulation oil to develop insulation diagnostic techniques of oil-immerged transformers. Electrode systems such as needle to plane, plane to plane, and particle electrodes were fabricated to simulate some defects of power transformers. In addition, the frequency spectrum and propagation characteristics of acoustic signals with partial discharge (PD) in insulation oil were analyzed. Although there were differences based on the type of defect, the frequency spectra of the acoustic signals measured by wide and narrow band acoustic emission (AE) sensors were distributed in the range of 50 kHz-400 kHz. Therefore, a narrowband AE sensor is suitable for the diagnosis of oil-immersed power transformers. We could find the position of the PD source with an error margin of 10% in the experiments by calculating the position of the PD occurrence using the time difference of arrival measured by five AE sensors.

Keywords: Acoustic signal, Partial discharge, Insulation diagnostic, Frequency spectrum, Positioning, Propagation

1. Introduction

High voltage is applied to power facilities in order to improve the efficiency of power transmission. Accordingly, research on insulation diagnostic techniques is being actively carried out. Electrical insulation is an important factor in the performance of power facilities; however, the insulation performance of the power facilities decreases because of mechanical, electrical, thermal, chemical, and environmental stress [1-4]. As power transformer accidents cause large outage areas and huge cost to repair, on-line monitoring and periodic diagnosis is required for stable power supply [5-8].

A recent important technique for insulation diagnosis is the partial discharge (PD) detection method, which can detect insulation deterioration or defects in its early stages because there is a concentrated electric field in the defective area of an insulator i.e., where PD occurs [9-11].

PD detection can be divided into two methods: one, electrical, the other, nonelectrical. The electrical method has high sensitivity, which enables precise measurement. However, some of the shortcomings of this method include the fact that it is likely to be affected by electromagnetic noise and its coupling network cannot be installed during operation. The nonelectrical method includes acoustic, optical, and chemical detection. The acoustic detection method is less sensitive than the electrical method [12]. This method, however, is less likely to be affected by electromagnetic noise as it is electrically insulated. Additionally, the AE sensor can be installed easily during operation. Locating the defect is possible by measuring the time difference of arrival (TOA) of the acoustic signal using multiple sensors [13].

This paper deals with the application of the acoustic detection method for the insulation diagnostics of oil-immersed power transformers. We analyzed frequency spectrum of acoustic signal produced by partial discharge in insulation oil. Moreover, the propagation characteristics of the acoustic signals and 3D positioning of the partial discharge were studied.

2. Experimental Set-up

As shown in Fig. 1, the experimental apparatus for the simulation of oil-immersed transformers was built using a metallic enclosure. We could generate partial discharges (PDs) by increasing the AC voltage from 0 to 50 kV while immersing the electrode system in insulation oil.

To detect acoustic signals generated by PDs in insulation oil, a wideband AE sensor, with a frequency range of 100 kHz-1 MHz, and a narrowband AE sensor, with a frequency range of 50 kHz-250 kHz, were used.

The two types of AE sensors that measured acoustic signals were installed on the outer surface of the metallic enclosure. As the AE sensor uses a single cable for transmitting both power and signal, we separated the

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† Corresponding Author: Division of Electrical and Electronics Engineering, Korea Maritime University, Korea. (kilgs@hhu.ac.kr)
* Division of Electrical and Electronics Engineering, Korea Maritime University, Korea. (dwpark77@hhu.ac.kr)

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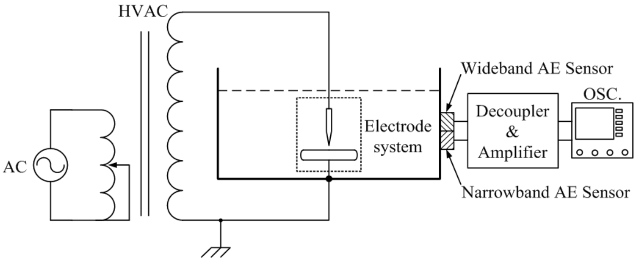


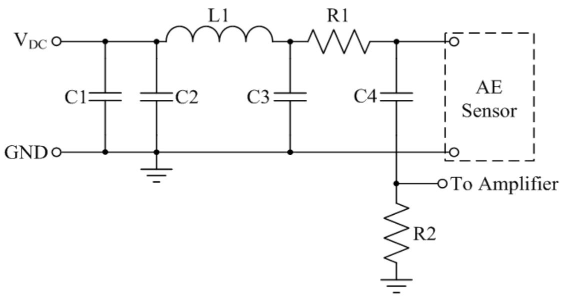
Fig. 1. Configuration of the experimental set-up (I)

acoustic signal from the DC voltage using a circuit with high-pass filter characteristics [13].

