A Study on the Design of a Planar Loop Sensor for Partial Discharge Diagnosis of 22.9 kV XLPE Power Cables

Kwang-Jin Lim*, Sang-Hyun Yang*, Dong-Hoon Shin, Noh-Joon Park* and Dae-Hee Park†**

Abstract – This study designed a new type of loop antenna that is able to detect partial discharges based on microstrip line technology. In the diagnosis of power cables, partial discharge signals are generally produced at a frequency range less than 100MHz because high frequency PD signals are lost along a propagation path in such cables. The new type of loop antenna sensor has been studied using simulation software known as CST microwave studio version 5.0. In partial discharge measurement experiments, a commercial HFCT sensor was used as a reference sensor. Several experiments were made over HFCT and loop antenna sensors for detecting partial discharges on 22.9kV MV XLPE cable. In this study, we showed the loop antenna designed in this study that can be applied as a commercial HFCT sensor.

Keywords: PD (Partial Discharge), Planar Loop Sensor, Cable Diagnosis, HFCT Sensor

1. Introduction

Power cable used for more than 30 years can cause accidents due to degradation of insulation [1,2].

A partial discharge measurement method can be used to solve the mentioned problem. However, noises produced in a partial discharge measurement process make a difference in the detection of micro partial discharge signals. The frequency range within 1MHz proposed by the IEC-60270 produces various noises and that makes significant differences in actual applications. Thus, the demands of reliability in the measurement technology of partial discharges occurred in a high frequency band from several MHz to hundreds MHz have been increased and studies on this issue have been continuously conducted [3,4].

Based on the results of the investigation performed in this study for the major frequency band in power cables, this study configured a band for the measurement of broadbands, such as 2~100MHz, because the highest frequency was presented with a frequency less than 100MHz. Also, this study attempted to apply an antenna-style sensor that is less affected by noises [5].

There are some limitations in the design and fabrication of antenna sensors, which detect partial discharge signals in power cables, due to their resonance frequencies and sizes. In the case of the partial discharge signals generated in a GIS (Gas Insulated Switchgear), it is easy to install the antenna sensors in which its resonance lengths can be determined from several cm to several tens of cm onto their sensor mount because these signals are detected at a wide range from hundreds of MHz to several GHz [6,7]. However, the frequency bands of partial discharges produced in power cables are less than 100MHz and that represents a difficulty in the installation of such an antenna, which has several meters of its resonance length, on their sensor mount. Thus, the length and scale of antennas increase in the design for a VHF band and that also represents numerous difficulties in its production.

This study implements a partial discharge measurement device that detects electromagnetic waves using the principle of loop antennas and applies a microstrip antenna structure, which is based on print circuit board technology, in order to provide easy design and fabrication. In addition, this study improves the shield effects for external noises in a planar loop antenna and develops a loop antenna sensor that shows excellent properties compared to the conventional loop sensors for noises. Then, this study proposes an effective way that measures the partial discharges produced in operated power cables using such a loop antenna sensor.

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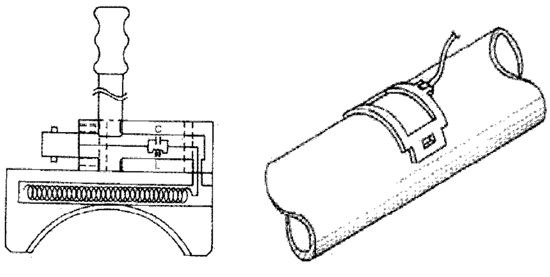
2. Main Subject

2.1 Design and Fabrication of Sensors

In various conventional sensors for diagnosing power cables, a helical antenna is used to detect electromagnetic waves and this conventional helical antenna shows a difficulty in the detection of various frequency bands of the electromagnetic waves partially discharged from cables by sensing a specific frequency band of 30MHz. Also, the helical antenna requires a proper earth due to its open loop as illustrated in Figure 1 (a) and is largely affected by the earth condition. In addition, it has a low gain level and requires an additional amplifier. Thus, it represents lots of deviations caused by the distributed capacity (C) component between the ground and the antenna. Furthermore, a partial discharge detection device with helical antennas is only installed onto a specific type of cable and that represents problems in the detection of partial discharges in other cables.



