Characteristics of Lightning Surges Induced in Telecommunication Center in Tropical Area

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***Abstract*—The characteristics of lightning-induced surges in telecommunication equipment due to a direct lightning strike at a telecommunication center building or tower should be investigated to maintain the reliability of advanced telecommunication systems. In particular, investigations in tropical areas are important because these areas have many thunderstorm days. We observed lightning surges induced in a telecommunication building in Kuala Lumpur, Malaysia. The results show that the peak value occurrence frequency and waveforms of direct strike lightning surges were almost the same as those in a temperate area. The peak current relationships between the cables in the building and the tower legs indicate a strong correlation between the current at the tower legs, waveguide, power line, and outer and inner conductors of the coaxial cables. However, the peak value correlations between the tower leg currents and interface cable voltages were not strong. Based on the observation results, we obtained the correlation factors between the peak value at the observation point and the tower legs, and calculated the peak value at the interface cables as a function of the number of thunderstorm days.**

***Index Terms*—Lightning, measurement, surge, telecommunication equipment.**

I. Introduction

RECENT progress in telecommunications technology has led to the development of high-speed and complex telecommunication systems. Many such systems are installed in telecommunication center buildings and their reliability is becoming more and more important. However, these systems have lower resistibility to lightning surges than older systems, because the high-speed and low-voltage devices used in them are easily damaged by a surge, and the systems are connected to each other in complicated ways and have many intrusion routes for lightning surges. Therefore, technologies should be developed to improve the resistibility of telecommunication systems to direct strikes on buildings.

Systems for protecting against direct strikes have been studied and protection methods have been published by International Electrotechnical Commission (IEC) [1] and International Telecommunication Union-Telecommunication Standardization Sector (ITU-T) [2]. In order to develop lightning protection systems, it is important to investigate the characteristics of direct lightning strikes, the distributions of surge currents in a building, the induced surge at interface cables, and so on. Lightning-surge protection technology for telecommunication systems is divided into two categories: 1) building-level protection systems such as lightning rods, down-conductor systems, and grounding systems; and 2) equipment-level protection systems for equipment installed in the buildings, which involves developing equipment test methods and protection devices.

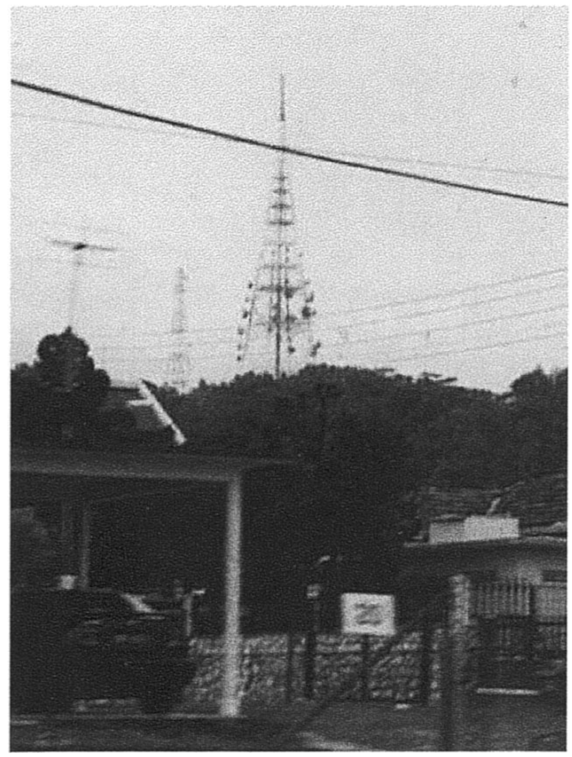

Fig. 1. Observed telecommunication station.

The effect of a lightning strike on a building has been studied based on observations and theoretical analysis, and the characteristics have been reported [3], [4]. The lightning surges induced in buildings have been observed in order to study the induction mechanism [5] and the mechanisms of surges induced in buildings by direct strikes have been studied experimentally and theoretically [6], [7]. Methods of designing protection system [8] and devices [9] have been developed. However, methods for protecting advanced telecommunication systems have not been clarified yet. Further studies are needed on lightning-surge characteristics in telecommunication buildings, induction mechanisms, and protection systems. Moreover, most of the studies

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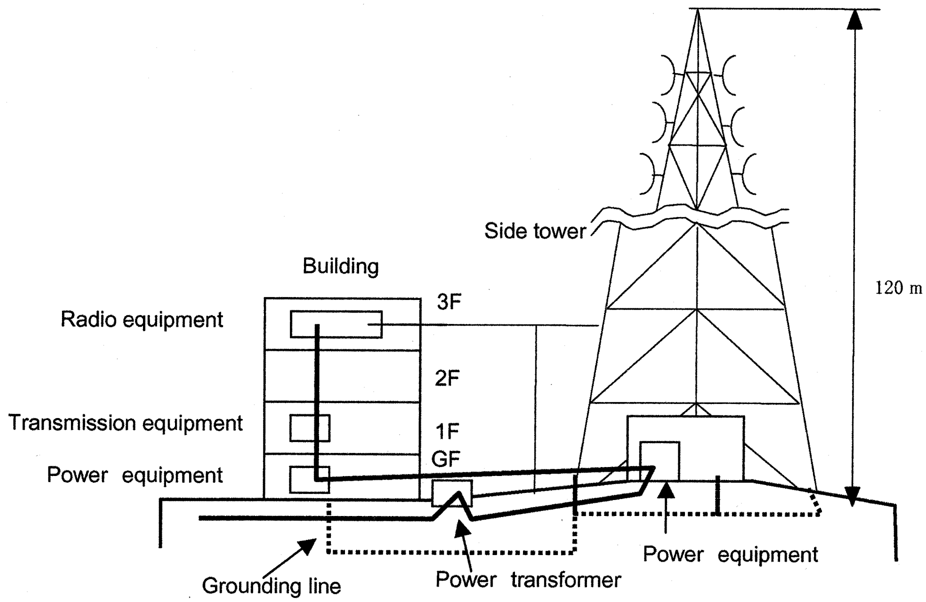


