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A New Lightning Surge Test Circuit for Telecommunications Equipment in Japan

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A New Lightning Surge Test Circuit for Telecommunications Equipment in Japan

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Abstract—This paper describes the development of a lightning surge test circuit that can predict malfunctions in telecommunications equipment. The test circuit is developed using the equivalent impedance of a telecommunications line and a voltage source that generates the test surge. The test surge waveform is determined from observed lightning surge data in Japan based on the equipment malfunction rate. In experiments using a key telephone, the malfunction rates predicted by the test are shown to closely agree with observed rates.

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I. Introduction

When a lightning discharge occurs near telecommunication lines, lightning surges are induced in the lines, and, in many cases, equipment is damaged. Modern telecommunications utilize a large variety of equipment, most of which contains a number of solid-state devices. Since these devices are easily damaged by high voltage surges, such as lightning surges, the equipment malfunction rate should be ascertained through a lightning surge test. However, although test circuits to predict such malfunctions in the equipment are needed, such circuits have not yet been successfully developed.

A study of lightning surge characteristics is required in order to develop lightning surge test circuits. Investigation of lightning surge induction mechanisms [1], [2] and lightning surge observations [3], [4] were made, and statistics on lightning surge waveforms were obtained from the accumulation of observed data. In this way, the traditional test circuit for lightning surges was developed. The circuit consisted of a surge generator in series with the resistance, where the surge waveforms of the generator were selected from observed surge waveform data and the resistance was a simulated telecommunications line [5]–[7]. The lightning surge was changed by the terminal impedance at the telecommunication line end. In particular, the lightning surges appearing between the equipment input terminal and ground were intricately changed because nonlinear devices, such as gas discharge tubes, which were installed to protect the equipment, were activated. However, traditional test circuits did not simulate this lightning surge change because a resistance that displayed no frequency characteristics was used for a simulated telecommunications line. Furthermore, since a method to calculate the surge waveform was not clearly defined, the equipment malfunction rate could not be estimated from the test.

This paper proposes an improved lightning surge test circuit that can estimate the malfunction rate for any equipment. To demonstrate the validity of the new test circuit, test circuit parameters were determined for equipment connected to subscriber lines in Japan. The malfunction rate of the key telephone switching system was calculated using the test circuit and was compared with the observed data.

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II. Outline of the Test Circuit Design

This section outlines the test circuit design that estimates the malfunction rate for any equipment.

Equipment at the line ends is usually connected to the telecommunications line through a primary protection circuit (P.P.), as shown in Fig. 1(a). When a lightning discharge occurs, an electromotive force appears in the line and propagates to its end. A surge voltage V_b, called the longitudinal surge, occurs between one of the wires of a balanced pair cable and the ground. An arrester in the P.P. discharges when the peak value of V_b exceeds the arrester discharge voltage. If the discharge voltages of the arresters in the P.P. are not identical to each other, the arresters do not discharge simultaneously, and then a surge voltage V_c, called a transverse surge, occurs between the two wires of the balanced pair. A new test circuit should consist of two output terminals and one earth terminal to combine both longitudinal and transverse surges.

Lightning surges are changed by the terminal impedance of equipment and by the terminal impedance change caused by the operation of the protection circuit. In the new test circuit, lightning surge changes at the telecommunications line end should be simulated. A new test circuit with a pair of voltage sources and impedance has been developed, shown in Fig. 1(b), where V_i is the equivalent voltage source, Z_i is the equivalent impedance, and the pair of circuits with V_i and Z_i expresses the longitudinal surge appearing at the balanced pair of the telecommunications line. Since the test circuit completely simulates the lightning surge change, it is able to test the equipment for any input impedance.