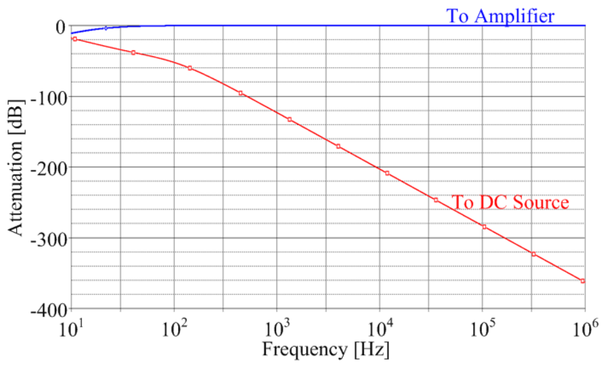
In this paper, we designed the decoupler circuit shown in Fig. 2(a) to separate the acoustic signals from the DC voltage. Also the output signal from the AE sensor has little influence on the DC source, as it is blocked by R1-C3-L1, and is transmitted to the input terminal of the amplifier through C4. The high frequency component of the DC voltage is blocked by L1-C2 and only the DC voltage is supplied to the AE sensor.

The prototype decoupler designed in this paper has the frequency response shown in Fig. 2(b). Acoustic signals over 10 kHz being transmitted from the AE sensor to the DC source are attenuated by more than 200 dB, but are transmitted to the input terminal of the amplifier without attenuation.

A needle-plane, plane-plane, and particle electrode system have been fabricated to simulate the defects that can be generated inside the oil-immersed transformer, as shown in Fig. 3.

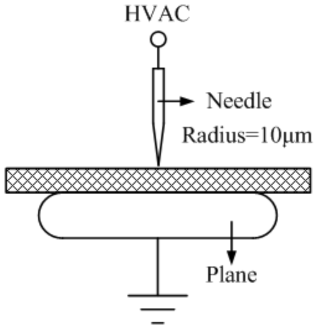


(a) Decoupler circuit

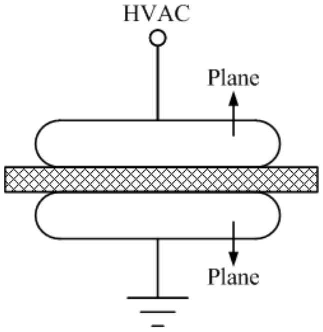


(b) Frequency response

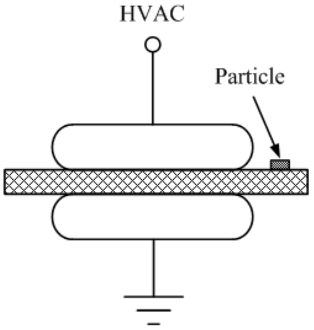
Fig. 2. Decoupler and its frequency response



(a) Needle-plane



(b) Pane-plane



(c) Particle

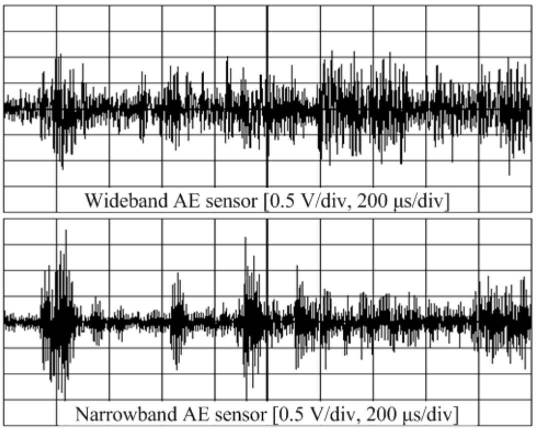
Fig. 3. Electrode system

A plane electrode was made from a tungsten-copper alloy disc 15 mm thickness and 60 mm diameter to avoid electric field concentration; the radius of curvature of the needle electrode was 10 μm. A pressboard of thickness 1.6 mm was inserted between the electrodes.