Fig. 2. Configuration of a telecommunication station.

for lightning protection were carried out in temperate areas, but telecommunications equipment is used all over the world, so protection methods for telecommunication systems installed in tropical areas should also be investigated because such areas have many thunderstorms. The lightning-surge characteristics appearing at the subscriber line end in a tropical area have been reported [10]. However, direct strike lightning-surge characteristics induced in a telecommunication center in a tropical area have not been reported. These are necessary in order to develop a protection system for telecommunications equipment installed in a tropical area.

This paper describes the lightning-surge characteristics induced in a telecommunication building in a tropical area. We selected a telecommunication station with a tower, and observed lightning-surge strikes to the tower. We compared the results with surges observed in a temperate area, and also compared the lightning surges appearing in the building with data at the tower. We investigated the correlation factors between lightning surges at the tower and the observation points in the building. From these results, we estimated the maximum peak value of the surge as a function of the number of thunderstorm days.

II. Observation Method

A. Observation Place

The lightning surges were observed in a telecommunication station on a hilltop in Kuala Lumpur, Malaysia. This area has about 200 thunderstorm days per year, which is about ten times as many as the average for Japan, which is in a temperate area.

An overview of the tower is shown in Fig. 1. The area surrounding the hill is an almost flat plane and the hill is about 200 m above it. The station has two buildings and a tower (Fig. 2). The main building has four floors and only contains radio-transmission equipment, so no subscriber lines come into it. The tower (height: 120 m) is beside the building. The ac power equipment is installed in the second building, and

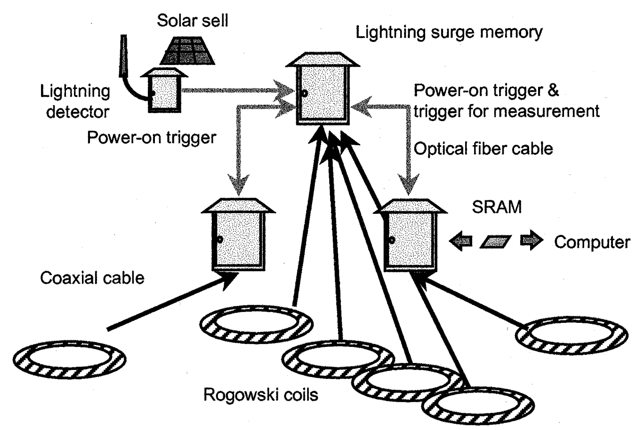


Fig. 3. Configuration of the measurement system (1).

the transformer is set outdoors. All the radio transmission equipment is on the third floor and connected to the antenna on the tower and to the transmitting equipment on the second floor. A grounding line is installed on the tower side of the building. In general, telecommunication towers are placed either on the building's rooftop or beside the building. In this paper, we investigate the surge induced in a building when the tower was located beside the building. The induction mechanism for a building with a rooftop tower is for future study.

B. Observation Equipment

Two systems were used for these observations. One was placed outside the buildings to observe lightning surges appearing at the tower. As shown in Fig. 3, it was composed of a lightning-surge detector, lightning-surge memories, and Rogowski coils [11]. The detector and memories were connected by optical fiber cable to carry the power-on trigger from the detector, which detected the electric field strength of a lightning discharge, to the memories. The detector operated from solar cells and the memories from batteries, so the memories

TABLE I
SPECIFICATIONS OF MEASUREMENT SYSTEM (1)

Lightning detector	detection threshold	4 kV/m
	power source	solar cell with battery
	frequency range	50 Hz to 250 kHz
Lightning surge memory	sampling rate	4 MS/s
	A/D converter resolution	8 bit
	number of stored waveforms	160
	operating time	more than 300 hours

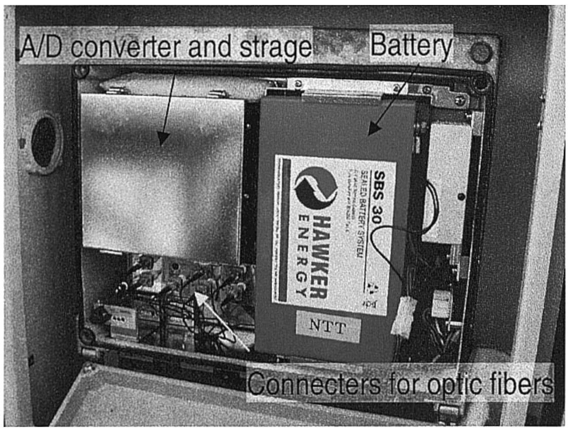


Fig. 4. Measurement system (1).

