Paper

Effect of Lightning Protective Devices Attached to Pole Transformers on Reduction of Overvoltage on Distribution Lines

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Abstract: Class-10 A solid-core insulators (BIL 90 kV) have been used instead of class-6 A pin insulators (BIL 60 kV) in order to improve the insulation level of distribution lines. However, lightning protective devices attached to pole transformers may have the effect of reducing the overvoltages on phase conductors. We have investigated the lightning protection effect of devices attached to pole transformers by experiment and analysis using the EMTP (Electro-Magnetic Transients Program). The sparkover rate changes from 2.0~3.3% to 5.5~9.9% and increases 2.4~2.8 times when the line insulator of the phase conductors is changed from class-10 A to class-6 A. It is thought that the insulation level of the line insulator can be reduced depending upon the local particularities, such as number of installed transformers, frequency of direct lightning stroke to the distribution line, and so on although the overall fault rate may increase to some extent.

Keywords: lightning, lightning protection, transformer, lightning protective device, distribution line

1. Introduction

A decrease in the cost of the protection of distribution lines from lightning is required while maintaining their reliability.

Since the 1970s, several electric power companies have adopted class-10 A solid-core insulators instead of class-6 A pin insulators in order to avoid causing sparkovers at phase conductors due to lightning strokes. Since the 1980s, lightning protective devices such as insulators with built-in surge arresters for transformers, primary cut-out switches with built-in surge arresters, transformers with built-in surge arresters and so on have been developed and introduced into distribution lines in order to protect transformers [1]. Although the protection effects of transformers of such devices were studied in detail [2], the protection effects on phase conductors were not clarified fully. We considered that lightning protection devices might also have protective effects on phase conductors. Lightning protection effects of an insulator with a built-in surge arrester are affected by the position of the transformer. Considering these characteristics, we have investigated the lightning protection effect of insulators with built-in surge arresters attached to pole transformers by means of experiment and analysis using the EMTP.

2. Experimental Methods

Experiments were performed using an actual-size distribution line at the UHV Shiobara Testing Yard of CRIEPI. The schematic diagram of the experimental distribution line is shown in Fig. 1. The setup of the lightning protective devices was in accordance with the lightning protection design of Hokuriku Electric Power Company. The surge arresters were installed every four

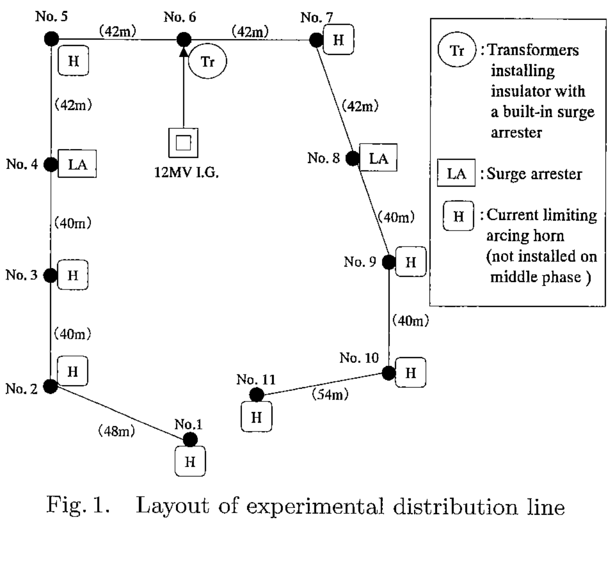

Fig. 1. Layout of experimental distribution line

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spans, and the insulators with built-in surge arresters were installed at the poles with transformers, and the current limiting arcing horns on outer two phase were installed at the remaining poles.

The configuration of the pole at which the lightning impulse current was injected is shown in Fig. 2. The experimental conditions are listed in Table 1. A direct stroke to a pole with transformers was assumed. A lightning impulse current was injected to the overhead ground wire (OHGW) for distribution lines with an OHGW, and was injected to the top of the pole or the outside phase conductor for distribution lines without OHGW. The peak value of the injected current was changed from 4 kA to 18 kA, and Tf (time-to-crest value of current) was changed from 0.5 μs to 3.5 μs. The transformer position (distance from a high-voltage crossarm to the transformer's attachment) was changed from 1.5 m to 8.0 m and the transformer earth resistance was changed from 55 Ω to 130 Ω.

