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PAPER

Evaluation of Lightning Surge Characteristics Induced in Subscriber Line at Telecommunication Center End in a Tropical Area

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SUMMARY Lightning surges induced on subscriber lines in Kuala Lumpur, Malaysia, which is located in a tropical region, were observed at telecommunication centers. More than 100 surges per line were observed during a three-month period. Peak values, observed using a lightning surge counter, show that lightning surge current occurrences normalized by the number of thunderstorm days and number of subscriber lines closely agreed with data observed in temperate areas, e.g., Japan. Surge waveforms appearing at several points ranging from underground cable ducts to exchange equipment were observed using a wave memory system. The results show that lightning surge currents on the cables were larger than those on a wire, but the correlation between them was weak. Common and differential mode surge waveforms observed using the wave memory system were almost the same. These results will be useful in designing protection circuits for equipment used in tropical areas.

key words: *EMC, lightning, measurement, surge, telephone equipment*

1. Introduction

Highly reliable telecommunication systems are required in an advanced information network providing multimedia telecommunications. Therefore, technologies that provide protection from lightning surges are important to maintain the reliability of the telecommunication system [1], [2]. In particular, recent telecommunication systems have lower resistibility to lightning surges because they use high-speed semiconductor devices that are easily damaged by them. Therefore, protection technology, systems, and devices with higher resistibility should be developed. In addition, though most telecommunication equipment is used worldwide, it is well known that the number of lightning strokes varies depending on the geographical location. In particular, tropical areas have a lot of lightning, around ten times as much as temperate areas [3]. However, telecommunication equipment is usually tested using a method developed based on the lightning in temperate zones. Thus, we should study how to estimate and improve the resistibility of equipment operating in tropical areas [3], [4]. Lightning has been studied by many researchers, and many papers have reported the current distribution of direct strikes, the number of surges induced per lightning strike, and the direction of current flow [5]. Lightning surges appearing at the subscriber end and their induction mechanisms have also been studied [3], [4], [6], [7]. The influence of the horizontal electric field component generated by lightning and the difference between near and far lightning have been clarified. However, most studies have been carried out for a simple telecommunication line model, such as one straight conductor above the ground [7]. Although lightning surges were observed at actual subscriber lines, they were measured between conductors and the ground [5]. The relationships between voltage and current and between common mode and differential mode surges have not been obtained when a subscriber line is connected to an actual subscriber line interface card (SLIC). These characteristics are needed in order to design protection systems and circuits. Although these characteristics are also needed in temperate areas, the relationship between surges in temperate and tropical areas has not yet been clarified. In this paper, to investigate the relationship between lightning surges in tropical and temperate areas, we observed lightning surges induced at the subscriber line end at telecommunication centers in Kuala Lumpur, Malaysia. The lightning surge waveform distributions were compared with distributions in Japan. The induced lightning surges, which appeared at several points between the cable duct at the center and the exchange equipment were investigated to obtain data for designing a protection system in the center and protection circuits for the telecommunication equipment. The relationships between the surges at a cable and pairs in the cable and between common and differential mode surges in each pair were investigated.

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2. Observation Method

2.1 Observation Place

The lightning surges were observed in telecommunication centers in Kuala Lumpur, Malaysia. In this tropical area, about 200 days per year have thunderstorms, which is about ten times as many as in Japan, which is located in a temperate area.

2.2 Equipment Used for Observations

The lightning surges were observed using two types of systems: a surge counter and a wave memory. The lightning surge counter was used to observe the occurrence frequency of the lightning surge peak value. Its specifications are listed in Table 1. It counted the number of surges during the measurement period of one minute and stored the data in a memory card. Its memory can store 6000 data records and it can operate for about three months on batteries. It has nine detection ranges (Table 2), which were determined from the sensitivity of the probes. According to data acquired in Japan, most peak values at the telecommunication center end are less than 2000 V [6], so the values were set from 20 to 2000 V.

Table 1 Specifications of lightning surge counter.

Input impedance	1 MΩ
Input Capacitance	30 pF
Minumum detection pulse width	2.0 μs
Minimum detection pulse rise time	0.5 μs
Detection repeatedly speed	200 μs
Maximun data number	6000

Table 2 Detection ranges of capacitve voltage probe.

Counter level	Voltage (V)
1	20–40
2	40–60
3	60–100
4	100–200
5	200–400
6	400–600
7	600–1000
8	1000–2000
9	2000–

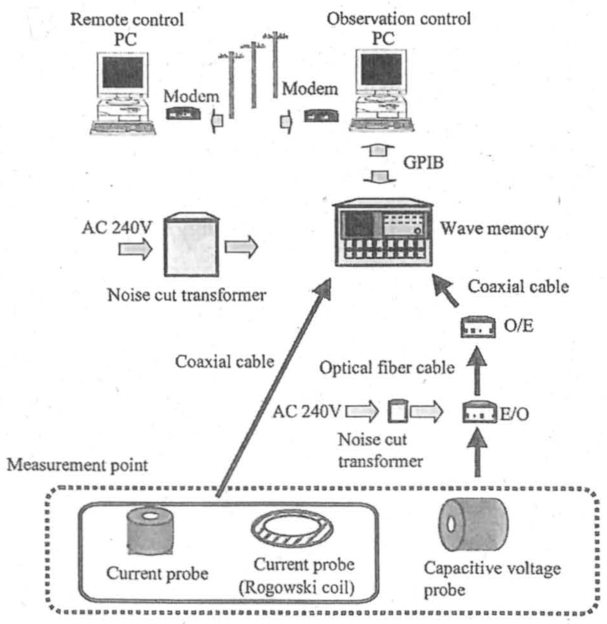


Fig. 1 Wave memory system for observing lightning surge waveforms.

