Detection of the Ultrasonic Signals due to Partial Discharges in a 154kV Transformer

Dong-Jin Kweon*, Sang-Bum Chin* and Hee-Ro Kwak**

Abstract - We have developed an on-line ultrasonic detector to monitor partial discharge in an operating transformer. The ultrasonic sensor has 150[kHz] resonance frequency and contains a pre-amplifier with 60[dB] gain. The on-line ultrasonic detector has 50~300[kHz] frequency band-pass filter to remove electrical and mechanical noises from the transformer. This detector has an ultrasonic signal discrimination algorithm which discriminates ultrasonic signals due to partial discharge in a transformer. A moving average method of ultrasonic signal number was employed to effectively monitor the increasing trend of the partial discharge. This paper describes an experience of partial discharge detection in a 154[kV] operating transformer using an ultrasonic detector. With regards to gas analysis in oil, C2H2 gas was produced with a warning level in this transformer. We detected ultrasonic signals on the transformer steel wall, and estimated the position of partial discharge. With further inspection, we found carbonized marks due to partial discharge on the supporting bolt which fastens the windings.

Keywords: ultrasonic, partial discharge, transformer, on-line monitoring, moving average, ultrasonic signal discrimination algorithm

1. Introduction

Studies on an ultrasonic technique to detect partial discharge in a transformer have been conducted in Korea since the early 1990's. The development of an ultrasonic detector and experimental studies using the model transformer and 22.9[kV] transformer in the laboratory has suggested the possibility of detecting partial discharge in the transformer[1~3]. However, it is known that an ultrasonic signal detection technique cannot be applied yet to the operating transformer since studies have only been done in the laboratory.

"Acoustic emission detection of partial discharge in power transformer"[4] a report by EPRI, "Mistras 2001 AEDSP32/16 user's manual"[5] by Physical Acoustics Corporation(PAC) and "A study on the development of the diagnostic system to prevent failure of the power apparatus"[6] a report by KEPRI, are representatives of the research results which analyzed ultrasonic signals due to partial discharge in the power transformer and external noises. According to the results by EPRI, the noise due to the electromagnetic force of the power transformer was 20~70[kHz], and the ultrasonic signal due to partial discharge in the power transformer which was sited in Korea was 100~250[kHz] and the resonance was about 150[kHz]. The user's manual of PAC presented many cases taken from ultrasonic signals in the operating transformer. However, it was unable to cover all characteristics of the ultrasonic signal due to the partial discharge in this manual. In Korea, field testing was carried out on 154[kV] power transformers in 1993, but the research results did not present the characteristics of the ultrasonic signal due to partial discharge and the noises. Thus, there has been doubts about how to apply the results of the laboratory to the field.

In this paper, the ultrasonic detector was applied to a 154[kV] operating transformer, and the results detecting the ultrasonic signals due to partial discharge in the transformer were presented. The transformer was operated at the warning level with C2H2 gas. We detected ultrasonic signals on the transformer steel wall, and estimated the position of the partial discharge. Eventually, a careful visual inspection was carried out based on the results from the ultrasonic detector.

2. Development of the on-line ultrasonic detector

Recently, many on-line monitoring devices such as a gas analyzer in oil, partial discharge detector, ultrasonic signal detector, thermometer and OLTC monitor, etc. have been

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developed to detect the abnormal symptoms leading to the failure of the transformer.[7 ~ 10] The data gathered from the on-line monitoring devices was stored in the server in a preventive diagnosis system. The abnormality of the transformer was determined by the fixed standard level and the increasing trend of the data. The preventive diagnosis system can determine the types of abnormality by analyzing the relation of the data collected by the on-line monitoring devices.[11]