The line insulator voltage was measured with a 100 kV probe when the injected current was low. In other cases, the line insulator voltage was calculated from the measurements of the phase conductor voltage to ground and the crossarm voltage to ground. Other items measured were the injected current, the current of the OHGW, the current of the insulator with a built-in surge arrester, and the current of the pole with the earth wire into the earth.

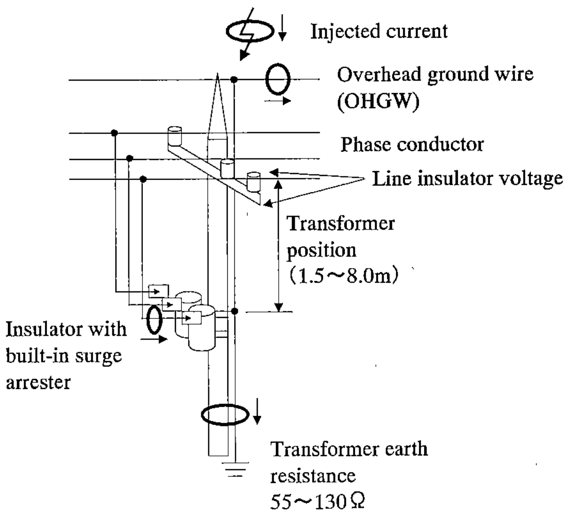


Fig. 2. Configuration of the pole at which the lightning impulse current was injected

Table 1. Experimental conditions

Item	Number	Conditions
Point of current injection	3	Overhead ground wire Top of the pole (without OHGW), Outside phase conductor (without OHGW)
Current peak value	3	4, 10, 18 (kA)
Current waveform	3	0.5/11, 1/11, 3.5/11 (μs)
Transformer position	4	150, 250, 500, 800 (cm)
Transformer earth resistance	3	55, 70, 130 (Ω)

3. Experimental Results

3.1 Influence of the Current Injection Point and Time-to-crest Value on Line Insulator Voltage The influences of the current injection point and time-to-crest value of the injected current on the line insulator voltage are shown in Fig. 3. In both cases, there is a linear relationship between the line insulator voltage and the injected current. The intercept of the approximate straight line with the y-axis corresponds to the discharge voltage of the insulator with a built-in surge arrester.

The line insulator voltage increases as Tf shortens in the case of a stroke to the OHGW, because the voltage generated by the inductance of the transformer lead wire and the concrete pole is proportional to the steepness of the current.

Regarding the current injection points, the line insulator voltage is smallest when the current is injected to the OHGW, which has many paths along which the current can flow. This clearly indicates the protection effect of the OHGW.

3.2 Influence of Transformer Position on Line Insulator Voltage The relationship between the line insulator voltage and the transformer position in the case of a stroke to the OHGW is shown in Fig. 4.