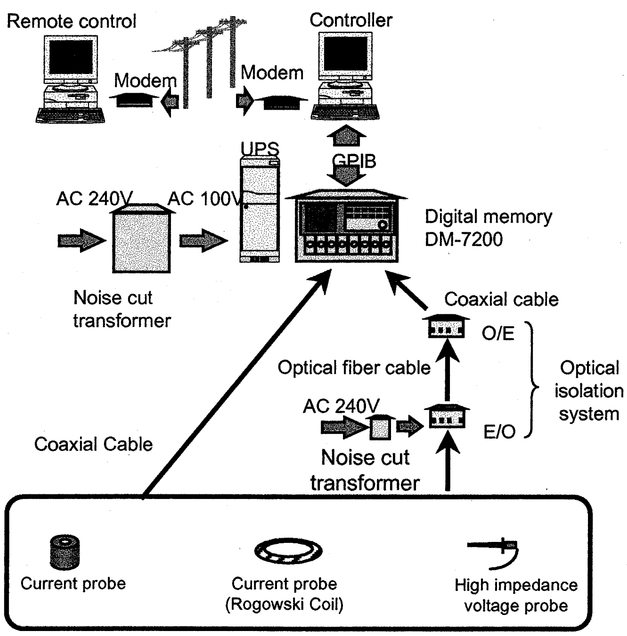


Fig. 5. Configuration of measurement system (2).

usually waited for the power-on trigger from the detector in order to reduce battery consumption. When the trigger arrived from the detector, they started to operate. The surge memory converted the lightning surge to a digital signal and stored it in a static random access memory (SRAM) card. A Rogowski coil (diameter: 4 m) was used to measure the lightning-surge current at the tower legs. The specifications are summarized in Table I, and an internal view of the system is shown in Fig. 4.

The second measurement system (shown in Fig. 5) was used to measure the lightning-surge waveforms in the building. The

TABLE II
SPECIFICATIONS OF MEASUREMENT SYSTEM (2)

Digital memory	frequency range	40 Hz - 5MHz
	sampling time	10 ns - 500 ms
	memory size	64 k word
	frequency range	DC - 30 MHz
Optical isolation system	rise time	Less than 50 ns
	optical fiber length	Less than 100 m
	input impedance	1 MΩ /25 pF
Current probe	frequency range	10 Hz - 10 MHz
Rogowski coil	frequency range	10 kHz - 1 MHz
High-impedance probe	frequency range	DC - 30 MHz

specifications used for the observations are summarized in Table II. A digital memory with a sampling rate from 500 ms to 10 ns and record length for 64 kilowords per channel was used. This was controlled by a personal computer (PC), which was remotely controlled from Japan via the telecommunication network. Noise-cut transformers were used for isolation from the ac mains port. An optical fiber system was used to isolate observation points and the location of the digital memory. A current probe (Peason CT488) and Rogowski coil were used to measure the surge current on each wire or on each pair of interface cables. A Rogowski coil is a kind of current probe and its frequency response is almost flat from 10 kHz to 1 MHz, which is the frequency range where the main lightning-surge energy component is. A high-impedance voltage probe, whose input impedance is more than 1 MΩ and parallel capacitance is less than 25 pF, was used and the frequency response was almost flat from dc to 30 MHz.

C. Observation Conditions

Lightning surges were observed to investigate the following characteristics:

1) peak value occurrence frequency of lightning surge current at the tower;
2) relationships between the peak values of the direct strike lighting current at the tower and the intrusion points of the building;
3) relationships between the peak values of the direct strike lightning-surge current at the tower and the interface cable end connected to equipment on the same floor;
4) relationships between the peak values of the direct strike lightning-surge current at the tower and the interface cable end connected to equipment on other floors.

Fig. 6 shows the observation points on the tower. The purpose of this observation was to measure the lightning-surge current caused by a direct strike to the tower. Usually, the current is measured at the lightning rod, and placed at the top of the tower. However, it is difficult to set the measurement equipment there because of the tower's height. Moreover, some lightning strikes other places instead of the lightning rod. Therefore, we measured the lightning-induced surge current at the tower leg (LS1), ladder (LS2), and rack support (LS3), and entry point of the building (DM1).The direct strike lightning current I_s can be expressed by

$$I_s = I_{\rm LS1} + I_{\rm LS2} + I_{\rm LS3} + I_{\rm DM1}$$

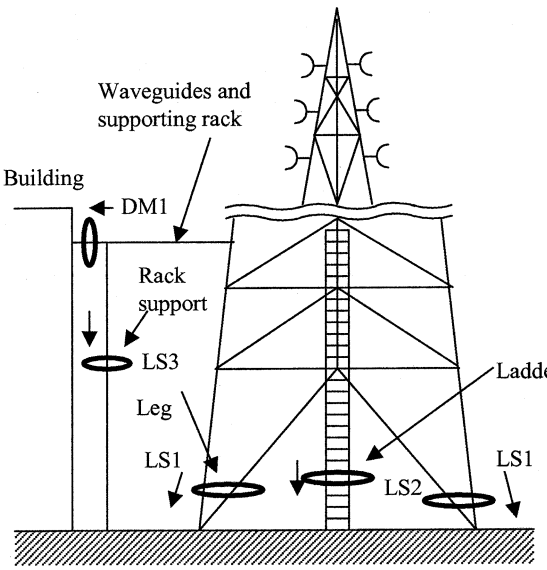


Fig. 6. Observation points at tower.