(a) Helical antenna (b) Loop antenna

Fig. 1. Antennas used for measuring partial discharges

However, a loop antenna that winds enamel coils into a loop shape can be used to detect electromagnetic waves and the length of a loop antenna can be calculated using Eq. (1.1).

$$h = \frac{3\times 10^8 m/s}{f} \cdot \frac{1}{12} \qquad (1.1)$$

where h is the length of a loop antenna and f is a frequency band that is to be detected. In Eq. (1.1), the wavelength can be determined by the frequency band (f) that is to be detected and the length of a loop antenna can be calculated according to the wavelength. Regarding the number of coil turns for the size of a sensing device when the length of a loop antenna is determined as a uniformed scale, the number of turns in a sensing device decreased according to the increase in the size of the device and increased according to the decrease in the size of the device. Regarding the size of a sensing device according to changes in coil turns when the number of turns applied to a loop antenna are controlled as a constant level, the size of a sensing device increased according to the increase in the length of the antenna and decreased according to the decrease in the length of the antenna [8].

However, it is possible to fabricate sensors that represent small sizes, easy production process, and wide detection bands through applying microstrip technology to such a loop antenna structure. To design an antenna that can be applied using the microstrip technology, the important factor is the gain of detected signals. The antenna should have wide frequency range of 0~100 MHz with the size being adapted with detector dimension. In Figure 2, CST-MWS software has been used for designing the antenna, which has a Planar Loop Sensor structure.

PCBs have 1.06 of relative permittivity, thickness of 1.6 mm and PEC in the electric supply ground part used to make a Planar Loop Sensor. The dimension of the electric supply part is 3 mm and the distance of the loop part is 4 mm. The dimension of the ground is 150 × 110 mm (width × height). Fig. 2 presents the designed sensor which is 150 × 150 mm (width × height).

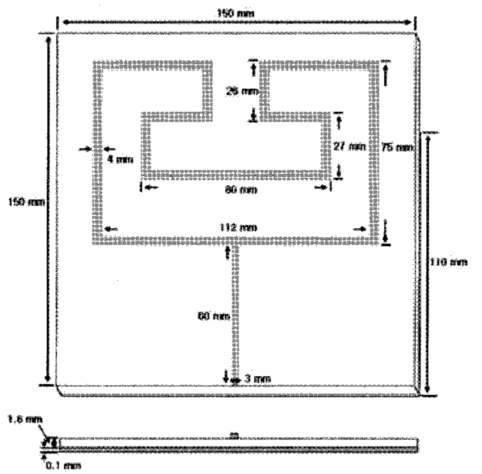


Fig. 2. Fabricated planar loop sensor

2.2 Measurement System and Method

Figure 3 shows the simulation system for detecting partial discharges in a laboratory. The cable used in this experiment was of distribution class TR-CNCV-W 325mm^2 in which 7M and 6M cables were connected using an intermediate distribution frame that connects different distribution cables and the termination was performed using a terminator kit identical to the actual distribution line. Also, simulated defects (interfacial discharge defects) were artificially configured in the intermediate distribution frame. In the process of this experiment, artificially generated discharge signals, which were quantitatively calibrated using a calibrator (PD, CAL1A), were applied to the power cable. Then, the signals were detected and compared using the planar loop sensor proposed in this study and the HFCT sensor (PD, CT-100), which was used to compare the results to that of the proposed sensor. In addition, the partial discharge signals produced by applying 22kV, which is the nominal voltage in XLPE power cables, to the cable were detected using a withstanding voltage tester (Hipotronics, 750-2CTS).

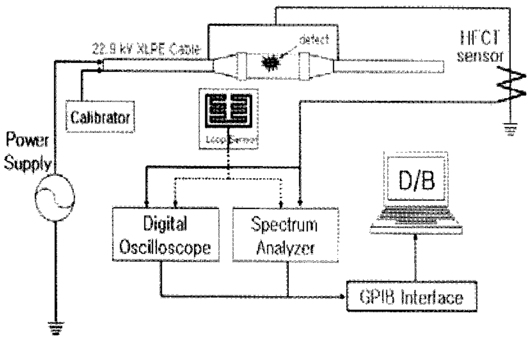
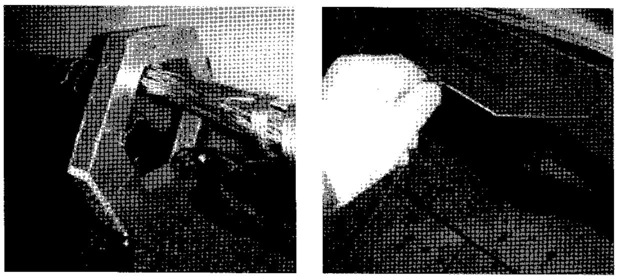