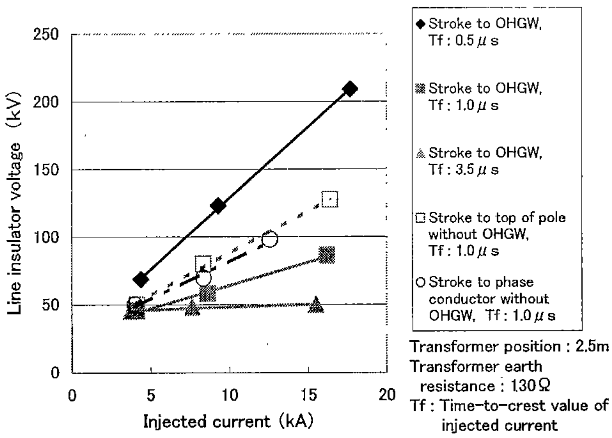


Fig. 3. Relationship between outside line insulator voltage and injected current

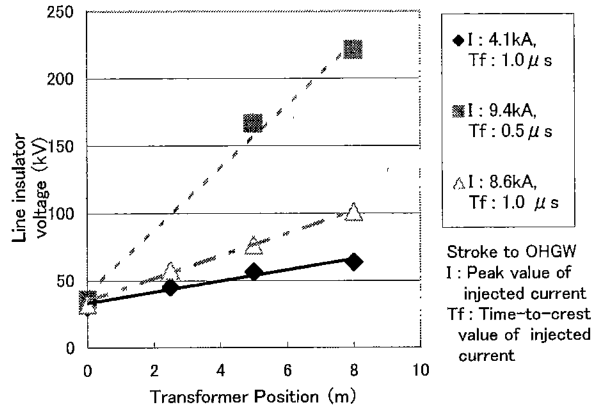


Fig. 4. Effect of transformer position on reduction of line insulator voltage

There is a linear relationship between the transformer position and the line insulator voltage. The reason for this is that the inductance of the transformer lead wire and the concrete pole is proportional to the length of them. If the transformer position is lowered, the overvoltage increases; in other words, the protection effect on the line insulator becomes small.

3.3 Influence of Earth Resistance on Line Insulator Voltage The relationship between injected current and line insulator voltage at various ground resistance values is shown in Fig. 5, in the case of a stroke to the OHGW with Tf of 1 μs.

It is found that the line insulator voltages are almost the same for different ground resistances. First, we consider that the current (Fig. 6, I_g) which flows into the earth and the current (I_{cp}) which flows through the concrete pole with an earth wire from the top to the transformer position become larger with a decrease of the earth resistance; on the other hand, the current (I_{tl}) which flows through the transformer lead wire becomes small. Therefore, the changes of currents (I_{cp}) and (I_{tl}) that cause line insulator voltage are counterbalanced, and the influence of the earth resistance on line insulator voltage becomes small.

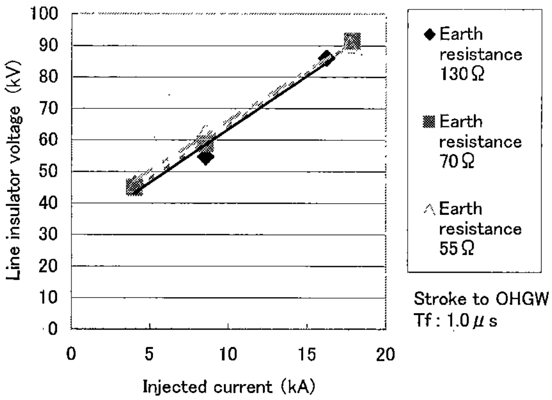


Fig. 5. Effect of earth resistance on reduction of line insulator voltage

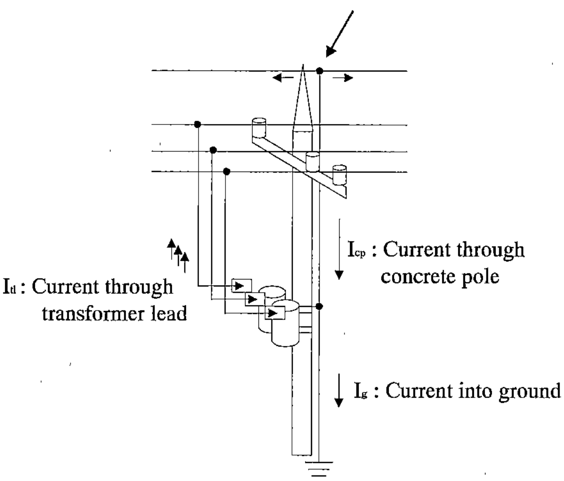


Fig. 6. Branches of lightning impulse current

4. Numerical Analysis

4.1 Analytical Method The EMTP was used for the analysis. First, the validity of the model was investigated by comparing it with the experimental results. Then, using a more generalized circuit, the sparkover rate of the distribution lines was calculated.

The analytical model of a pole with transformers is shown in Fig. 7. The calculation conditions are listed in Table 2.

For modeling the transformer lead wire and the concrete pole with an earth wire, the mutually-coupled R-L branch model which simulates the self-inductance and the mutual inductance between the leads and the pole, and the R-L-C branch model which simulates the electrostatic capacity, were used. The self-inductance of the transformer lead (L_1) was calculated from Eq. (1). Regarding the self-inductance of the pole (L_2), it is generally accepted that the surge impedance of a pole with an earth wire is 70~250 Ω. In this study, we adopted the value of 250 Ω [3][4] and the equivalent inductance was calculated using Eq. (2). For the part of the pole with