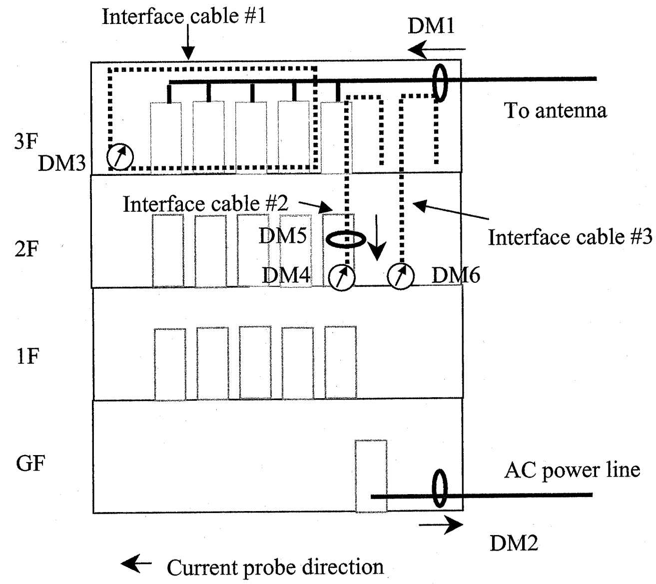


Fig. 8. Observation points in building.

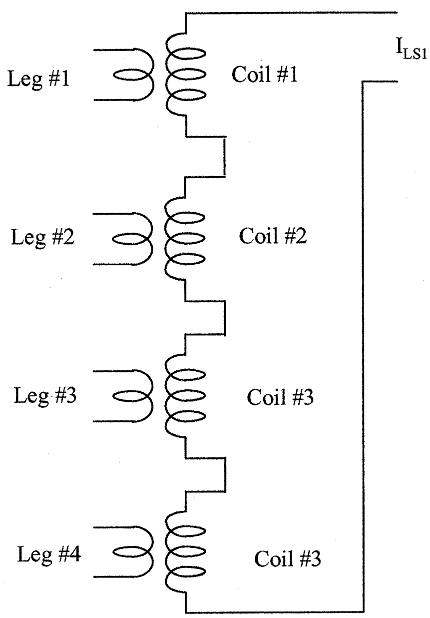


Fig. 7. Configuration of Rogowski coils.

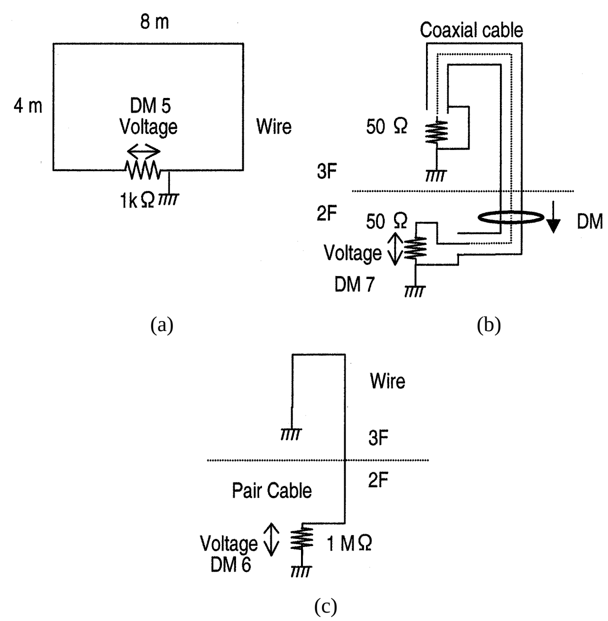


Fig. 9. Configurations of artificial interface cables.

where I_{LS1}, I_{LS2}, I_{LS3}, and I_{DM1} are the waveforms at each measurement point. This tower has four legs, so we used four Rogowski coils. Their configurations are shown in Figs. 3 and 7. The total surge current in the tower legs was the sum of those in each tower leg; therefore, we connected the four Rogowski coils in series. The waveforms of I_{LS1}, I_{LS2}, and I_{LS3} were measured using measurement system (1) and the waveform of I_{DM1} was measured using measurement system (2). The arrows in Fig. 6 indicate the current direction when the measured value was positive.

Fig. 8 shows the observation points in the building. The entry points of the waveguide (DM1) and power line (DM2) were measured to investigate the intrusion of lightning surges into the building. At DM1, five waveguides currents were measured with a Rogowski coil using an optical isolation system among the 57 waveguides at the intrusion point. The power-line intrusion point was also measured with a Rogowski coil with an optical isolation system. We also measured the bonding line (DM3), which connected to the waveguides.

We measured the interface cable connecting equipment on the same floor with equipment on another floor. Three additional interface cables were installed on the second and third floors (Fig. 9) for test purposes. Interface cable #1 was installed on the third floor, and interface cables #2 and #3 connected between the third and second floors. Interface cable #1 was a loop wire 4×8 m and terminated by 1 kΩ (DM3). A high-impedance probe with an optical isolation system was used for the measurements. This measured the induced voltage at the cable end connecting equipment on the same floor. Interface cable #2 was a coaxial cable whose outer conductor was connected to ground

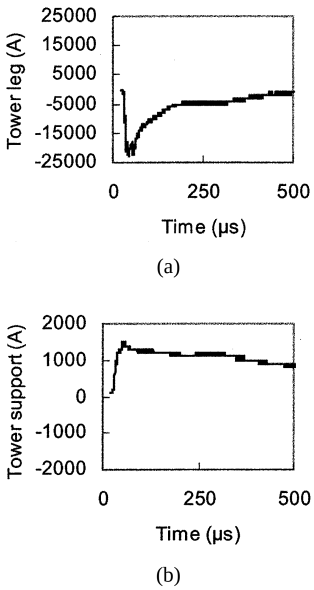


Fig. 10. Lightning-surge waveforms appearing at the tower.

at each floor. Both ends of this cable were terminated by 50 Ω, which is the characteristic impedance of the cable. It measured the current and voltage induced at the cable end, DM4 and DM5. The optical isolation system was used to measure the voltage and a current probe was used to measure the current. Interface cable #3 was a wire whose third-floor end was connected directly to ground and second-floor end was connected to ground through a 1-MΩ resistance at point DM6. A high-impedance probe with an optical isolation system was used for measurement. It measured the voltage potential difference between floors. Measurement system (2) was used for observations at DM1-DM6.