Fig. 3. Partial discharge measurement system in cables

Figure 4 shows sensors for measuring partial discharges. Fig. 4 (a) presents a type of commercial high frequency current transformation (HFCT) style sensor that detects the frequencies determined as 2~50MHz and can be installed at the connection section of cables in order to detect high frequency signals of the circulating current in a sheath layer. Fig. 4 (b) illustrates a planar loop sensor proposed in this study that can be installed at the outside of the connection frame and can be used to receive electromagnetic waves as well as partial discharge signals.



(a) HFCT sensor (b) Planar loop sensor

Fig. 4. Sensor installation for the simulation cable of 22.9kV

3. Results and Consideration

3.1 Evaluation of the Planar Loop Sensor

Figure 5 represents return losses obtained by the calculation of the measured sensitivity of the antenna sensor designed by the simulation performed in this study. The designed sensor showed a resonance band of about 50MHz based on the -6dB bandwidth proposed by IEEE Standard 400.3 and presented the measured sensitivity at about 52MHz. Whereas, the return losses of a -10dB of bandwidth was the sensing 90% of the source signal and -20dB and -30dB bandwidths were the sensing of 95% and 97.5% of the source signal, respectively.

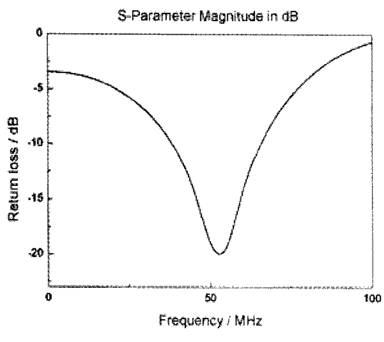


Fig. 5. Return loss characteristics in the simulation

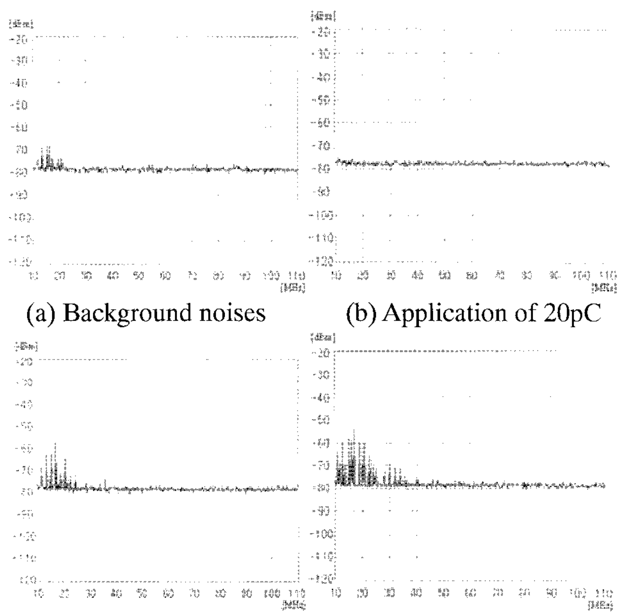
3.2 Evaluation of Cable Lines

3.2.1 Evaluation of Calibration Signals

It was difficult to verify partial discharges in actual sites. Therefore, it is necessary to apply simulated signals, which are similar to that of partial discharge signals, in which the signals can be detected by applying periodical discharges with a specific level. This study applied calibrated signals, 20, 50, and 100pC, and analyzed the signals coming from them.

(1) Frequency domain analysis

Figure 6 illustrates the frequency characteristics obtained from the application of different calibration signals to a HFCT sensor.