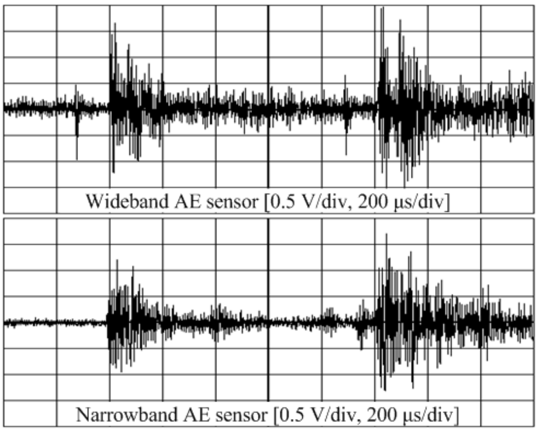
3. Characteristic Analysis

3.1 Frequency spectrum of acoustic signal

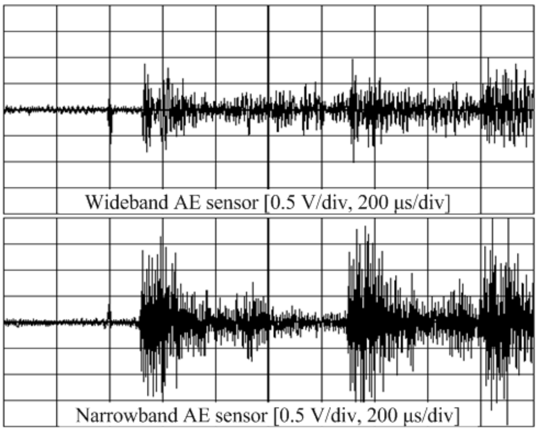
The detected acoustic signals and their FFT results produced in each electrode system are presented in Fig. 4 and Fig. 5.



(a) Needle-plane

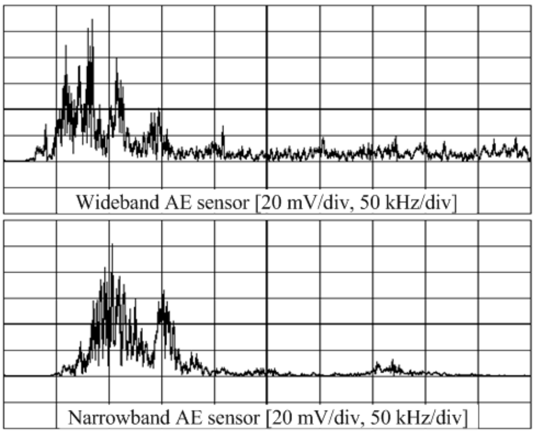


(b) Plane-plane

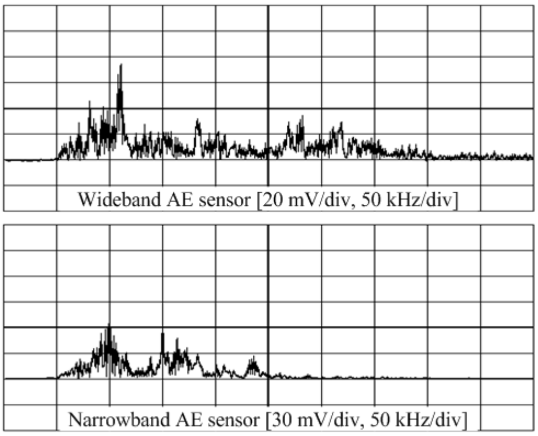


(c) Particle

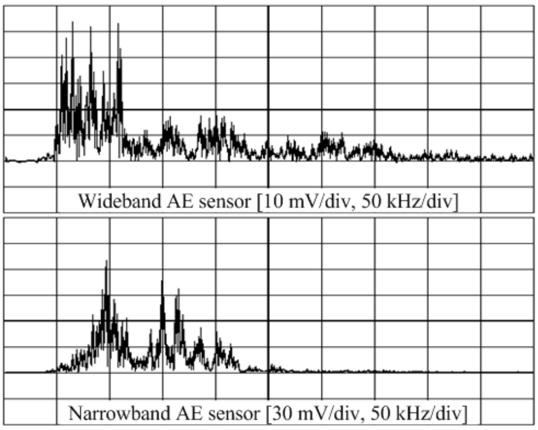
Fig. 4. Example waveforms of detected acoustic signal