The lightning surges appearing at the telecommunications line end are represented by distributions [3] and [4]. In the

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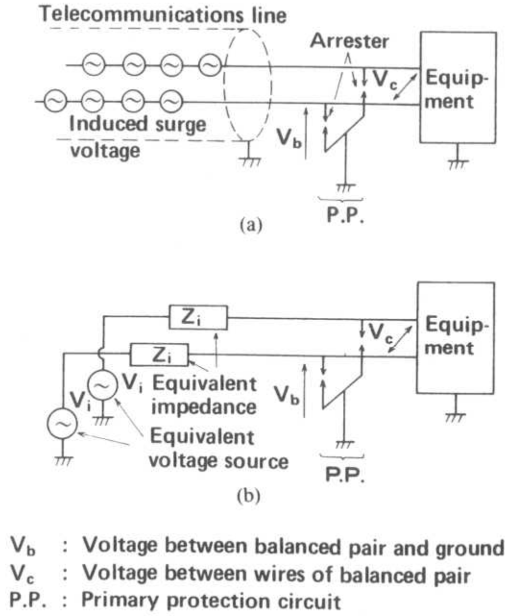

Fig. 1. Lightning surge test circuit for equipment. (a) Telecommunication line within the distributed electromotive force-induced lightning surge, and the lightning surge fed to the equipment and its protection circuit. (b) Basic construction of the new test circuit.

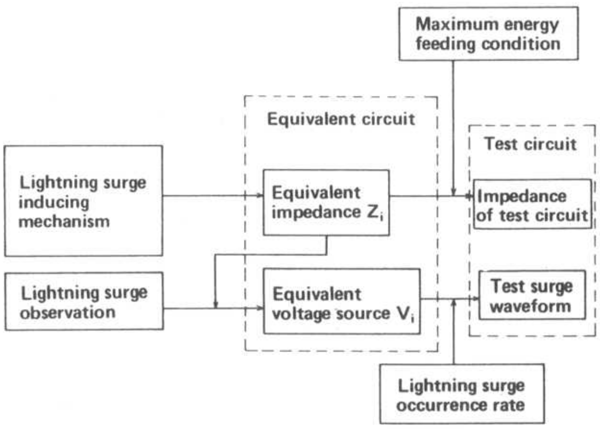

Fig. 2. Design flow for the lightning surge test circuit and the test waveform.

new test circuit, the surge waveform of V_i, called the test surge waveform, is calculated from the longitudinal surge occurrence to estimate the equipment malfunction rate.

The design flow of the equivalent impedance and the test surge waveform is outlined in Fig. 2. First, equivalent impedance Z_i is determined on the basis of the lightning surge inducing mechanism, and the test circuit impedance is determined on the basis of the maximum energy feeding condition, the severest equipment condition. Second, equivalent voltage source V_i is determined from the observed lightning surge data and equivalent impedance, and the test surge waveform is calculated from the equivalent voltage source based on the lightning surge occurrence rate.

III. Lightning Surge Equivalent Circuit

A. Equivalent Impedance

The lightning surge inducing mechanism is shown in Fig. 3. Line $a - b$ represents one wire of the balanced pair cable.

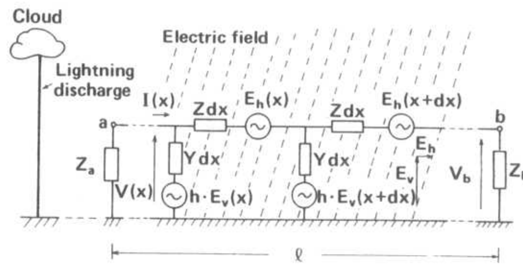

Fig. 3. Lightning surge induction model for the circuit between one wire of the balanced pair and ground.

When a lightning discharge occurs, electromagnetic fields are generated in the atmosphere. The electric field has vertical and horizontal components, which together induce an electromotive force in the line. The surge current $I(x)$ and voltage $V(x)$ in the line produced by this force are given by

$$-\frac{d}{dx} V(x) = ZI(x) + E_h(x) \quad (1)$$

and

$$-\frac{d}{dx} I(x) = Y[I(x) - hE_v(x)] \quad (2)$$

where Z and Y are the impedance and admittance per unit length between one wire of a balanced pair and ground, $E_h(x)$ and $E_v(x)$ are the horizontal and vertical electric fields against earth, h is the cable height from the earth, and x is the distance from one end of the cable.