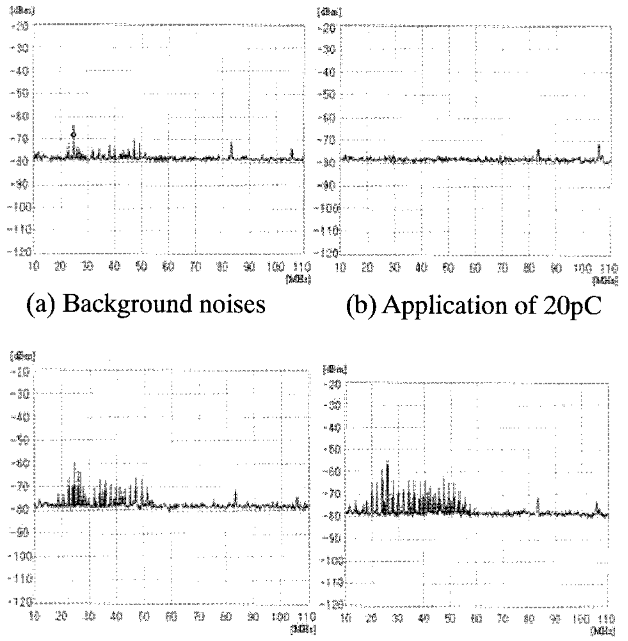
(a) Background noises (b) Application of 20pC

(c) Application of 50pC (d) Application of 100pC

Fig. 6. Frequency characteristics of the HFCT sensor with calibration signals

As shown in Fig. 6 (a), it was possible to verify that there were no particular external noises and abnormal signals. Also, Fig. 15 (b)-(d) indicates that the detected sensitivity of the applied calibration signals represented a linear property, such as -68dBm, -58dBm, and -53dBm for the application of 20pC, 50pC, and 100pC, respectively, in which it was evident that the typically detected frequency band was 10~30MHz and the detection characteristics of the abnormal signals detected at more than 30MHz were decreased.

Figure 7 presents the frequency characteristics obtained from the application of different calibration signals to the proposed planar loop sensor.



(a) Background noises (b) Application of 20pC

(c) Application of 50pC (d) Application of 100pC

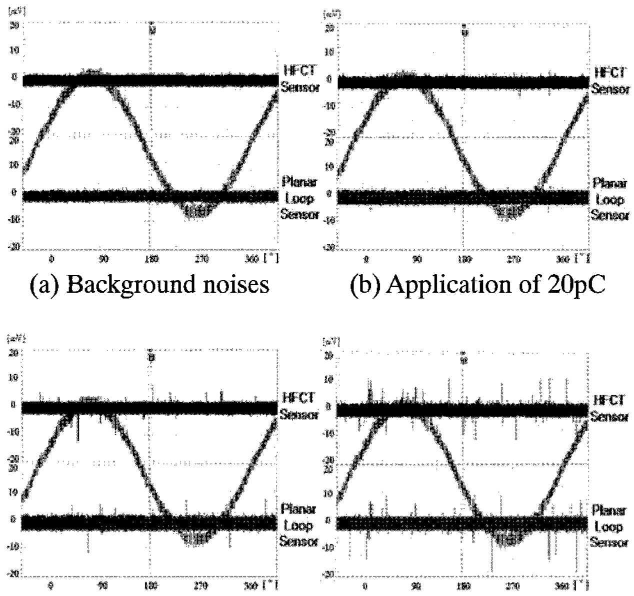
Fig. 7. Frequency characteristics of the planar loop sensor with calibration signals

In the characteristics of the background noises detected in a state without applying calibration signals as shown in Fig. 7 (a), certain characteristic noises were detected after the frequency of 83MHz and 100MHz. It is the abnormal signals generated from other power and communication devices in a laboratory that can be produced by the characteristics of antenna sensors and these signals were not detected in a HFCT sensor that has a low band property less than 30MHz. Also, it was not determined as calibration signals but certain noises based on the characteristics of its waveforms.

The detected sensitivity of the applied calibration signals as revealed in Fig. 7 (b)-(d) represented a linear property, such as -68dBm, -60dBm, and -53dBm for the application of 20pC, 50pC, and 100pC, respectively, in which it was verified that there were no differences in the maximum measurement gain compared to that of the HFCT sensor. However, it indicated certain differences in frequency bands that were considered in the design of antenna sensors and it was possible to verify a wide band determined as 10~60MHz. It showed more than twice for the detection band of the HFCT sensor and it was considered that the results increased the detection width of partial discharges that might have otherwise been lost due to the guarantee of broadbands.