(a) Needle-plane



(b) Plane-plane



(c) Particle

Fig. 5. Frequency spectra of acoustic signal

The frequency ranges of the acoustic signals generated at the needle-plane, plane-plane, and particle electrodes were in the ranges 50 kHz-170 kHz, 50 kHz-400 kHz, and 50 kHz-370 kHz, respectively. Although the signals vary depending on the type of defect, the frequency spectra of the acoustic signals distributed in the range of 50 kHz-400 kHz.

Therefore, it should be noted that a narrowband AE sensor with a frequency range of 50 kHz-250 kHz is suitable for the diagnosis of oil-immersed transformers by acoustic detection.

3.2 Propagation of acoustic signal

Relationships between acoustic signals and distances were analyzed to determine the propagation characteristics of acoustic signals in the insulating oil. To determine the sensitivity of the measurement system, a calibration experiment was carried out with a standard PD calibrator (CAL 1A, Power Diagnostix Systems GmbH, 1 pC-100 pC), as shown in Fig. 6.

The output voltage of the measurement system increased linearly in proportion to the injected charge. The sensitivity of the measurement system was measured as 23.65 mV/pC.

We compared the magnitude of a PD pulse to the acoustic signal while increasing the distance between the AE sensor and the electrode. Typical waveforms of the measured PD and acoustic signal are shown in Fig. 7.

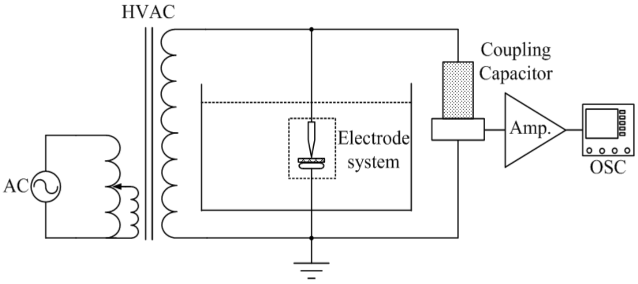


Fig. 6. Configuration of the experimental set-up (II)

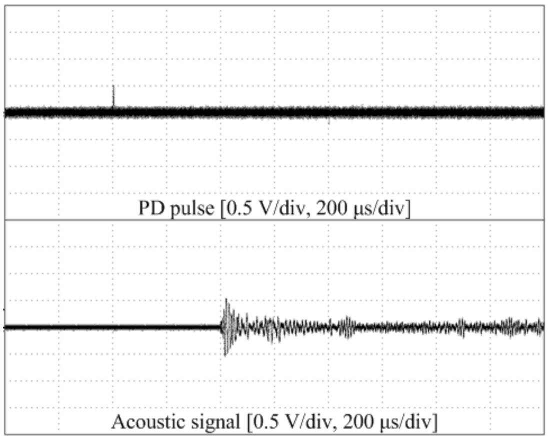


Fig. 7. Typical waveforms of PD pulse and acoustic signal

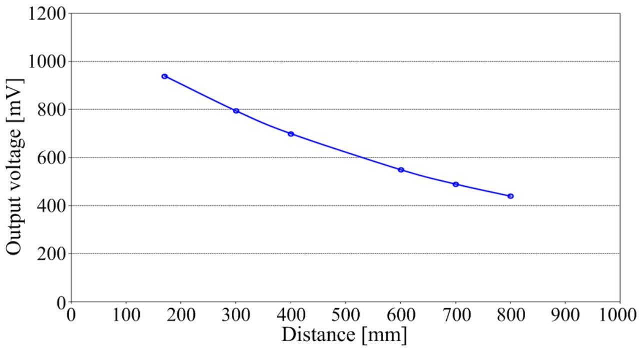


Fig. 8. Attenuation of acoustic signal as a function of distance

When a PD of 23.3 pC occurred, the magnitude of the acoustic signal appeared to be 940 mV, 795 mV, 700 mV, 550 mV, and 440 mV at distances of 170 mm, 300 mm, 400 mm, 600 mm, and 800 mm, respectively. The acoustic signal was nonlinearly attenuated with respect to distance, as shown in Fig. 8.