III. Observation Results

A. Direct Strike Lightning-Surge Waveform and Its Occurrence Frequency

Lightning surges were observed from December 1998 to December 1999. Twenty-two waveforms were observed at tower leg, LS1. Examples of the waveforms are shown in Fig. 10. The currents at the tower legs were negative. This means that the current flowed from ground to the antenna tower as shown in Fig. 6. On the other hand, the current at the supporting rack was positive. This means that the current flowed from the ground to the clouds through the tower.

The peak value, front time, and time to half value of the observed surge are summarized in Table III. Only two waveforms were observed at the supporting rack, and no waveform was observed at the tower ladder (LS2). This caused the trigger levels of LS2 and LS3 to be 100 A, which was too large to measure the current at these points although the trigger level was 1/10 that of the level at the LS1 point. Therefore, we think that the current at the legs was almost the total current of the direct strike. The average value of the peak value, the front time, and the time to half value at the tower legs were 32 kA, 10 μs, and 66 μs, respectively. These values were close to those observed in a temperate area (30 kA, 6 μs, and 75 μs) [3]. 86% of the observed data had

TABLE III
WAVEFORM PARAMETERS OF OBSERVED SURGES AT TOWER

Position	Date & time	Peak value (kA)	Front time (μs)	Time to half value (μs)
LS1	1998/12/26 (15:45:41)	4	6.75	-
	1998/12/30 (17:58:29)	-29	5.5	59.75
	1999/2/13 (14:53:08)	-75	1.25	125.5
	1999/3/11 (15:07:45)	-25	28.5	60.75
	1999/3/11 (15:27:01)	-49	16.25	80.75
	1999/3/11 (15:30:59)	-62	9.75	54.5
	1999/3/12 (15:35:51)	-26	7.75	56.25
	1999/3/12 (20:28:54)	-11	2.5	17.6
	1999/3/31 (18:08:38)	8	2.5	10
	1999/5/9 (16:06:10)	-25	5	75
	1999/5/16 (16:38:35)	-31	11.75	46.75
	1999/5/16 (16:44:34)	-29	7	59.75
	1999/5/18 (15:41:06)	-25	6	56.25
	1999/8/25 (19:54:12)	-52	19.25	95.4
	1999/8/28 (15:40:19)	-34	17.25	70.75
	1999/8/28 (15:41:43)	-23	12.75	66
	1999/10/10 (18:29:58)	-38	18.25	83
	1999/10/10 (18:31:08)	-40	14.25	84.5
	1999/10/10 (18:34:23)	-24	4.5	44.25
	1999/10/11 (14:47:00)	4	13.5	-
	1999/10/11 (14:53:30)	-71	15.25	147
	1999/10/16 (16:02:07)	-24	3	15.5
	Average	32.2	10.4	65.5
LS2	1999/8/28 (15:40:20)	2.1	35	635.5
	1999/8/28 (15:41:44)	1.5	33.25	659.75

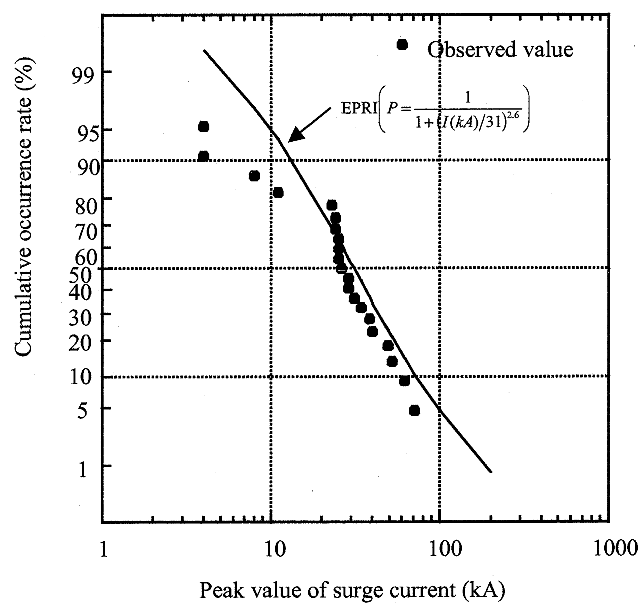
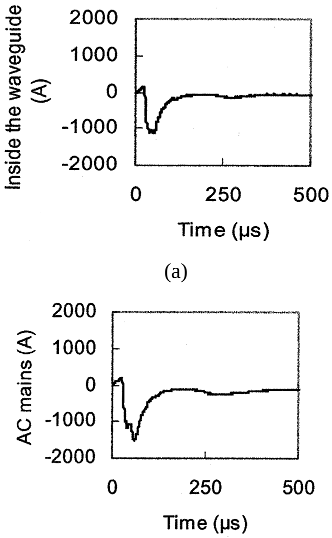


Fig. 11. Cumulative-occurrence frequency of direct stroke lightning-surge peak current.

negative polarity, as shown in Table III, which is similar to data for Japan in summer (90% had negative polarity) [12]. The peak value and time to half value of the positive lightning-surge current were smaller than those of the negative lightning surge.