The wave memory system was used to measure the lightning surge waveforms. Its configuration is shown in Fig. 1. The specifications used for the observations are summarized in Table 3. A digital memory with a sampling rate of 500 ms to 10 ns and memory size of 64 kilo-words per channel was used. The digital memory was controlled by a personal computer, which was remotely controlled from Japan via the telecommunication network. Noise-cut-transformers were used for isolation at the AC mains port. An optical fiber system was used to isolate the observation point from the point where the wave memory was placed. A current probe (Peason CT488) was used to measure the surge current on each wire or each pair. A Rogowski coil [8] was used to measure the surge current on the cable. An example of the Rogowski coil installation at a cable is shown in Fig. 2. This coil is a kind of current probe, and its frequency response is almost flat from 10 kHz to 1 MHz, where the major lightning surge energy component is. We used a capacitive voltage probe [9] to measure the lightning surge voltage. Its external view is shown in Fig. 3. This probe measured the voltage between a conductor and ground via capacitive coupling. This is useful for measuring the voltage of an in-service cable because it does not require contact with the wire transmitting the communication signal in order to measure the lightning surge. The probe is composed of two coaxial conductive cylinders and a high-input-impedance voltage probe. The outer conductor acts as an electrostatic shield to reduce the measurement error. The high-impedance probe (input impedance $>$ 1 MΩ, parallel capacitance $<$ 10 pF) is connected between the outer and

Table 3 Specifications of wave memory.

Sampling rate	10 ns to 500 ms
Frequency range	DC(40 Hz) to 5 MHz
Memory length	64 kWord
Supply voltage	90 to 110 V_{AC}
Power	700 W
Dimensions	420 W × 249 H × 573 L (mm)
Weight	31 kg

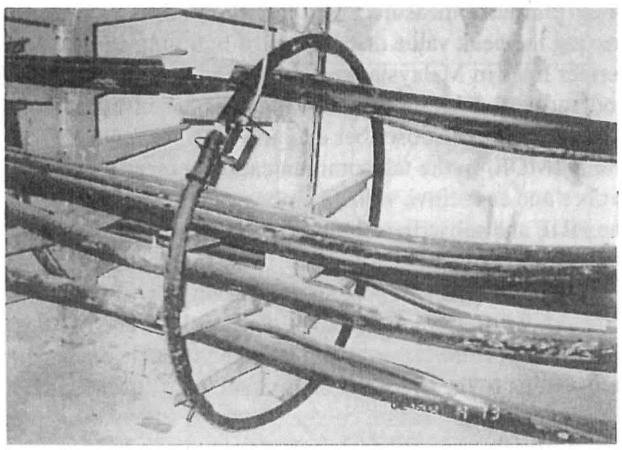


Fig. 2 External view of Rogowski coil installation.

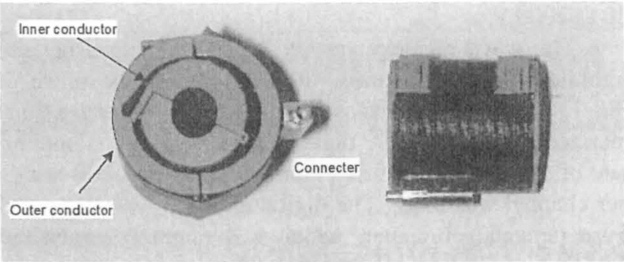


Fig. 3 External view of capacitive voltage probe.

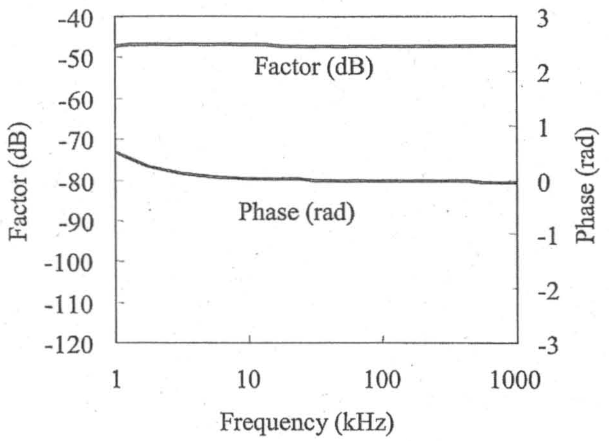
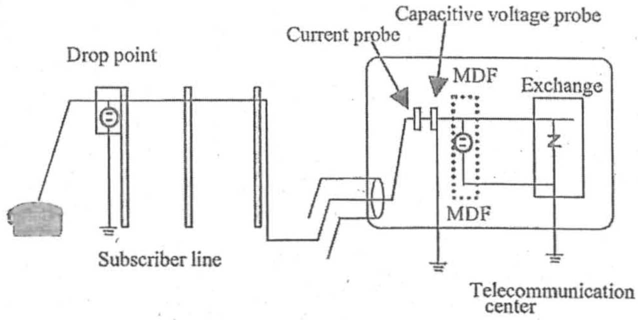