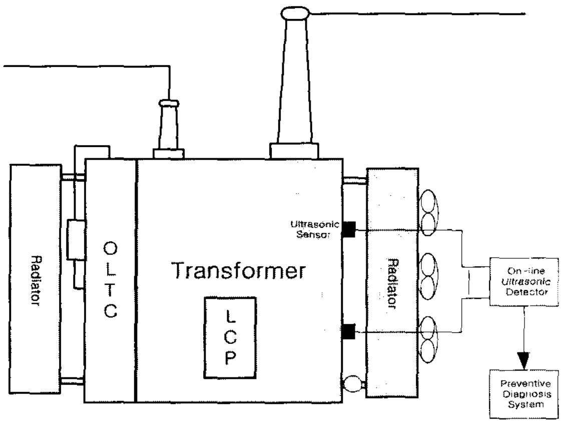


Fig. 1 Block diagram of the on-line ultrasonic detector applied to the power transformer

Fig. 1 shows an example where the on-line ultrasonic detector is applied to a power transformer. As shown in Fig. 1, several ultrasonic sensors are mounted on the exterior steel wall of the transformer to continuously measure the ultrasonic signals due to the partial discharges, and the signals measured by the sensors are processed by the on-line ultrasonic detector, and then transferred to the preventive diagnosis system. This system monitors the occurrence of the ultrasonic signal and its growth.

As shown in Fig. 2, the on-line ultrasonic detector consists of ultrasonic sensors, pre-amplifiers, analog signal processing modules, digital signal processing modules and a main control module.

The ultrasonic sensor has 150[kHz] resonance frequency that corresponds to the frequency characteristic of the ultrasonic signal due to partial discharge in the transformer, which makes the sensitivity of the ultrasonic signal higher. The sensors were mounted with a magnet that holds them on the steel wall of the transformer.

In addition, a pre-amplifier of 60[dB] gain is installed after the sensor to make the signal analysis easier in signal processing modules and robust to various noises from a substation when the signals are transferred to the on-line ultrasonic detector.

The analog signal processing module has a 10[kVp-p] surge protector to protect it from the surge. The ultrasonic signal passes through a signal converter to electrically insulate the external ground by input signal from the ground in the on-line ultrasonic detector.

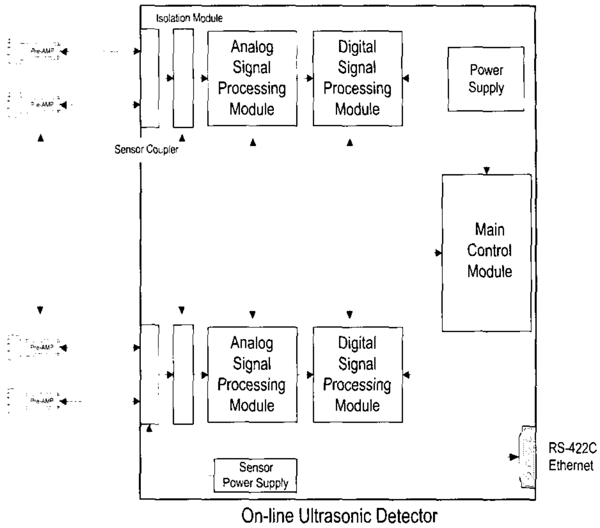


Fig. 2 Configuration of the on-line ultrasonic detector

When the ultrasonic sensors which detect partial discharge in the power transformer are mounted on the steel wall of the transformer, the sensors detect various mechanical noises from the transformer as well as ultrasonic signals due to partial discharge in the transformer. Therefore, it is important to design the proper analog signal processing module with a filter to remove these noises.

The noises affecting the ultrasonic signal measurement are divided into mechanical noise, electromagnetic noise and electrical noise. The frequency of ultrasonic signals due to the partial discharge from the needle to plane electrodes in the model transformer was 20 ~ 200[kHz] and its duration was about 30[ms][12]. In addition, when we measured the various noises from the 345[kV] operating transformer, 120[Hz](2 times of the power frequency) and its harmonics(240, 360[Hz]), the following were remarkably measured because of the vibration of the core in the transformer. But the frequency over 2.5[kHz] did not appear. The noise due to the operation of the cooling pump was below 2[kHz], the cooling fan was below 4[kHz], the magnetic switch of the cooling pump and fan was below 2[kHz] and the on load tap changer(OLTC) was below 1[kHz][13].