3.3 Positioning of PD origin

To find the source of the PD inside oil-immersed transformers by the acoustic method, three or more AE sensors are required. In this paper, we used five AE sensors to estimate the position in 3-D using the TOA of the acoustic signals. We marked coordinates on the enclosure to calculate the location of the PD occurrence and installed AE sensors, as shown in Fig. 9. Fig. 10 shows the configuration of the experimental set-up.

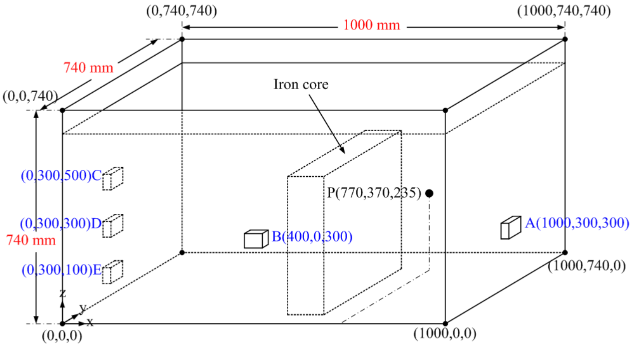


Fig. 9. Configuration of the coordinate system

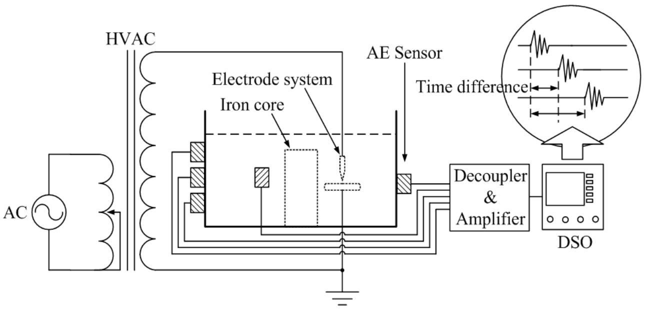
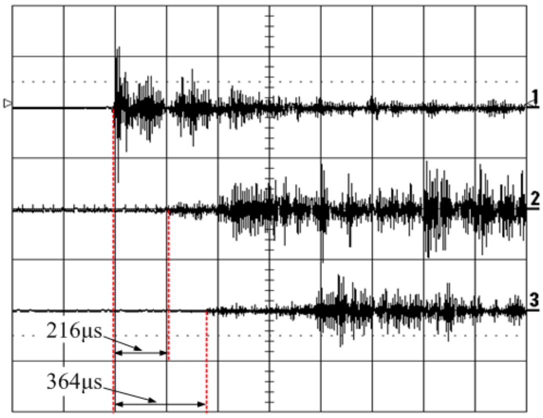


Fig. 10. Configuration of the experimental set-up (III)

Acoustic signals detected by each AE sensor are shown in Fig. 11. The TOA of the AE sensors are listed in Table 1.

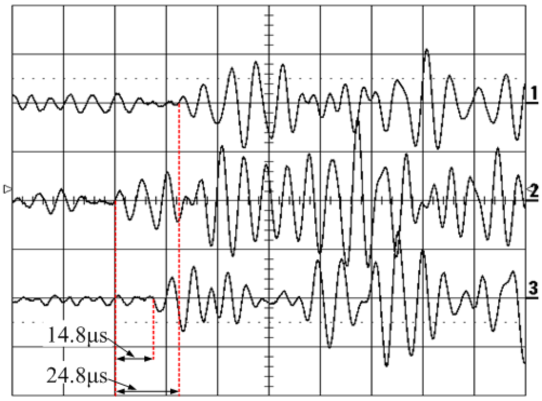
The following equations are derived on the basis of the coordinates of the enclosure shown in Fig. 9 and the TOAs in the assumption that the signals travel along the line of sight from the PD source to the sensor without reflections

$$t_{B-A} = \frac{1}{v}\left(\sqrt{(x-400)^2 + y^2} - \sqrt{(x-1000)^2 + (y-300)^2}\right) \tag{1}$$



Ch.1: AE sensor A [5 V/div, 200 μs/div]
Ch.2: AE sensor B [2 V/div, 200 μs/div]
Ch.3: AE sensor C [5 V/div, 200 μs/div]