Fig. 4 Frequency response of capacitive voltage probe.

inner connectors. The frequency response of the probe is shown in Fig. 4. The conversion factor from the common mode voltage to the output voltage was almost constant from 1 kHz to 1 MHz. This is sufficient for measuring the lightning surge.

2.3 Observation Conditions

Lightning surges were observed at two telecommunication centers. At one, the lightning surge occurrence frequency was measured and at the other, the lightning surge waveforms induced in a cable, one pair of the cable, and one wire of the pair were measured. Figure 5 shows the set-up for observing the peak value distribution of lightning surges. Subscriber lines in Malaysia are constructed with overhead and underground cables. Protection devices are installed at the drop point of the subscriber end and at the main distributed frame (MDF) in the telecommunication center. The current probes and capacitive voltage probes were installed between the MDF and subscriber cable to measure the common mode current and voltage of each line. The surge counters were used to measure them. Five subscriber lines, with lengths of 1.08 to 6.9 km, were selected for observation. The lightning surge waveforms at several points from the cable entry point at the center to the exchange equipment were observed at another telecommunication center. Figure 6 shows the set-up for observation. 28 subscriber cables arrive at the telecommunication center. Lightning surge current waveforms were



Line No.	Distance from center (km)	Cable length (km)
1	0.31	3.12
2	0.45	1.08
3	0.98	1.36
4	3.69	6.9
5	1.01	1.26

Fig. 5 Set-up for observing lightning surge occurrence at subscriber line end.

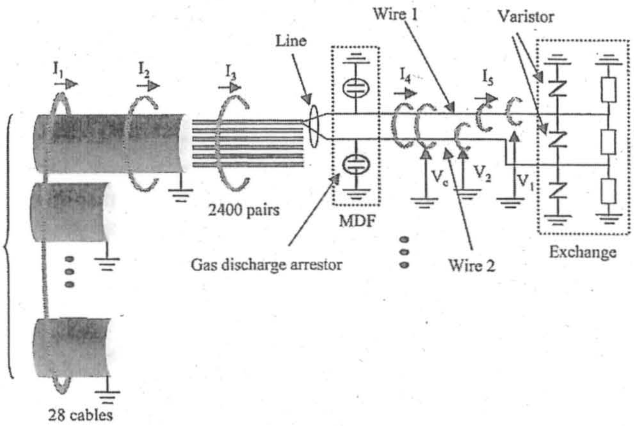


Fig. 6 Set-up for observing lightning surge characteristics.

measured at the following five points:

1. all cables, I_1,
2. one of the cables before its metallic sheath grounding, I_2,
3. the cable after the sheath grounding, I_3,
4. one pair of the cable, I_4, and
5. one wire of the pair, I_5

Currents I_1, I_2, and I_3 were measured using the Rogowski coil (Fig. 2), and I_4 and I_5 were measured using the current probe. Lightning surge voltages V_c, V_1, and V_2 were measured at the following three points:

1. between a pair and ground, V_c,
2. between one wire of the pair and ground, V_1, and
3. between the other wire of the pair and ground, V_2.

The voltages were measured using the capacitive voltage probe (Fig. 3) and an optical fiber isolation system was used to isolate the observation point from the wave memory. The

2400 pairs observed using the wave memory (Fig. 1) were in service when observed, so their telecommunication terminals were connected at both ends.

3. Observation Results

3.1 Differences between Malaysia and Japan

3.1.1 Occurrence Frequency of the Lightning Surge Current

The peak values of lightning surges current were observed from Feb. 19th 1998 to April 17th 1998 using the set-up shown in Fig. 5. During this period, there were 35 thunderstorm days. We obtained 669 sets of data. The peak value occurrence normalized by the number of thunderstorm days is shown in Fig. 7. The horizontal axis is the amount of peak surge current and the vertical axis is the occurrence frequency per thunderstorm days and lines: F_0, which is given by

$$F_0 = \frac{n}{DM}, \tag{1}$$

where, n is the number of lightning surge which exceed a certain value. D is the number of thunderstorm days (D = 35), M is the number of lines (M = 5). Solid triangles are for lightning surges observed in Malaysia and solid lines show the peak value distribution observed in Japan [10]. The peak values measured in Malaysia almost agree with the data at the subscriber end in Japan over the lighting surge current of 10 A, which is given by