However, when the OLTC operated, 4 ultrasonic signals of about 45 ~ 50[ms] were detected. This is because of the diverter switch of the OLTC which consists of 4 contacts(two main contacts and two transition contacts). The frequency of the ultrasonic signals due to the OLTC is 50 ~ 250[kHz] centering around 143[kHz] likely to be similar to partial discharge in the power transformer[11], which was taken for granted because arc occurred when the OLTC operated. Therefore, a special algorithm is required to remove ultrasonic signals due to the OLTC, since they might affect the detection of the ultrasonic signals due to partial discharge in the power transformer.

There are many kinds of electromagnetic waves such as broadcasting waves that act as an electromagnetic noise induced in the detecting circuit. TV frequency and radio frequency can be enumerated as broadcasting waves, and the former is divided into VHF, UHF and SHF. The domestic band width of the TV frequency is 6[MHz] per channel, and the frequency of VHF is 30~300[MHz], UHF is 300~3,000[MHz], and SHF is 3~30[GHz]. In Korea, 54~60[MHz] is used for CH 2, and 746~752[MHz] for CH 60. The radio wave is somewhat different in the provinces, but 500~1,500[kHz] is generally used as AM, and 90~100[MHz] as FM.

The electrical noises from a substation are represented by aerial discharge pulses due to corona from overhead transmission lines, pulses due to leakage current on the bushing surface and discharge noises in switching circuits. Out of these, the corona noises from high voltage transmission lines were approximately 9~18[MHz][13] and the noises in switching circuits do not create serious problems because they intermittently occurred.

As we mentioned, other noises besides the noise caused by the OLTC can be removed by properly designing the filter of the on-line ultrasonic detector, since they are far different from the ultrasonic signal due to the partial discharge in the transformer. Based on the results acquired from studies on the various noises in the operating transformer, a band-pass filter of the on-line ultrasonic detector was designed with a narrow band frequency of 5 0~300[kHz]. The output of the main amplifier can be varied 0~60[dB](at every 10[dB] step) to make the signal analysis easier.

In the digital signal processing module, 1.2[Msamples/sec], 16[bit] A/D converter were used to analyze the ultrasonic signal more accurately. By comparing the digital value from the A/D converter with the standard value, the ultrasonic signal is distinguished from the back ground noise. On the other hand, the ultrasonic noise caused by the OLTC operation which was not removed by the filter because of similar characteristics to partial discharge in the transformer was actually removed by the ultrasonic signal detection algorithm in the digital signal processing module.

The ultrasonic signal due to partial discharge in the transformer is exponentially decreased, and its duration is several tens of milliseconds. However, the duration of the electrical noise signal due to the corona from the overhead transmission lines is less than a few microseconds, and the duration of the ultrasonic noise caused by the OLTC operation is over a few hundred milliseconds.[11]

The ultrasonic discrimination algorithm calculates the duration(Ta) from the first maximum peak above the Vb(Threshold level) to Va(Settling level), as shown in Fig. 3. The algorithm discriminates the ultrasonic signal from the noises only when the signals are less than Tb or more than Ta(the duration of the ultrasonic signal due to partial discharge in the transformer). The ultrasonic signals over the standard value are counted at 1 second time intervals. The number of the ultrasonic signal is transferred to the preventive diagnosis system per fixed time intervals, and is stored in the database.