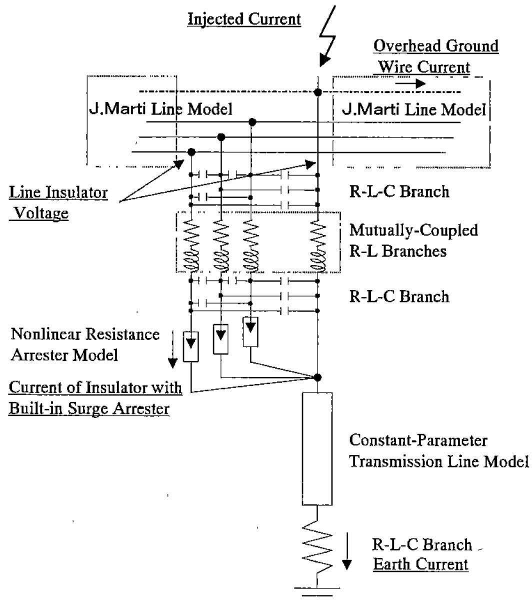


Fig. 7. Analytical model of a pole with transformers

Table 2. Calculation conditions

Item	Conditions
Hight-voltage conductor	OC 60sq
Ground wire	Fe 22sq
Grounding resistivity	800 Ω·m
Transformer lead wire	PDP 5.5sq
Surge impedance of concrete pole & its propagation velocity	250 Ω 300m/μs
Earth resistance of concrete pole	150 Ω
Earth resistance of transformer	70 Ω (steady resistance 130 Ω)
Insulator with a built-in surge arrester	$V_{2.5kA}$ = 20kV discharge voltage= 29kV
Surge arrester	$V_{2.5kA}$ = 20kV discharge voltage= 29kV
Current limiting arcing horn	$V_{2.5kA}$ = 20kV discharge voltage= 90kV

an earth wire below the transformer, the distributed-parameter line model of a surge impedance of 250 Ω was used.

An example of a comparison between an experimental result and an analytical result is shown in Fig. 8. This is the case of a stroke to the OHGW; Tf is 0.5 μs, and transformer resistance is 130 Ω. The measured waveforms agree with the calculated waveforms very well, except that there is noise in the measured waveforms. Similar analyses were carried out for other cases, and it is confirmed that the calculated results agree with the experimental result shown in Fig. 3. Therefore, it is concluded that this analytical model is applicable to the following analysis.

$$L_1 = \frac{\mu_0}{2\pi}\left\{ l \log\left(\frac{l+\sqrt{a^2+l^2}}{a}\right) - \sqrt{a^2+l^2} + a \right\} \quad \cdots\cdots (1)$$

l: Length (m), a: Radius (m)

$$L_2 = \frac{Z_0}{c_0} l \quad \cdots\cdots (2)$$

Z_0: Surge impedance (Ω)

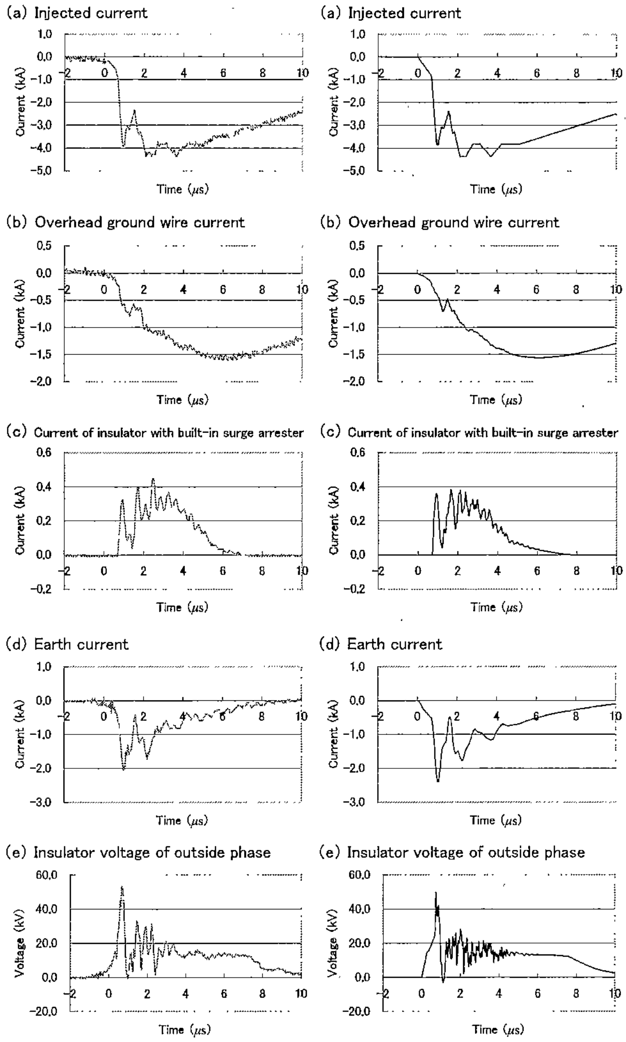
c_0: Velocity of light (3.0 × 108 m/s)