$$F_{i_0} = 11 I_p^{-1.8}. \tag{2}$$

In Japan, the subscriber cable sheath in the center is connected to the MDF ground. However at the site in Malaysia, the observed cable sheath was not connected to the MDF ground, but the cable sheath at the subscriber end was not connected to the ground of the primary protection circuit either. This is why the observed values agreed well with the Japanese subscriber end data, because they were observed when the cable sheath was not connected to ground at the observation side. From this results, if we assume that the peak value occurrence normalized by thunderstorm days in a tropical area is the same as that in a temperate area, the lightning surge occurrence of over 10 A at a telecommunication cable in a tropical area is ten times as high as in a temperate area, because there are ten times as many thunderstorm days. This result is informative to design the protection systems and circuits in tropical area.

3.1.2 Occurrence Frequency of the Lightning Surge Voltage

Figure 8 shows the lightning voltage occurrence. The horizontal axis is the peak value and the vertical axis is the occurrence frequency given by Eq. (1). The capacitive voltage probe (Fig. 3) was used to measure the surge voltage appearing between a line and ground (Fig. 5), and the lightning surge counter was used to store the observed data. The observation period was the same as for the lightning surge current observations and 669 sets of data were also obtained in this period. In Fig. 8, circles indicate observed values and the solid line shows the trend, given by

$$F_{v_0} = A V_p^q, \tag{3}$$

where V_p is the peak value A and q is a constant representing the distribution. We calculated A of 4×10^2 from the observed values and used q of -1.8 for the distribution in Japan [6]. The A value for Japan is 6×10^4, which is about 150 times the observed values in Malaysia, which had different observation conditions from Japan. The Japanese data was observed on lines having both ends terminated by 200 Ω

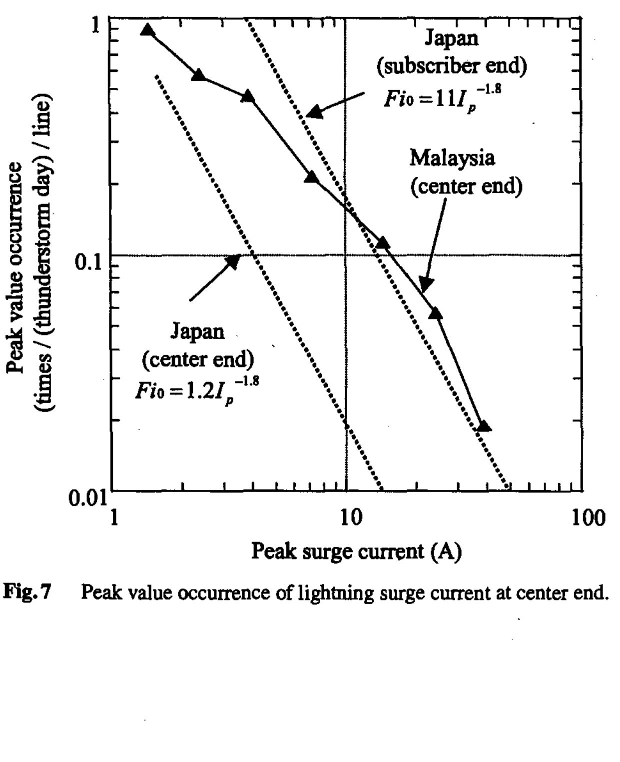


Fig. 7 Peak value occurrence of lightning surge current at center end.

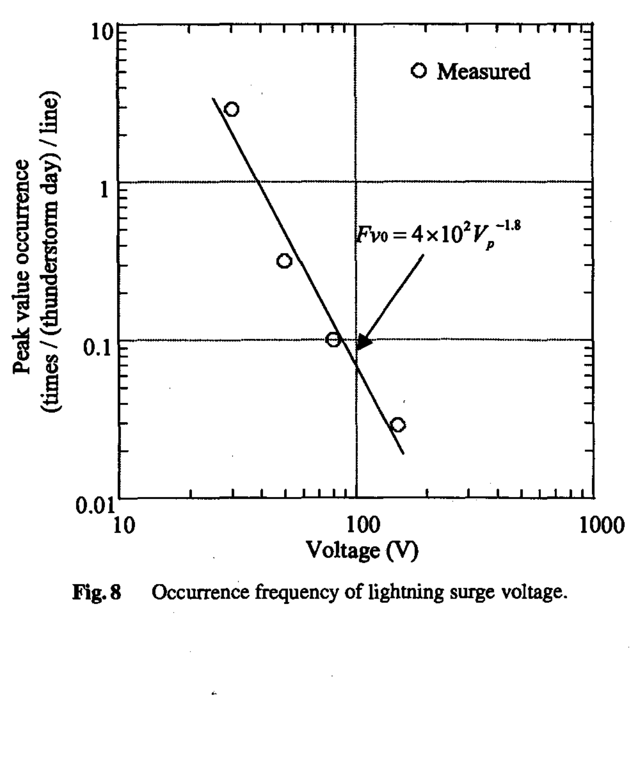


Fig. 8 Occurrence frequency of lightning surge voltage.