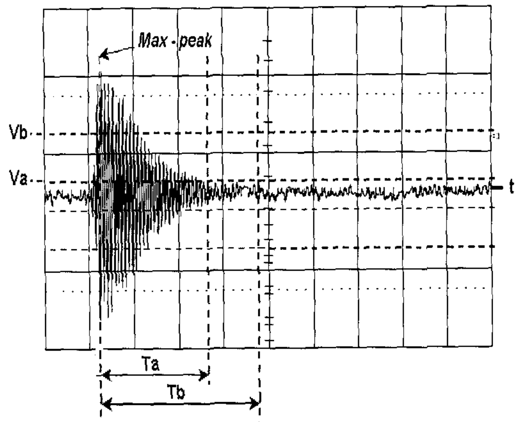


Fig. 3 Ultrasonic signal discrimination algorithm

The main control module has a simultaneous sampling function to simultaneously detect the data from several sensors, and each module is synchronized by clock synchronization. The preventive diagnosis system has to display the trend of the ultrasonic signal number to understand the growth of partial discharges. However, the ultrasonic signal number by one second measurement until the insulating paper was punctured by partial discharges was dramatically changed by time. Therefore, the preventive diagnosis system has difficulty in choosing the alarm level. The moving average of the ultrasonic signal number was indicated in the preventive diagnosis system to clearly show the growing trend.[14]

The moving average can be written as follows ;

$$\begin{aligned} y(n) &= \frac{1}{M_1+M_2+1}\sum_{k=-M_1}^{M_2} x(n-k) \\ &= \frac{1}{M_1+M_2+1}\{x(n+M_1)+x(n+M_1-1) \\ &+ \cdots +x(n)+x(n-1)+ \cdots +x(n-M_2)\} \end{aligned}$$

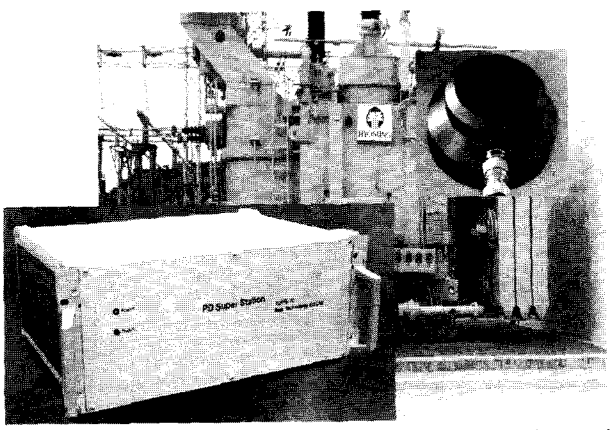


Fig. 4 Ultrasonic sensor and developed on-line ultrasonic detector

Here, M1 is M1th data leading nth data, and M2 is M2th data following nth data. This is the nth results averaging M1+M2+1 data fore and back nth data from the original signal. As shown, applying the moving average algorithm helps us monitor the trend of the partial discharge easily. The preventive diagnosis system displays the increasing trend by time. The ultrasonic sensor and the developed on-line ultrasonic detector are shown in Fig. 4.

3. Results

To detect the ultrasonic signals due to partial discharge, 6 ultrasonic sensors were mounted on the 154[kV] transformer steel wall and a recorder was connected to the on-line ultrasonic detector to save the ultrasonic waveform. The 154[kV] transformer has been in service since 1998, and reached a warning level of C2H2 gas since January 2001 as shown in Table 1. Generally, C2H2 gas in the transformer is produced by the arc due to the shortness of the winding, the discharge in liquid or solid insulator.

The ultrasonic detecting tests were carried out 3 times, respectively, to confirm the existence of the partial discharge and estimate the position of it. First, it was examined whether the ultrasonic signals due to partial discharge existed in the transformer(2001.7.23-24). After detecting the ultrasonic signals, the 2 ultrasonic sensors were placed in the second test(2001.7.24-25), where the estimated position of partial discharge occurred to detect ultrasonic signals more accurately. Gas in oil was analyzed again after the second ultrasonic detecting test. As a result, it was confirmed that C2H2 gas was constantly produced. After 1 month, the ultrasonic test was carried out again in the third test(2001.8.20-21). In this test, the position of partial discharge was estimated more accurately. Based on the results of the gas analyses in oil and the ultrasonic detecting tests, the transformer was de-energized to find the partial discharge.