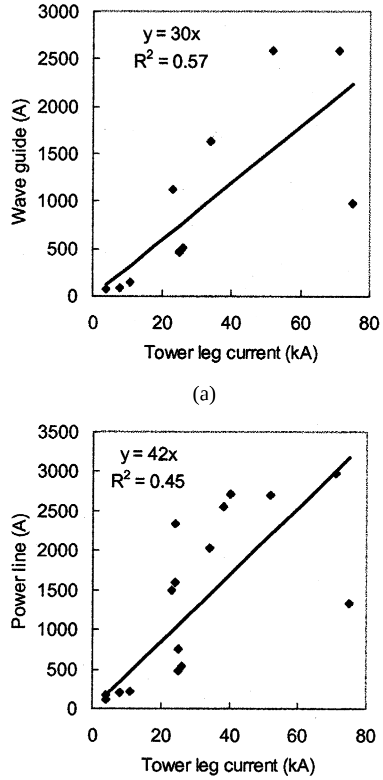
The cumulative-occurrence frequency of the peak value is shown in Fig. 11. The solid line indicates the peak value cumulative occurrence frequency in a temperate area [12]. Fig. 11 shows that the occurrence frequency of the observed data almost



(a)

(b)

Fig. 12. Surge current waveforms appearing at (a) wave guide (b) and power line.



(a)

(b)

Fig. 13. Relations between building intrusion points and tower legs.

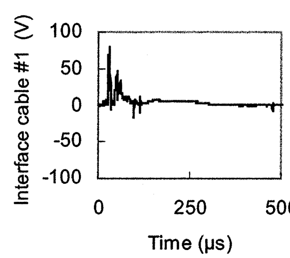


Fig. 14. Surge-voltage waveforms appearing at interface cable on the same floor.

agrees with data for a temperate area, but the observed data deviated from the solid line when the peak value was less than 10 kA. This may be because the trigger level of the observation equipment was small, so we eliminated this data. From these results, we can conclude that the cumulative occurrence frequency of direct strike lightning-surge current in a tropical area agrees well with that in a temperate area.

B. Lightning-Surge Current Distribution at Intrusion Points of the Building

The lighting-surge current at the waveguide (DM1 in Fig. 4) and power line (DM2) were observed. The relationships between the waveforms at DM1, DM2, and the tower legs were identified from the observation time. We obtained 44 and 51 waveforms, respectively. Examples of these are shown in Fig. 12. The surges were generated by a surge current at the tower legs, as shown in Fig. 10. These figures indicate the similar waveforms observed at the waveguide and power line in this building.

The relationships between the peak values at the building intrusion points and the tower legs are shown in Fig. 13. The solid lines in these figures are recursive lines. The relationships are almost linear, and the correlation factor is more than 0.6. This means that the peak values of the current do have a correlation. These figures show that the peak value at the waveguide was 0.03 times that at the tower legs; five out of 57 waveguides were measured, so this corresponds to 0.34 times for all the waveguides, and the peak value at the power line was 0.042 times that at the tower legs.

C. Lightning-Surge Voltage Appearing at the Interface Cable End

Fig. 14 shows an example of the waveform observed at interface cable #1, which connected equipment on the same floor. The cable configuration is shown in Figs. 8 and 9(a). The relationships between the observed waveforms and the tower leg current waveforms were identified from the observation time. And 18 identified waveforms were obtained. The surges were generated by the waveforms at the tower legs, as shown in Fig. 10. The front time and time to half value of the waveform in Fig. 14 were shorter than those for the waveform in Fig. 10 and the voltage appeared when the current at the tower legs changed. This means that the coupling between the current at the tower legs and the voltage at the interface cable was mainly capacitive and inductive coupling.

The relationships between peak values at interface cable #1 and the tower legs are shown in Fig. 15. The solid line in this figure represents the recursive equations shown in Fig. 15. We did not obtain a strong correlation between the current at the tower legs and interface cable #1. This means that the waveform at the tower legs influenced the peak value at cable #1 because the coupling was mainly capacitive and inductive coupling. Although the correlation was weak, Fig. 15 shows that the peak value at cable #1 had a trend 0.0019 times that at the tower legs.

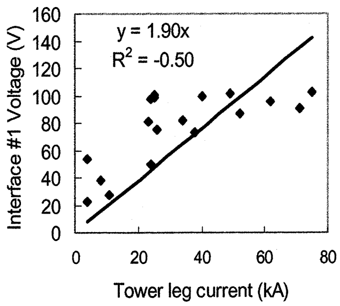
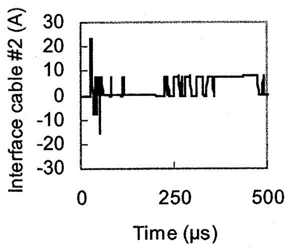
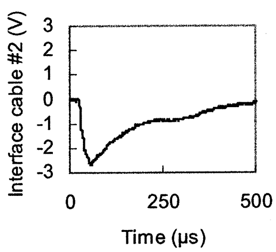


Fig. 15. Relation between voltage at interface cable #1 and tower legs current.



(a)



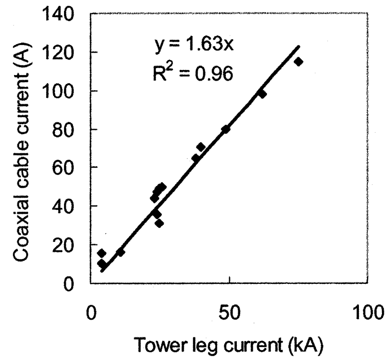
(b)

Fig. 16. Surge-voltage waveforms appearing at interface coaxial cable on another floor.