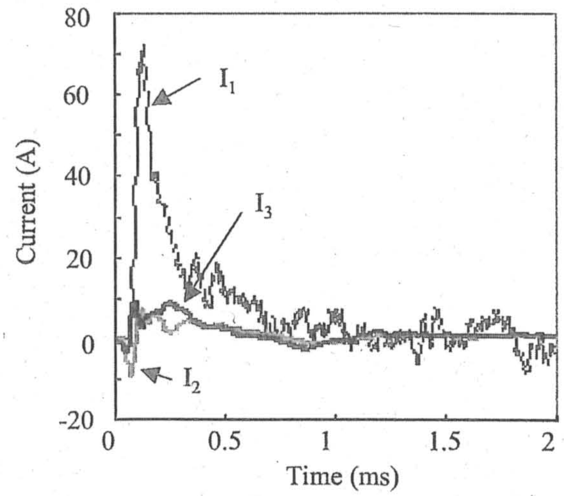
between conductors and ground. In Malaysia, we observed surges at the lines, which is used for service and terminated to ground by a low resistance while protection devices (e.g., a varistor or arrester) were operating. When the impedance between wires and ground is calculated assuming that the occurrence frequency of the current and voltage is equal, the impedance of Malaysia is 7.4 Ω and that of Japan is 120 Ω respectively. The occurrence frequency in Fig. 8 is obtained from the data when the protection device not operating because the voltage was clipped at the operational voltage of the devices. In this case, the termination impedance might be more than 100 Ω. This means that the difference of the terminal impedance could not explain the difference of the *A* values. Although we can not find the reason why the occurrence frequency of the voltage is different between Japan and Malaysia, the observations indicate that the occurrence frequencies of voltage and current are proportion to −1.8th power in both Japan and Malaysia. This is important information to design the lightning protection system in tropical area.

3.2 Lightning Surge Difference between Cable and Line

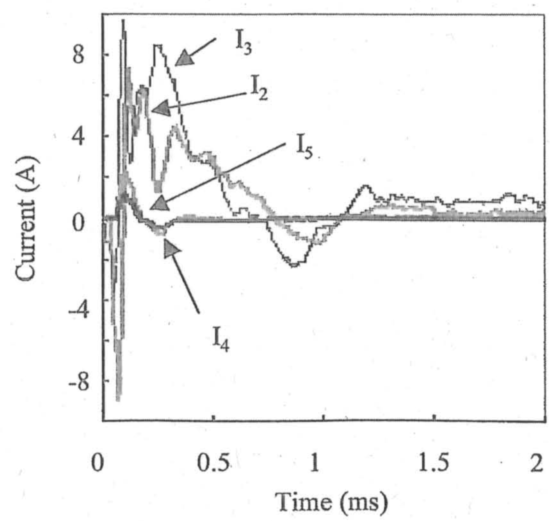
Subscriber cables are composed many pairs of line, and a pair of lines are used for telecommunication like Figs. 5 and 6. The lines are connected between users and a telecommunication center, and they are distributed around the center like a net. When a lighting discharge appears at a point in this net, a different surge current could be induced on each line. The lightning surge current on the cable might simply be the sum of the currents on all the lines. If these assumptions are true, then a significantly large current could flow in the cable, but they had not previously been confirmed by actual observation, so we decided to observe the lightning surge current in cables and lines induced by the same lightning discharge. Lightning surge waveforms at cable and lines were observed from March 20th 1999 to March 10th 2000 using the set-up shown in Fig. 6. From 116 to 193 data (depending on the position) were observed during this period, as shown in Table 4. Figure 9 shows an example of lightning surge current waveforms that were identified as being caused by the same lightning discharge. Figure 9(a) shows the waveforms of I_1, I_2, and I_3 and Fig. 9(b) shows those of I_2, I_3, I_4, and I_5. The peak value of I_1 is significantly larger than those of other waveforms. As the current flowed from point I_1 to I_5, the peak values, front time, and time to half value of the waveform became smaller, slower, and narrower. The relationships among peak values are shown in Fig. 10. The horizontal axis is the peak value of I_1 and the vertical axis is the peak value of I_2, I_3, I_4, or I_5. The dots in this figure are values identified as being caused by the same lightning. The correlation coefficient is 0.56 for Fig. 10(a), 0.37 for Fig. 10(b), 0.11 for Fig. 10(c), and 0.05 for Fig. 10(d). These results show that I_1 had little correlation with I_2, I_3, I_4, and I_5 due to each lightning, which means that the lightning surge current flow was unevenly distributed among the 28 cables, because those cables were widely distributed in the service area and at various distances from the lightning stroke point. However, the relation between I_1 and I_4 or I_5 is important for designing the protection system in the center building. Then we try to an-

Table 4 Avarage values of waveform parameters.