In the frequency domain, solutions of these differential equations are given by [8]

$$V(x) = Z_0[(A + S(x)) \exp(-\gamma_0 x) + (B + Q(x)) \exp(\gamma_0 x)] \quad (3)$$

where

$$S(x) = \frac{1}{2Z_0} \int_0^x [-E_h(u) + \gamma_0 h E_v(u)] \exp(\gamma_0 u)\, du \quad (4)$$

and

$$Q(x) = \frac{1}{2Z_0} \int_0^x [-E_h(u) - \gamma_0 h E_v(u)] \exp(-\gamma_0 u)\, du. \quad (5)$$

In (3)–(5), Z_0 and γ_0 are the characteristic impedance and the propagation constant of the transmission line composed of one wire of the balanced pair and earth, respectively. These values can be calculated using [2] and [9]. A and B are constants determined on the basis of the line terminating conditions, and u is the integral variable.

When the line is terminated by Z_a and Z_b, the lightning surge at the B end is given by

$$V_b = \frac{Z_0(1 + P_b)}{\exp(\gamma_0 l) - P_a P_b \exp(-\gamma_0 l)} [S(l) - P_a Q(l)] \quad (6)$$

with

$$P_a = \frac{Z_a - Z_0}{Z_a + Z_0}, \quad P_b = \frac{Z_b - Z_0}{Z_b + Z_0} \quad (7)$$

where l is the line length.

A method used to determine the equivalent circuit is illustrated in Fig. 4. According to the network analysis theory, the circuit shown in Fig. 3 can be represented by the circuit

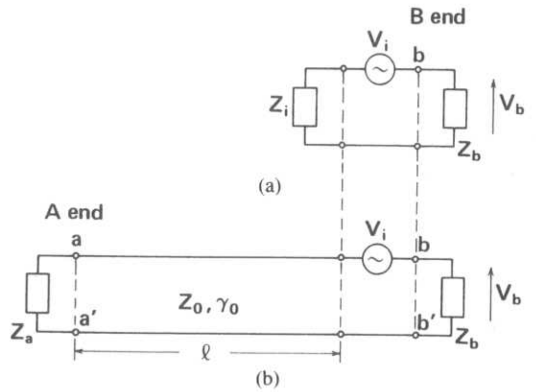

Fig. 4. Equivalent circuit for Fig. 3. (a) Lightning surge V_b at the telecommunication line end B is represented by the equivalent impedance Z_i and equivalent voltage source V_i. (b) Lightning surge V_b is represented by a transmission line and a equivalent voltage source V_i.

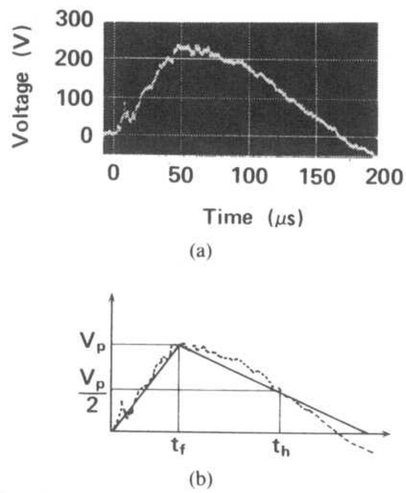

Fig. 5. Typical lightning surge waveform. (a) Lightning surge observed by the lightning surge waveform recorder. (b) Definition of the peak value, the front time, the time to half value and the triangular waveform.

shown in Fig. 4(a). In Fig. 4(a), b represents the B ends in Fig. 3, and Z_i and V_i are the equivalent impedance and the equivalent voltage source, respectively.

Considering the circuit in Fig. 4(a), the equivalent impedance is defined as

$$Z_i = \frac{V_{b1} - V_{b2}}{\dfrac{V_{b2}}{Z_{b2}} - \dfrac{V_{b1}}{Z_{b1}}} \tag{8}$$

where V_{b1} and V_{b2} are the voltages when the B end in Fig. 4(a) is terminated by Z_{b1} and Z_{b2}, respectively. Using (6), the equivalent impedance Z_i is given by

$$Z_i = Z_0 \frac{1 + P_a \exp(-2\gamma_0 l)}{1 - P_a \exp(-2\gamma_0 l)}. \tag{9}$$

Equation (9) shows that the equivalent impedance Z_i is represented by the input impedance of the transmission line with characteristic impedance Z_0, propagation constant γ_0, and reflection coefficient P_a at the A end. Thus, the equivalent impedance in Fig. 4(a) is expressed by the circuit in Fig. 4(b). In Fig. 4(b), line $a - b$ represents one wire of the balanced pair cable, and the line $a' - b'$ represents the ground. Since (9) does not contain Z_b and V_i, the equivalent impedance Z_i does not depend on the equivalent voltage source V_i and the terminal impedance Z_b at the B end.