Table 1 Results of the gas analysis in oil of the 154[kV] transformer

Gas	H_2	CO_2	C_2H_2	C_2H_4	C_2H_6	CH_4	CO	Remarks
Jan. 10, 2001	0	644	***65***	38	2	28	289	C_2H_2 gas warning
Aug. 10, 2001	15	1,092	***58***	14	0	14	240	C_2H_2 gas warning
Nov. 20, 2001	22	1,327	***61***	33	0	30	486	C_2H_2 gas warning
Jan. 19 2002								Inspection
Warning level	400	5,000	25	300	250	250	400	
Abnormal level	800	7,000	80	750	750	750	700	

3.1 The first test

3.1.1 Positions of the ultrasonic sensors

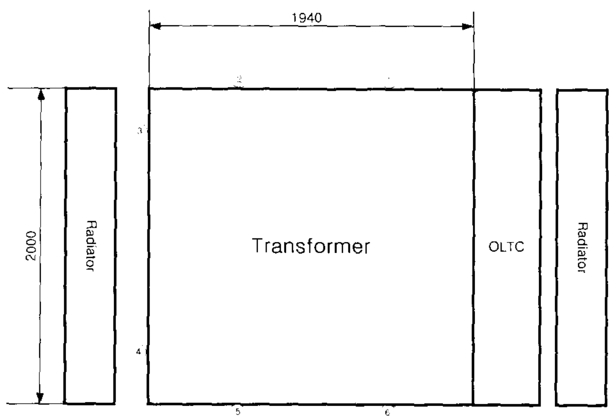


Fig. 5 Positions of the ultrasonic sensors in the first test

In the first test, the ultrasonic sensors were mounted at equality intervals on the transformer steel wall to detect the ultrasonic signals due to the partial discharge as shown in Fig. 5. The ultrasonic sensors were mounted on the middle point of the transformer.

3.1.2 Test results

In the first test, the 18 ultrasonic signals occurred for 14 hours of measuring time. 11 of them had the maximum value in magnitude at sensor ⑥, 3 of them had at sensor ①, 2 of them had at sensor ③, and the rest were at sensors ② and ④. The delayed time from the ultrasonic source to the sensor was the shortest where the magnitude of the ultrasonic signal was the maximum.

Fig. 6 shows an example of ultrasonic signals in the first test. The magnitude of ultrasonic signals was in the order of sensors ⑥, ①, ② and ⑤. The result of Fig. 6 illustrates that the partial discharge was the closest to the sensor ⑥

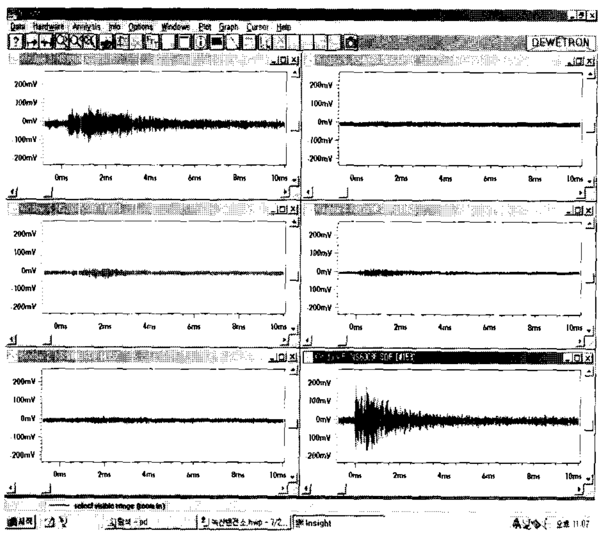


Fig. 6 Ultrasonic signals in the first test

and nearly the same distance from sensors ② and ③. The reliability of detecting sensitivity which was doubted due to the signal prolonged by the transformer structure from the core and winding was confirmed by the result of Fig. 6. This is because the ultrasonic signals could now be detected by both sensors ⑥ and ③ mounted diagonally.