		I_1	I_2	I_3	I_4	I_5
Peak value (A)	Average	41.0	12.3	18.7	0.7	0.4
	A value in Eq. (3)	1.8	1.7	1.7	1.1	1.1
	q value in Eq. (3)	-0.03	-0.06	-0.1	-1.1	-1.9
Front time (μs)	Average	87.2	46.6	48.0	42.9	43.9
	Standard deviation	52.6	33.8	39.6	19.4	32.4
Time to half value (μs)	Average	198.6	170.3	105.9	62.8	69.6
	Standard deviation	113.4	120.8	78.1	38.5	34.6
Number of data		123	192	193	116	133



(a) Current I_1, I_2, and I_3



(b) Current I_2, I_3, I_4, I_5

Fig. 9 Example of observed lightning surge waveforms.

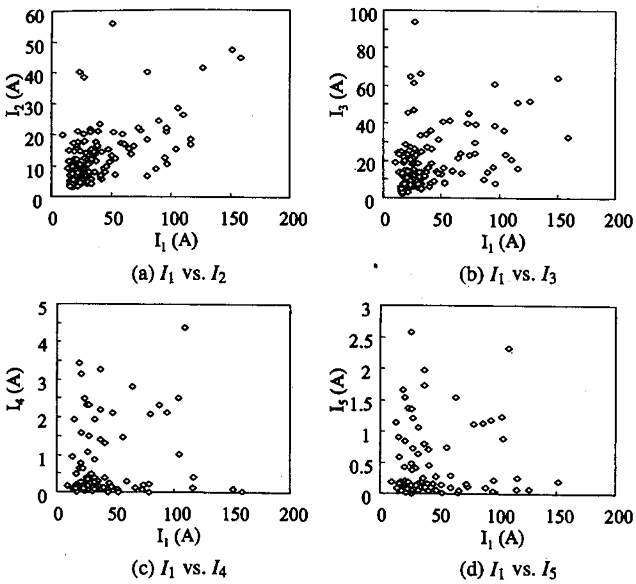


Fig. 10 Relationships between the total current I_1 and other points current I_2, I_3, I_4, and I_5.

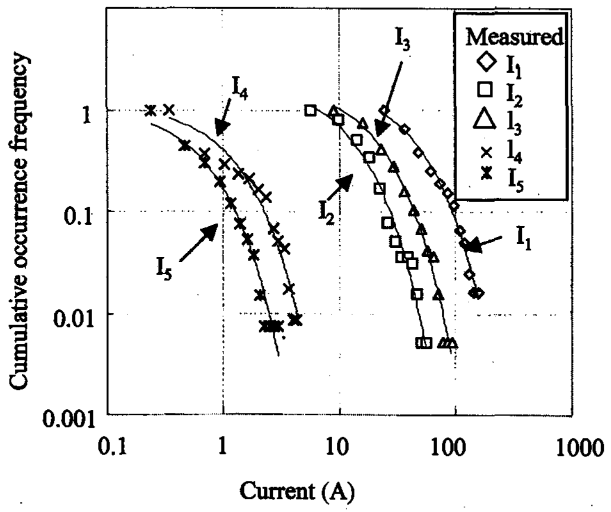


Fig. 11 Cumulative occurrence frequency of peak value.

alyze another point of view, which is the cumulative occurrence frequency. The cumulative occurrence frequencies of the peak values are shown in Fig. 11. The horizontal axis is the peak value and the vertical axis is cumulative occurrence frequency, given by

$$C_0 = \frac{n}{N}, \tag{4}$$

where N is the total number of data (from 116 to 193, as shown in Table 4) and n is a number of data which exceed a certain value. The cumulative occurrence frequency is almost proportional to the exponent of the peak value, and is given by

$$C_0 = Ae^{-qI_p}, \tag{5}$$

where A and q are constants, as shown in Table 4. The solid lines in Fig. 11 are the trend curves calculated by Eq. (5). These currents all had similar trends as the observation point changed from I_1 to I_5. Figure 11 shows that the peak value occurrence of I_1, I_2, and I_3 was more than 10 times that of I_4 and I_5. This means that I_1 and I_2 both measure the current flowing on the cable sheath. The number of wires contributing to the measured current decreased as the observation point changed from I_1 to I_5. On the other hand, the cable had 2400 pairs. If the surge current of all the pairs were summed, the total current I_3 might be 2400 times I_4. However, this was not found, indicating that it is difficult to estimate the surge current on a cable from the value for one pair. The occurrence frequencies of front time and time to half value are shown in Fig. 12. The horizontal axis is the time in milliseconds and the vertical axis is the occurrence frequency. The standard deviations of front time and time to half value are shown in Table 4. They became smaller as the observation point changed from I_1 to I_5. The reason for this has not been clarified and remains for future work. The averages of the waveform parameters are summarized in Table 4. The ratio of peak value at one wire to that at the cables is 1:100.

From these considerations, we should observe the lightning surges appearing at both cables and pairs. The former data might be used to design the protection system in the telecommunication buildings, for example the grounding system, while the latter might be used to design protection circuits such as those for the MDF and SLIC.