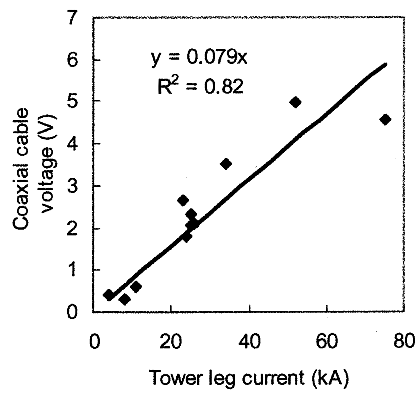
D. Lightning Surge Appearing at Interface Cable End Connecting to Equipment on Another Floor

Fig. 16 shows an example of the voltage waveform observed at interface cable #2, which connected to equipment on another floor with coaxial cable. The cable configuration is shown in Figs. 8 and 9(b). The relationships between the observed waveform and the tower leg current waveform was identified from the observation time and 11 identified waveforms were obtained. The surge was generated by the waveforms at the tower legs shown in Fig. 10. The current waveform at the outer conductor of the coaxial cable was similar to that for interface cable #1 in Fig. 14. This means that the coupling was mainly capacitive and inductive coupling. The waveforms of the inner and outer conductors of the coaxial cable were different. This might be caused by the transfer impedance of the outer conductor, which has a frequency dependence [13].

The relationships between peak values at interface cable #2 and the tower legs are shown in Fig. 17. The solid lines are the indicated recursive equations. The correlation factor of the current shown in Fig. 17(a) is more than 0.9, so good correlation was obtained. The peak value at the outer conductor of cable #2 was 0.0016 times that at the tower legs. And the correlation factor of the voltage shown in Fig. 17(b) was more than 0.8, so good correlation was obtained. The peak value at the inner conductor of cable #2 was 0.000 079 times that at the tower legs.



(a)



(b)

Fig. 17. Relations between interface cable #2 and tower legs.

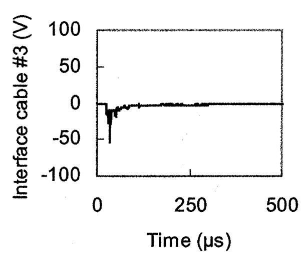


Fig. 18. Surge-voltage waveforms appearing at interface cable on another floor.

Fig. 18 shows an example of the observed waveform appearing at interface cable #3, which connected to equipment on another floor. The cable configuration is shown in Figs. 8 and 9(c). The relationships between the observed waveform and the tower leg current waveform was identified from the observation time and 17 identified waveforms were obtained. The surge was generated by the waveforms at the tower legs shown in Fig. 10. The front time and time to half value of the waveform in Fig. 18 were shorter than those of the waveform in Fig. 10 and the voltage appeared when the current at the tower legs changed. This means that the coupling between the current at the tower legs and voltage at interface cable #3 was mainly capacitive and inductive coupling.

The relationships between peak values at interface cable #3 and the tower legs are shown in Fig. 19. The solid line is the indicated recursive equations. As with cable #1, strong correlation was not obtained between the current at the tower legs and interface cable #3. This means that the waveform at the tower legs influenced the peak value at cable #3 because the coupling was

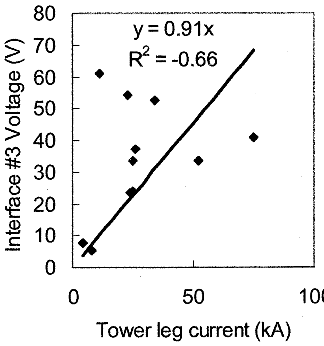


Fig. 19. Relation between voltage at interface cable #3 and tower leg current.

mainly capacitive and inductive coupling. Although the correlation was weak, Fig. 19 shows that the peak value at cable #3 had a trend 0.0009 times that at the tower legs.

E. Relationships Between Induced Surge Current and Lightning Current

The relationships between the peak value among the tower legs and the observation points (obtained from Figs. 10, 13, 15, 17, and 19) are summarized in Fig. 20. The dotted line indicates that the coupling might be conductive, which is usual when the waveform at the observation point is similar to that at the tower legs as shown in Figs. 10 and 12. The conductive coupling with self-inductance is represented by an inductor and it is estimated when the front time and time to half value are longer than those at the tower legs, as shown in Fig. 10. The inductive and capacitive coupling is represented by a capacitor and transformer. This is estimated when the front time and time to half value are shorter than those at the tower legs, as shown in Fig. 10. Cables #1 and #3 were isolated from the ground, as shown in Fig. 9. This is why the coupling was mainly capacitive and inductive coupling in these cables.

IV. OCCURRENCE PROBABILITY OF LIGHTNING SURGE AT INTERFACE CABLE

It is important to obtain the occurrence probability of the lighting surge current and voltage caused by direct strikes. From our investigation, we obtained the relationships between the direct strike current and interface cable shown in Fig. 20. Here, we calculate the occurrence probability of the peak value.

Our investigation also indicates that data observed in a temperate zone is applicable if we consider with the number of thunderstorm days in the area. According to these observations, the cumulative occurrence of the peak value for a direct strike is given by [12]

$$P = \frac{1}{1+\left(\frac{I_p}{31}\right)^{2.6}} \tag{1}$$

where I_p is the peak value of the direct strike in kA.