3.2 The second test

3.2.1 Positions of the ultrasonic sensors

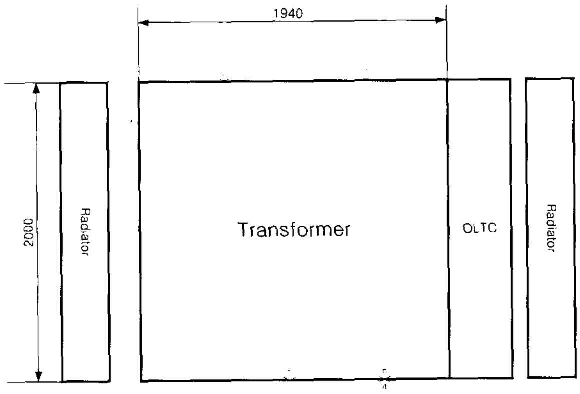


Fig. 7 Positions of the ultrasonic sensors in the second test

As the result of the first test, the ultrasonic signals due to partial discharge were located around sensor ⑥. Therefore, sensors ④ and ⑤ in Fig. 5 were moved around sensor ⑥ to detect ultrasonic signals more precisely, as shown in Fig. 7. Sensor ④ was mounted at the lower position of the transformer, and sensors ⑤ and ⑥ were mounted at the upper position.

3.2.2 Test results

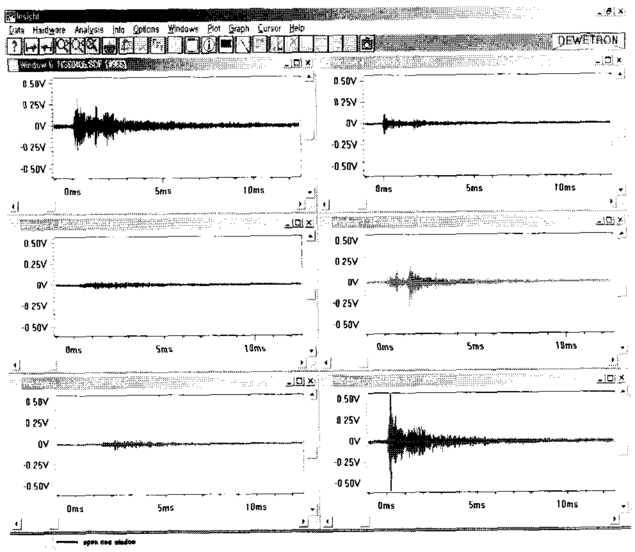


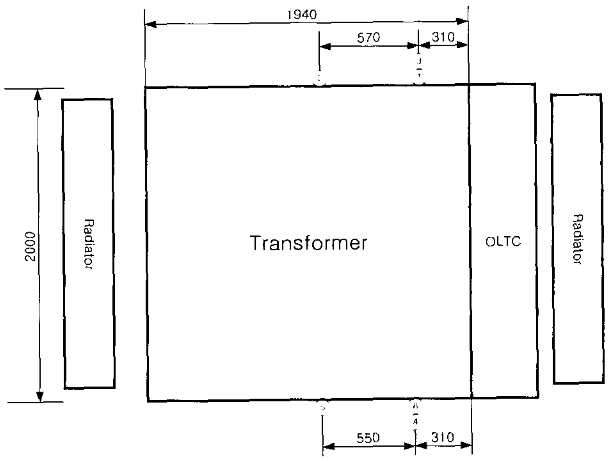
Fig. 8 Ultrasonic signals in the second test

Fig. 8 shows some examples of ultrasonic signals in the second test. The 19 ultrasonic signals occurred for 9 hours of measuring time. 17 of them had the maximum value in the magnitude at sensor ⑥, one had at sensor ⑤, and another had at sensor ①. As shown in Fig. 8, the magnitude of the ultrasonic signals was in the order of sensors ⑥, ①, ⑤ and ④. In addition, the ultrasonic signals were clearly measured at sensors ④ and ⑤. Therefore, the existence of the partial discharge in the transformer was confirmed by the analysis of the magnitude and the time difference of the ultrasonic signals.