3.3 Difference between Common and Differential Modes

We observed the lines, which were inserted in the line a varistor with an operating voltage of 120 V and a gas tube arrester with an operating voltage of 230 V as Fig. 6. The line length was about 2 km and there was no surge protector at the subscriber end. The capacitive voltage probe (Fig. 3) was used to measure the voltage between each wire and ground V_1 and V_2, and common mode voltage V_c. Because of a pair of telecommunication lines is a pair of two-conductor symmetrical lines, the differential mode voltage V_d was calculated from the voltage in each wire using the following equation.

$$V_d = V_1 - V_2. \tag{6}$$

Examples of the waveforms are shown in Fig. 13. Figures 13(a) and (b) are the waveforms when the varistors operated, and Figs. 13(c) and (d) are the waveforms when they did not. The observed common mode voltage V_c in Figs. 13(b) and (d) is the mean value of the voltage between a wire and ground, V_1 and V_2, in Fig. 6. This relationship is given by

$$V_c = \frac{(V_1 + V_2)}{2}. \tag{7}$$

When the varistors operated, the common mode voltage was clipped by the varistor voltage, as shown in Fig. 13(b) and the surge current appeared as shown in

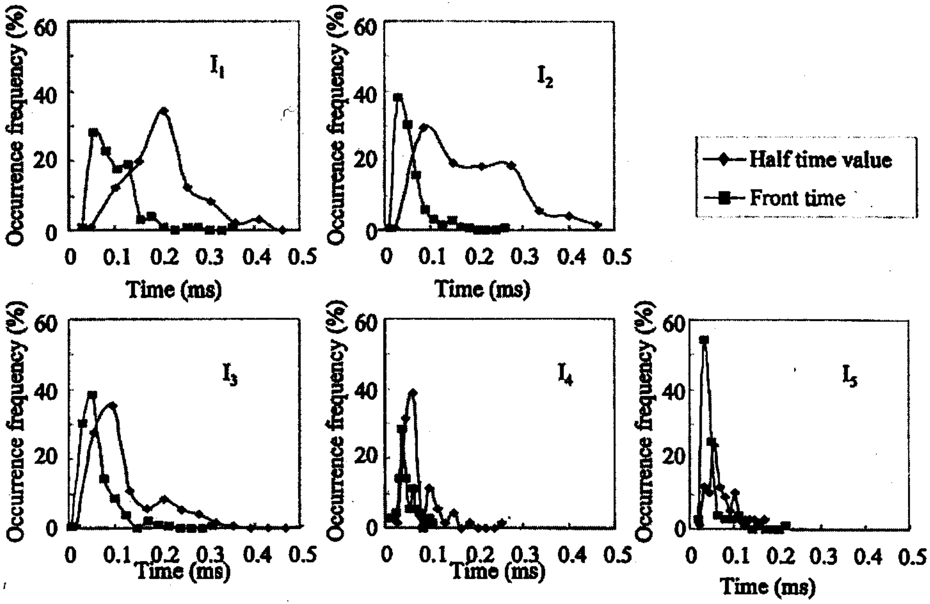
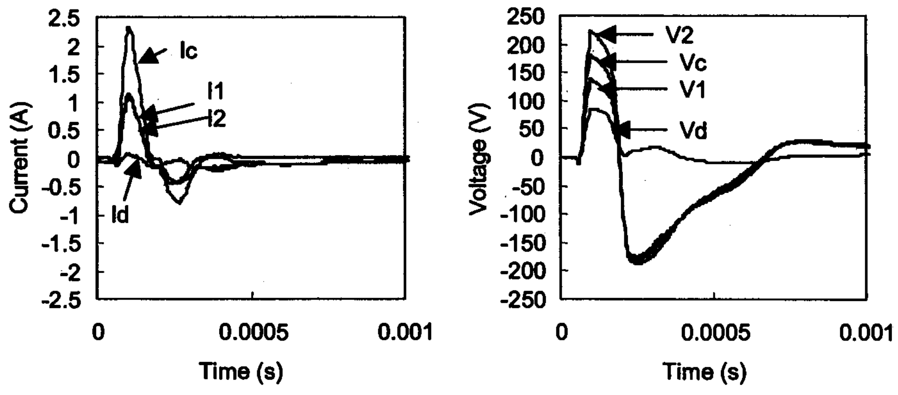


Fig. 12 Occurrence frequencies of front time and time to half value at I_1, I_2, I_3, I_4, and I_5.



(a) Current when protection circuit is operating (b) Voltage when protection circuit is operating

(c) Current when protection circuit is not operating (d) Voltage when protection circuit is not operating

Fig. 13 Example of observed lightning surge wave forms appearing between wires and ground and between wires.

Fig. 13(a). The varistors had various different operating voltages, so a differential mode voltage appeared as shown in Fig. 13(b). When the varistors did not operate, the differential mode voltage, which was generated only by the unbalance on the line, was small because the unbalance on the line was small in the frequency range of the lightning surge.