The number of direct strikes per unit area is given by

$$N_d = S_d C_d D_{\text{th}} \tag{2}$$

where S_d is the area over which lightning step leaders are attracted to the tower, and S_d is given by

$$S_d = \pi h^2 \tag{3}$$

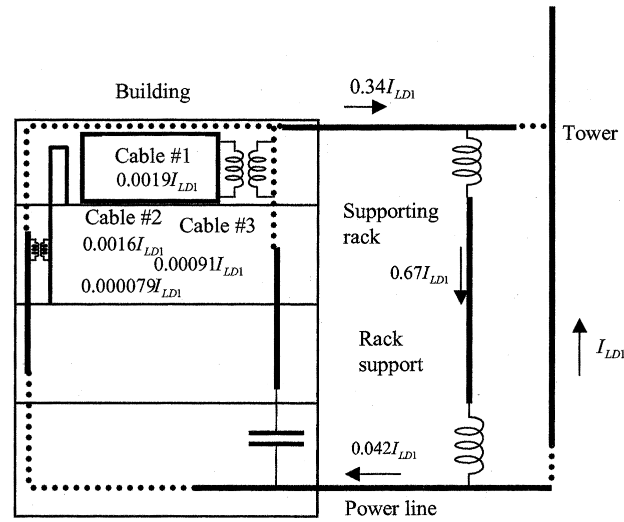


Fig. 20. Relationship between tower legs current and other observation points.

where h is height of the tower. When the tower is on a hill surrounded by flat land, we consider the height of the hill above the flat land. C_d is the return strike frequency per thunderstorm day per unit area. According to [14], the return stroke frequency per thunderstorm day was 15 times in a 10×10-km area, giving $C_d = 1.5 \times 10^{-7}$ times$/(\text{day} \cdot \text{m}^2)$. D_{th} is the number of thunderstorm days during the period, which we should take into account when considering system reliability.

From (1)–(3), the relationship between thunderstorm days and maximum estimated peak value of the direct strike current $I_{p\,\max}$ is given by

$$P = \frac{1}{N_d} = \frac{1}{1.5 \times 10^{-7} \pi h^2 D_{\text{th}}} = \frac{1}{1+\left(\frac{I_{p\,\max}}{31}\right)^{2.6}}. \tag{4}$$

Then, we get

$$I_{p\,\max} = 31 \times (N_d - 1)^{1/2.6} = 31 \times \left(1.5 \times 10^{-7} \pi h^2 D_{\text{th}} - 1\right)^{1/2.6}. \tag{5}$$

In (5), we set $N_d = 1$ when $N_d < 1$.

The peak value of the current at the interface cable end is given by

$$I_{pN} = F_N I_{LD1} = F_N I_{p\,\max} \tag{6}$$

where F_N is the relationship shown in Fig. 20.

Calculation examples are shown in Fig. 21. The horizontal axis is the number of thunderstorm days and the vertical axis is the peak value. Fig. 21 shows that a peak value of 300 V might appear at the interface cable end (cable #1) during a 10-year period because there are 200 thunderstorm days per year in the observation area.

Here, the correlation factors were determined from observation data for only one telecommunication building. More data may be needed to determine the test waveform for telecommunications equipment used in telecommunication buildings. However, our findings may be useful for designing it because currently there is no data at all about lightning surges at interface cables.

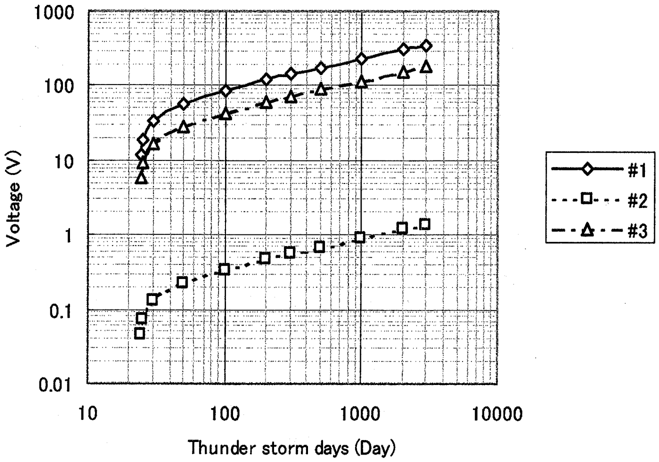


Fig. 21. Occurrence probability of lightning surge at interface cable.

V. Conclusion

Lightning surges induced in a telecommunication building by direct strikes were observed in Kuala Lumpur, Malaysia, from December 1998 to December 1999. The telecommunication station had a side tower and is located on a hilltop. The results show that the peak-value-occurrence frequency is almost the same as that in a temperate area, so the data obtained from observations in temperate areas is applicable to tropical areas if we take into account the number of thunderstorm days in the area.

The relationships between the waveform observed in the buildings and the tower leg current waveform was identified from the observation time and 11–19 identified waveforms were obtained. Investigating the correlations between the peak value in the building and at the tower legs, we obtained the following results:

There was strong correlation between the waveforms observed at the waveguide (DM1), power line (DM2), outer conductor of the coaxial cable (DM4), and the inner conductor of coaxial cable voltage (DM5).

Strong correlation was not obtained for the waveforms observed at the interface cable connecting to equipment on the same floor (DM3) or at the interface cable connecting to equipment on another floor (DM4).

Based on the observation results, we obtained the correlation factors between the peak value of the observation point and the tower leg. Although we could not get a good correlation, the factors indicate a trend in the relation between the peak values. Using the correlation factors, we calculated the peak value at the interface cable as a function of the number of thunderstorm days. The results indicate that a peak value of 300 V might appear at the interface cable end once in 10 years when the number of thunderstorm days per year is 200.

More observation data may be needed to determine the test waveform and a study to calculate the correlation factor is also needed to improve the resistibility of equipment to direct strikes.

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