(2) Phase analysis

Figure 8 illustrates the characteristic graph of the calibration signals for the signals measured in the HFCT and planar loop sensors. As shown in Fig. 8 (b), it was difficult to verify the detection characteristics of signals with the naked eye due to the surrounding noises. Also, the exact analysis was possible from the application of 50pC and the signals were verified through Fig. 8 (c) and (d). In the case of the application of 100pC, it was possible to verify the average voltage level determined by 10mV in which the detection sensitivity of the planar loop sensor was superior to that of the HFCT sensor by about 1~4mV.



(a) Background noises (b) Application of 20pC

(c) Application of 50pC (d) Application of 100pC

Fig. 8. Voltage characteristics in each sensor with calibration signals

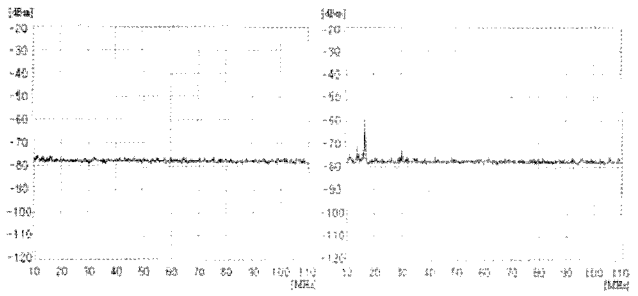
3.2.2 Evaluation of Partial Discharge Signals

A test was performed to apply commercial voltages after the experiment with calibration signals. The partial discharges generated in power cables showed different patterns in time and number of generations according to the deterioration condition and hardness of the cables. The cables applied in this study did not represent partial discharges as a quantitative manner but showed different detection characteristics according to the application conditions. In addition, noises generated by the high application voltage possibly affected this experiment. The experiment was performed by considering these characteristics and using the same method as the experiment with calibration signals. However, the voltage was applied from 500V with a rate of 1 [kV/s] in order to observe the state of lines and verify the breakdown voltage when the voltage was applied. In this study, the partial discharge was initiated from 20kV.

(1) Frequency domain analysis

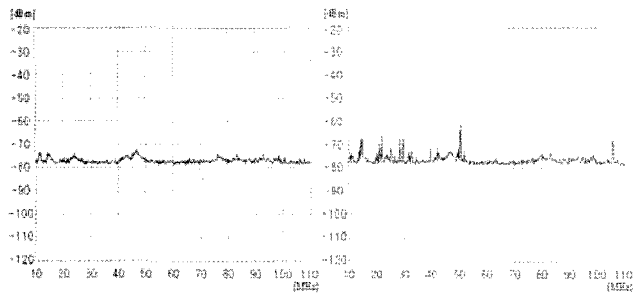
Figure 9 (a) and (b) show the frequency characteristics measured by using the HFCT sensor before and after the generation of partial discharges. In the case of the HFCT sensor, as illustrated in Fig. 9 (b), the partial discharges were only detected in a natural frequency range of 10~40MHz in the sensor itself when the partial discharges were generated. Also, the detection sensitivity when the partial discharges were generated was -60dBm. It was similar to the value of -58dBm produced by the calibration signal of 50pC.

Figure 10 (a) and (b) give the measured partial discharges generated after applying commercial voltages to the planar loop sensor proposed in this study. In Fig. 10 (b), the frequency bands of the antenna sensor were about 10~60MHz, similar to the frequency generated in the application of calibration signals.



(a) Application of 19kV (b) Application of 22kV

Fig. 9. Frequency characteristics of the HFCT sensor with commercial voltages



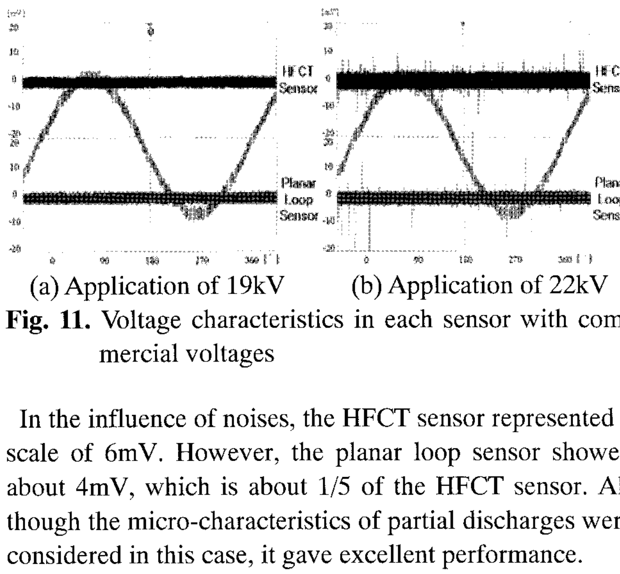
(a) Application of 19kV (b) Application of 22kV