4.2 Calculation of Sparkover Rates The probability of sparkover at the line insulator, which supports a phase conductor by one direct lightning stroke to the pole with transformers, is defined as the "sparkover rate". Class-6A and class-10 A solid-core insulators were compared in terms of sparkover rate.

In this calculation, it was assumed that the transformer position was 2.5 m, and the earth resistance of the transformer was 100 Ω. These set values are standard design values used by Hokuriku Electric Power Company that examines the decrease of the insulation level.

The injected lightning current waveform was a ramp wave. Because the peak value and the time-to-crest value have a significant influence on the line insulator voltage, they were considered as statistical parameters. The statistical distributions of these parameters were assumed to be logarithmic normal distributions with the 50% and 16% values shown in Table 3. The time-to-half value of the current was fixed at 70 μs, because the line insulator voltage is small at the wave tail and the influence of the time-to-half value on the line insulator voltage is small, and this value has been used in reseaches into the lightning protection design of distribution lines [6][7].

The length of the distribution line model was eight spans (320 m) to one side from the current injection point and the phase conductors were terminated with 400 Ω in order to prevent reflections. It was assumed that the surge arresters were installed at intervals of four spans and the current limiting arcing horns were installed at the remaining poles as well as shown in Fig. 1. It is considered that the reflection from the surge arresters that are farther than eight spans from the current injection point may reduce the line insulator voltage if the time-to-crest value is long. Therefore, arresters that



(1) Measured waveforms (2) Calculated waveforms

Fig. 8. Comparison between measured waveforms and calculated waveforms (Stroke to OHGW, time-to-crest value of injected current is 0.5 μs, transformer earth resistance is 130 Ω)

correspond to those of 30 spans were installed at the eighth span in the calculation, and it was confirmed that the difference in the line insulator voltage of the current injection pole was less than 1% from the value without the arresters.

Regarding the sparkover voltage of the line insulator, the 50% flashover voltages shown in Table 4 were used. These are the measured values. Using the 50% flashover voltages with the time-to-half value of 50 μsec is a safety side because the sparkover voltages may rise with shortening of the length of the time-to-half value [8].

The sparkover rate was calculated as follows. First, the injected current threshold that generated the sparkover at each time-to-crest value was calculated, as shown in Fig. 9. Next, the sparkover rate in relation to the stroke point and the type of line insulator was calculated using Eq. (3), as shown in Fig. 10. The probability density functions of the lightning current peak and the time-to-crest value were assumed to be independent.

It is shown in Fig. 10 that the sparkover rate changes from 2.0~3.3% to 5.5~9.9% and increases 2.4~2.8 times when the line insulator of the phase conductor is changed from class-10 A to class-6 A. There is a possibility that the sparkover rates of both line insulators may be smaller for the real case, because we adopted the 50% flashover voltage and did not take the v-t characteristics into consideration.

The sparkover rate according to the stroke point becomes the order of stroke to top of pole ≧ stroke to phase conductor > stroke to OHGW. Therefore, the protection effect is greatest when there is an OHGW.

$$p_f = \int_0^{+\infty} \left\{ \int_{y(T)}^{+\infty} f(I)dI \right\} g(T)dT \quad \cdots\cdots\cdots\cdots (3)$$

$f(I)$: Probability density function of peak value I

$g(T)$: Probability density function of the time-to-crest value T

$y(T)$: Minimum current required to sparkover for the time-to-crest value T

Table 3. Cumulative frequency distribution of lightning current waveform

Parameter	50%-value	16%-value	Ref.
Peak value (kA)	26	55	(1)
Time-to-crest value (μs)	3.5	2.3	(5)