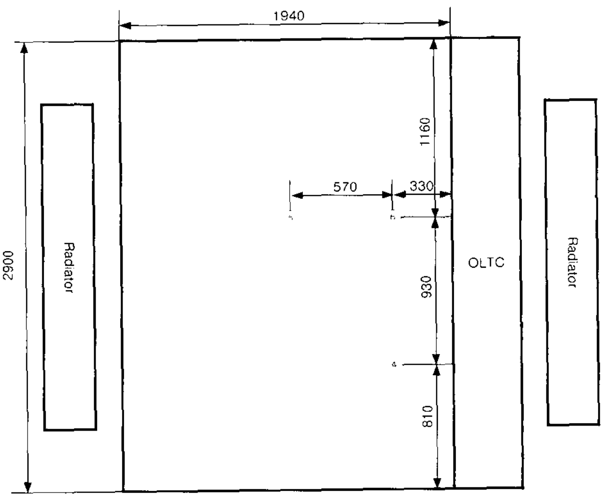
3.3 The third test

3.3.1 Positions of the ultrasonic sensors

After the second test, the gas in oil was analyzed again. The C2H2 gas was still produced at the warning level. After 1 month, the ultrasonic test was carried out again to estimate the position of partial discharge. The 6 ultrasonic sensors were mounted on the right side around the OLTC at which the partial discharge is likely to occur, as shown in Fig. 9.



(a) ground plane



(b) profile

Fig. 9 Positions of the ultrasonic sensors in the third test

3.3.2 Test results

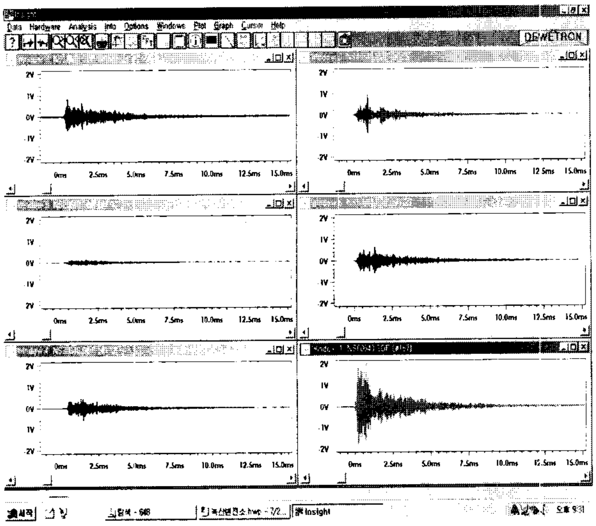
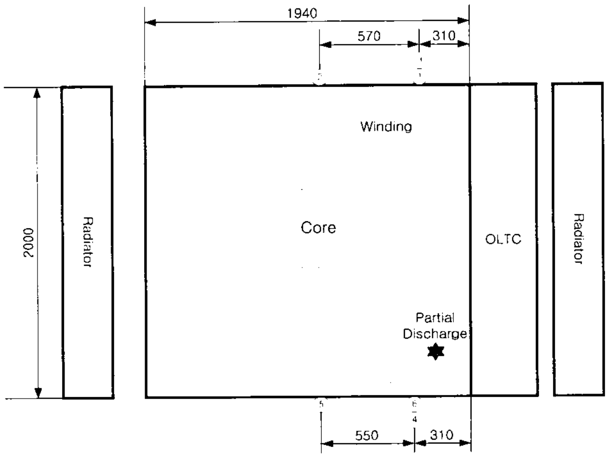