193 waveform sets were identified as being induced by the same lightning stroke. The correlations between the

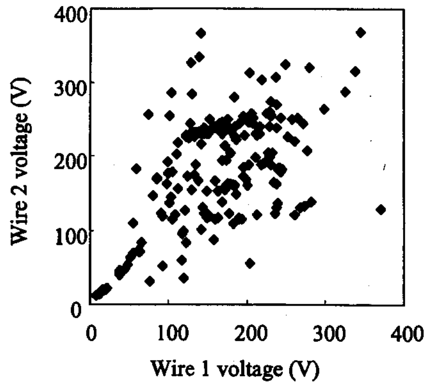
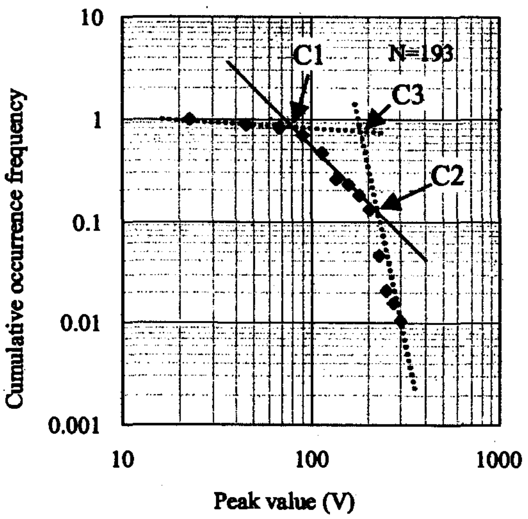
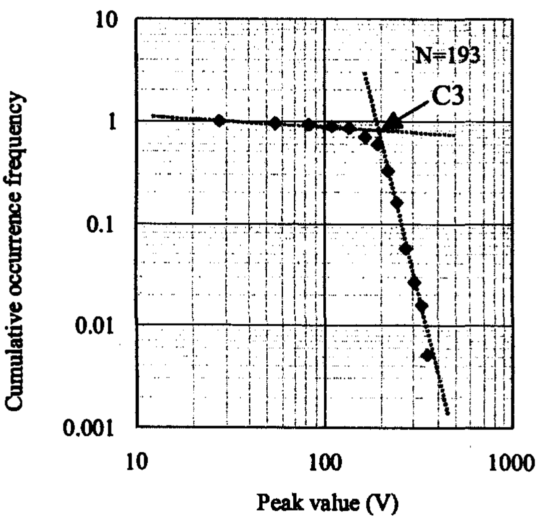


Fig. 14 Relationships between peak values appearing between V_1 and V_2.



(a) Differential mode voltage



(b) Common mode voltage

Fig. 15 Cumulative occurrences of peak vale for common and differential mode lightning surges.

surge voltage at wires 1 and 2 are shown in Fig. 14. Up to 80 V, the correlation was strong, with a coefficient of almost 1. Above than 80 V, the correlation was weak, because of the difference in varistor operating voltages.

The cumulative occurrence frequencies of the differential mode voltage V_d and common mode voltage V_c are shown in Fig. 15. The horizontal axis is the peak value and vertical axis is the occurrence frequency calculated using Eq. (4). It is thought that the reason why the data of less than 100 V is a few is that smaller than 100 V data was not able to be taken because the trigger setting of the observation device, the trigger level was larger. The probability of V_d has two corners, C_1 and C_2, whereas the frequency of V_c has one corner C_3. The broken lines in Figs. 15(a) and (b) represent the trend of the V_c distribution in Fig. 15(b). The lines almost agree with the V_d distribution in Fig. 15(a). This shows that differential and common mode voltages have almost the same occurrence frequency. C_3 in Figs. 15(a) and (b) might be due to the varistor installed in the line between the wire and ground and between wires. C_1 and C_2 might be due to the difference in varistor operation. These results indicate that we should design protection circuits and select protection devices to have the same resistibility to both common and differential mode surges.

4. Conclusion

Lightning surges induced at telecommunication centers were observed in Kuala Lumpur, Malaysia, which is in a tropical area. In-service subscriber lines were used and measurements were taking using a lightning surge counter and wave memory system. (1) Observing lightning surges in a tropical area provides useful data about lightning surges. We obtained more than 100 data per line in a three-month period. (2) Lightning surge current occurrence normalized by the number of thunderstorm days and number of lines agreed closely with data observed in a temperate area. Therefore, surge data observed in a temperate area can be used to design protection circuits for equipment installed in a tropical area if we take into account the number of thunderstorm days in the area. (3) Lightning surge voltage occurrence observed in an actual subscriber line differed from the value observed when the line between wires and ground was terminated by 200 Ω, because of the presence of a protector device. Therefore, surge voltage observation data are needed for designing protection circuits. (4) Lightning surge currents on cables were larger than those on the wires in the cable, but the correlation between them was weak. (5) Differential and common mode surge voltage occurrences were almost the same. Therefore, similar protection circuits and devices should be used both common and differential modes. Investigating a mechanism that can explain the observation data is a future problem.

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