Table 4. Sparkover voltage of insulator

Insulator	50% flashover voltage (positive 1.2/50 μs)
Class- 6A	96 kV
Class-10A	150 kV

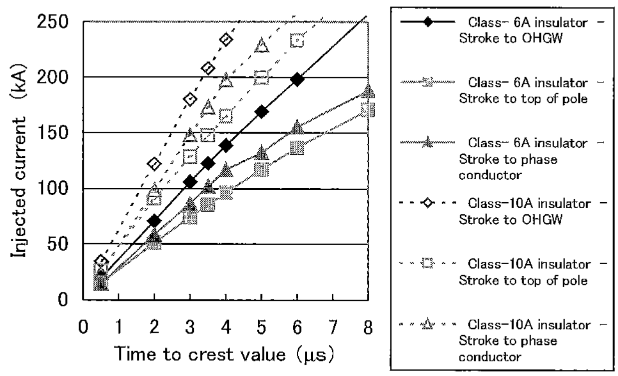


Fig. 9. Relationship between time-to-crest value and peak current for line insulator sparkover

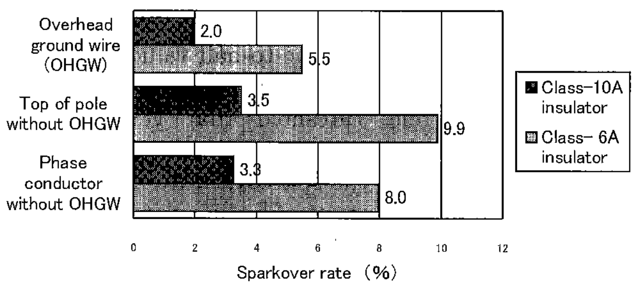


Fig. 10. Effect of insulation level of distribution lines on sparkover rate

5. Conclusions

By experiment and analysis, the influence of using line insulators with decreased insulation strength to support the phase conductors was examined, considering the protective effect of the lightning protective device (insulator with a built-in surge arrester) attached to the transformer. The main results are as follows.

(1) The line insulator voltage of a phase conductor is the sum of the voltages of the inductance of the transformer lead wire, the pole, and the discharge voltage of the insulator with a built-in surge arrester when there is a direct stroke to the pole with transformers. Therefore, the line insulator voltage has a linear relationship with the steepness of current and the transformer position. It is preferable that the position of the transformer installed with the insulator with a built-in surge arrester be close to the phase conductor to increase its protective effect on the phase conductor.

(2) The influence on the line insulator voltage of the earth resistance of the transformer is small in the case of a stroke to the OHGW. The reason for this is that the change of earth resistance increases the current to the earth and decreases the current to the transformer lead wire. The two effects compensate for one another and thus the line insulator voltage remains almost constant.

(3) The sparkover rate changes from 2.0~3.3% to 5.5~9.9% and increases 2.4~2.8 times when the line insulator of the phase conductors is changed from class-10 A to class-6 A. The sparkover rate according to the stroke point becomes the order of stroke to top of pole ≧ stroke to phase conductor > stroke to OHGW. Therefore, the protective effect is greatest when there is an OHGW.

It is thought that the insulation level of the line insulator can be reduced depending upon the local particularities, such as number of installed transformers, frequency of direct lightning stroke to the distribution line, and so on although the overall fault rate may increase to some extent, because the sparkover rate is the value assumed for the direct stroke to the pole with transformer.

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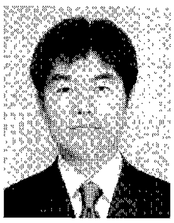

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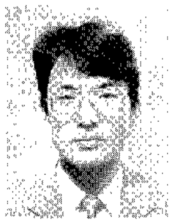

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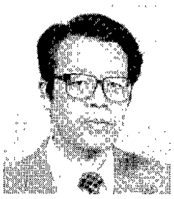

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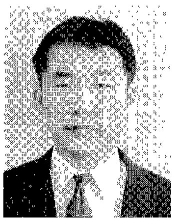

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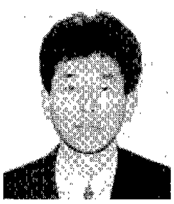

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