Fig. 10. Frequency characteristics of the planar loop sensor with commercial voltages

(2) Phase analysis

The experiment applied in this section was attempted to verify the characteristics of partial discharges when the commercial voltages were applied using an oscilloscope. Each sensor was configured at a single screen in order to process observations at the same time when partial discharges were generated. The phases of applied voltages were configured to verify the location and pattern of occurred partial discharges. In addition, this experiment investigated to what extent noises did affect the HFCT and planar loop sensors.

Figure 11 provides the results of the scale and pattern of the partial discharges when the commercial voltages were applied. There were no particular partial discharges until the voltage of 19kV was applied and active partial discharges when the voltage of 22kV was applied. Fig. 11 (b) illustrates the results of the measured partial discharges for 1 minute after applying the specific voltage in which the patterns of partial discharges were observed according to changes in phases. In the comparison of the characteristics of signal levels for each sensor, the planar loop sensor showed larger voltages than the HFCT sensor by about twice and the detection frequency was a similar value in both sensors.



(a) Application of 19kV (b) Application of 22kV

Fig. 11. Voltage characteristics in each sensor with commercial voltages

In the influence of noises, the HFCT sensor represented a scale of 6mV. However, the planar loop sensor showed about 4mV, which is about 1/5 of the HFCT sensor. Although the micro-characteristics of partial discharges were considered in this case, it gave excellent performance.

4. Conclusion

This study designed and fabricated antenna-style sensors to improve the measurement sensitivity of partial discharges and control noises in XLPE underground distribution cables. Also, this study measured the return losses of the sensor. In addition, the characteristics of the planar loop sensor designed in this study were investigated by applying calibration pulse signals. Then, the detection performance of designed sensors was tested and analyzed using a HFCT sensor in the simulated cable lines with specific defects. The results of the test can be summarized as follows:

First, the IEE 6dB bandwidths of the planar loop sensor designed and fabricated in this study were about 25MHz~75MHz and that represented more wide bands than the conventional loop antennas whereas the maximum sensitivity showed a -19dB of return loss at 52MHz.

Second, in the results of the analysis of frequency characteristics, the frequency band of the planar loop sensor represented more wide bands than the HFCT sensor whereas the gains were the same in both cases.

Third, in the results of the scale of detected signals when the partial discharges were generated in cables, the planar loop showed larger values than the HFCT sensor about twice. It showed excellent detection performance compared to that of the HFCT sensor.

Fourth, in the results of the analysis of noises, the planar loop sensor minimized the affection of noises by about 20% compared to that of the HFCT sensor.

This study investigated the measurement performance of the proposed planar loop sensor and verified frequency bands and detection gains through applying experiments. In addition, it was verified that the influence of noise can be reduced to less than that of the conventional sensors. Futhermore, it was evident that the designed low-price sensor performed better diagnosis functions compared to that of high-price professional diagnosis sensors.

Acknowledgements

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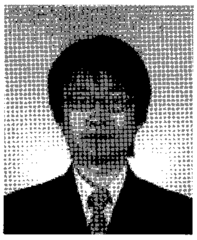

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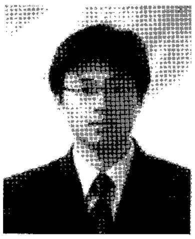

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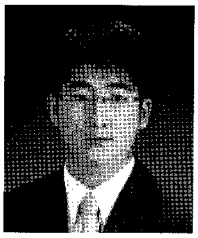

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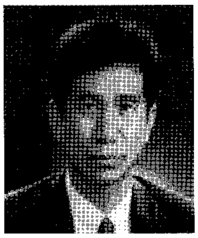

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