B. Equivalent Voltage Source

Considering the circuit in Fig. 4(a), the equivalent voltage source V_i is defined as

$$V_i = \frac{Z_b + Z_i}{Z_b} V_b \tag{10}$$

where V_b is the lightning surge voltage at the telecommunications line end.

From (6), the equivalent voltage source is given by

$$V_i = 2Z_0 \frac{S(l) - P_a Q(l)}{\exp(\gamma_0 l) - P_a \exp(-\gamma_0 l)}. \tag{11}$$

Equation (11) indicates that the equivalent source voltage does not depend on the terminal impedance Z_b at the B end. However, it is difficult to theoretically calculate the equivalent voltage-source distribution, because (11) contains the electromotive force $Q(l)$ and $S(l)$, which are not fully calculated. The distribution is then calculated from the lightning surge observation data.

A typical lightning surge observed by the lightning surge waveform recorder [3] is shown in Fig. 5(a). Since the lightning surge waveform is complex, the waveform is expressed by three parameters: the peak value V_p, the front time t_f, and the time to half value t_h. These parameters are defined in Fig. 5(b). Furthermore, as shown in Fig. 5(b), the waveform is approximated using a triangular waveform to simplify the calculation.

According to the lightning surge observations, the peak value occurrence rate $N(V_{bp})$ greater than abscissa value V_{bp} is given by [3], [4]

$$N(V_{bp}) = K V_{bp}^{-p} \tag{12}$$

where the K and p values are constants representing the peak value distribution of the equivalent voltage source.

The cumulative probability distributions of the front time $n(t_f)$ and the time to half value $n(t_h)$ are given by log normal distributions [3], [4], which are expressed as

$$n(t_f) = \frac{1}{\sqrt{2\pi}\sigma_f} \exp\left[-\frac{1}{\sqrt{2}\sigma_f} \ln\left(\frac{t_f}{\mu_f}\right)\right]^2 \tag{13}$$

and

$$n(t_h) = \frac{1}{\sqrt{2\pi}\sigma_h} \exp\left[-\frac{1}{\sqrt{2}\sigma_h} \ln\left(\frac{t_h}{\mu_h}\right)\right]^2 \tag{14}$$

where σ_f and σ_h are the standard deviations of the front time and the time to half value, respectively; μ_f and μ_h are the mean values of the front time and the time to half value, respectively.

From (10), the equivalent voltage source is given by

$$v_i = \frac{1}{2\pi} \int_{-\infty}^{\infty} \frac{Z_b + Z_i}{Z_b} \left[\int_{-\infty}^{\infty} v_b \exp(-j\omega t)\, dt\right] \exp(j\omega t)\, d\omega \tag{15}$$

where v_b and v_i are the observed lightning surge and the equivalent voltage source in the time domain, respectively, and Z_b and Z_i are the terminal impedance at the line end and the equivalent impedance, respectively.

IV. Basic Design of the Test Circuit

A. Impedance of the Test Circuit

The impedance of the test circuit is expressed by the distributed constant circuit in Fig. 4(b). This configuration is not useful for testing equipment due to its large size requirements. It is important that the equivalent impedance is expressed by a lumped constant circuit. The terminal impedance Z_a is determined to obtain the lumped constant circuit based on the maximum energy feeding condition, the severest equipment condition.