(a) Horizontal



Ch.1: AE sensor C [2 V/div, 20 μs/div]
Ch.2: AE sensor D [2 V/div, 20 μs/div]
Ch.3: AE sensor E [2 V/div, 20 μs/div]

(b) Vertical

Fig. 11. Typical waveforms of acoustic signal

Table 1 Time difference of arrival of each AE sensor

Sensor	A-B	A-C	C-D	C-E
Time difference [μs]	216	364	14.8	24.8

$$t_{C-A} = \frac{1}{v}\left(\sqrt{x^2+(y-300)^2} - \sqrt{(x-1000)^2+(y-300)^2}\right) \quad (2)$$

$$t_{D-C} = \frac{1}{v}\left(\sqrt{x^2+(z-500)^2} - \sqrt{x^2+(z-300)^2}\right) \quad (3)$$

$$t_{E-C} = \frac{1}{v}\left(\sqrt{x^2+(z-500)^2} - \sqrt{x^2+(z-100)^2}\right) \quad (4)$$

Where,

$t_{B\text{-}A}$: Time difference of AE sensor between A and B [s]
$t_{C\text{-}A}$: Time difference of AE sensor between A and C [s]
$t_{D\text{-}C}$: Time difference of AE sensor between C and D [s]
$t_{E\text{-}C}$: Time difference of AE sensor between C and E [s]
v: Velocity of acoustic signal in insulation oil [m/s]

The propagation velocity of acoustic signals in insulating oil was measured as 1460 m/s, and the coordinates calculated in equations (1-4) were x = 778.1 mm, y = 430.4 mm, and z = 256.9 mm. Considering that the coordinates of the position of the electrode in this experiment were x = 770 mm, y = 370 mm, and z = 235 mm, and the dimensions of the metallic enclosure were 1000 × 740 × 740 mm, the positioning error should be within 10%. The positioning error was due to the nonlinear propagation characteristics of the acoustic signal, the iron core, and the time resolution of the measurement system.

4. Conclusion

This paper studied the frequency spectrum of acoustic signals based on the presence of defects, propagation characteristics of acoustic signals in insulating oil, and 3-D positioning of the PD occurrence for use in insulation diagnostics of oil-immersed transformers. When comparing the frequency ranges of acoustic signals measured by wide and narrow band AE sensors we found that although they varied depending on the type of defect the frequency spectra of the acoustic signals were in the range of 50-400 kHz. Therefore, it was noted that a narrowband AE sensor with a frequency range of 50 kHz-250 kHz is suitable for the diagnosis of oil-immersed transformers. We installed five AE sensors to estimate the position of the PD source in 3-D by using the differences in the TOA of the acoustic signals.

From the experimental results, we were able to calculate the position of the PD source with an error margin of 10%. The positioning error was due to the nonlinear propagation characteristics of the acoustic signal and the time resolution of the measurement system.

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Dae-Won Park He received the B. S., M. S., and Ph. D. degrees in Electrical and Electronics Engineering from Korea Maritime University, in 2003, 2005, and 2011, respectively. From 2005 to 2007, he has been researcher of Korea Railroad Research Institute. He is currently a post-doctor at division of electrical and electronics engineering, Korea Maritime University. His research interests are in the area of high voltage engineering, insulation diagnosis, and lightning protection.

Hyang-Eun Jo She received the B. S. and M. S., degree from Korea Maritime University, in 2010, and 2012 respectively. She is currently a Ph. D. candidate at division of electrical and electronics engineering, Korea Maritime University. Her research interests are in the area of high voltage engineering and insulation diagnostic techniques.

Sun-Jae Kim He received B. S. and M. S. degrees in Electrical and Electronics Engineering from Korea Maritime University, Korea in 2009 and 2011. He is currently a Ph.D. candidate at division of electrical and electronics engineering, Korea Maritime University. His research interests are high voltage engineering and diagnostic techniques for power facilities.

Gyung-Suk Kil He received the B. S., M. S. and Ph. D. degrees from Inha University, Korea in 1984, 1987, and 1996, respectively. Since 1996, he has been a professor at division of electrical and electronics engineering, Korea Maritime University. He was with the Cardiff University as a visiting professor in 2003. His research interests are in the area of high voltage engineering, insulation diagnosis, and lightning protection.