Fig. 10 Ultrasonic signals in the third test

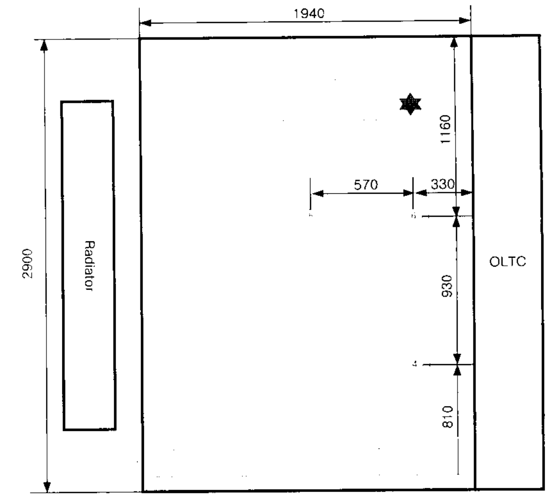
Fig. 10 shows some examples of ultrasonic signals in the third test. The 18 ultrasonic signals occurred for 24 hours of measuring time. 17 of them had the maximum value in magnitude at sensor ⑥, and the other was at sensor ①. As shown in Fig. 10, the ultrasonic signals at its maximum were measured at sensor ⑥, and the minimum at sensor ②. From this, it was inferred that the partial discharge source was estimated around the sensor ⑥, that is, the upper position of the transformer.

3.4 Results of the inspection

Based on the results of the gas analyses in oil and the ultrasonic detecting tests that find the partial discharge, an internal inspection was carried out to the transformer. After draining the oil, the inside of the transformer was visually inspected. After 5 minutes of inspection, the partial discharge was found to be based on the estimated position result of ultrasonic detecting tests as shown in Fig. 11.



(a) ground plane



(b) profile

Fig. 11 Location of the partial discharge

As shown in Fig. 12, the carbonized marks due to partial discharge on the pressboard supporting the bolt which fastens the windings and the frame were at the upper position of the transformer. It was considered that the partial discharge occurred due to the phenomena of the loose bolt. Even though another partial discharge was inspected as well, it could not be found anymore. After the transformer was repaired by erasing the carbonized marks and fastening the bolt, the transformer is in service without any abnormal symptoms. The reliability of the developed on-line ultrasonic detector used in this study could be confirmed by measuring the ultrasonic signals due to partial discharge in the power transformer.

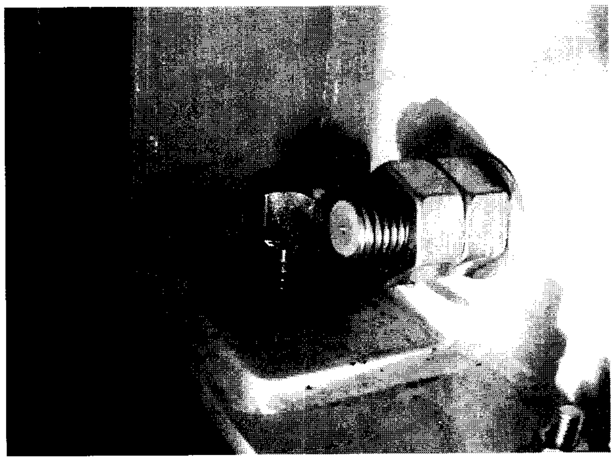


Fig. 12 Carbonized marks due to the partial discharge

4. Conclusions

This paper showed the results of detection on the ultrasonic signals due to partial discharge in the 154[kV] operating transformer using a developed on-line ultrasonic detector.

1. The ultrasonic signals were detected on the transformer which produced C2H2 gas at the warning level.
2. The position of the partial discharge was estimated. With inspection, we found carbonized marks due to partial discharge on the supporting bolt which fastens the windings.
3. The reliability of the ultrasonic technique to detect partial discharge in the transformer was confirmed.

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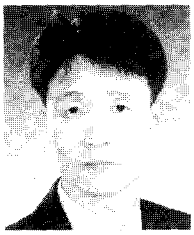

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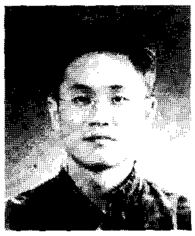

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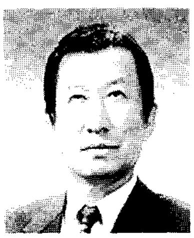

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