In the circuit shown in Fig. 4(b), the lightning surge is fed to the equipment through Z_a. When Z_a is zero, the energy spent on the telecommunication line is smallest in the region below 10 kHz, where the lightning surge energy is almost fully contained, and conversely, that spent on the equipment is at a maximum. Therefore, $Z_a = 0$ is selected for the calculation. The equivalent impedance expressed by (9) is rewritten as

$$Z_i = Z_0 \tanh(\gamma_0 l). \tag{16}$$

Equation (16) is expanded in series and two terms are taken from the top. The impedance of test circuit is given by

$$Z_i = \frac{1}{j\omega C_i + \dfrac{1}{R_i + j\omega L_i}} + R_i' \tag{17}$$

where

$$R_i = \frac{8}{\pi^2} Rl, \qquad L_i = \frac{8}{\pi^2} Ll,$$
$$C_i = \frac{l}{2} C, \qquad R_i' = Rl\left(1 - \frac{8}{\pi^2}\right) \tag{18}$$

and R, L, and C are the primary constants of the line where the lightning surge propagates.

From Fig. 1(a) and (17), the test circuit can therefore be expressed in terms of the circuit in Fig. 6, where V_i is the low impedance surge generator that generates a test surge.

B. Test Surge Waveform Design Method

The test surge waveform has a certain rate of occurrence and can be determined from distributions of equivalent voltage-source waveforms. Two assumptions underlie the test waveform calculation: 1) Lightning surge distributions are represented by the same equations that describe the observed lightning surge distributions, and 2) the peak value occurrence rate of the test surge waveform is equal to the energy occurrence rate of the test surge waveform.

From Assumption (1) and (12), the peak value occurrence rate Q_p is given by

$$Q_p(V_p) = K V_p^{-p} \tag{19}$$

where V_p is the peak value of the test surge.

The front time and the time to half values of the test waveform are determined on the basis of surge waveform energy.

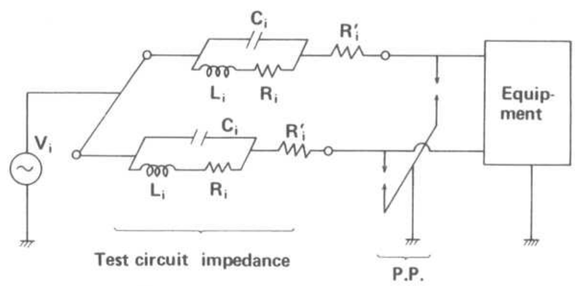

Fig. 6. New test circuit for the equipment at the subscriber end

The surge energy occurrence rate Q_e is given by [10]

$$Q_e = \int_0 \frac{d}{dV_p} Q_p(V_p) \left[\int_{t_{0s}}^{\infty} n(t_0)\, dt_0 \right] dV_p. \tag{20}$$

Here

$$t_{0s} = \ln\left(\frac{E_s}{K_e V_p^2}\right). \tag{21}$$

In Equations (20) and (21), E_s is the surge energy and $n(t_0)$ is the cumulative probability distribution of the time to zero value t_0. The surge energy is given by

$$E_s = K_e V_p^2 t_0. \tag{22}$$

Here, K_e is a constant that depends on terminating conditions. The time to zero value is defined as

$$t_0 = 2t_h - t_f. \tag{23}$$

The cumulative probability distribution of the time to zero value is calculated from the front time and the time to half value distributions. From Assumption (1) and (13) and (14), assuming that the standard deviation of the front time and the time to half value are the same, $n(t_0)$ is also given by [10]

$$n(t_0) = \frac{1}{\sqrt{2\pi}\sigma_0} \exp\left[-\frac{1}{\sqrt{2}\sigma_0} \ln\left(\frac{t_0}{\mu_0}\right)\right]^2 \tag{24}$$

where σ_0 is the standard deviation of the time to zero value and μ_0 is the mean value of the time to zero value; these are shown as follows: [10]

$$\mu_0 = 2\mu_h \exp\left[0.45\left(\frac{\mu_f}{2\mu_h}\right)\sigma_h^2\right] - \mu_f \exp\left[0.45\left(\frac{\mu_f}{2\mu_h}\right)\sigma_f^2\right] \tag{25}$$

and

$$\sigma_0 = \left(1 + \frac{\mu_f}{\mu_h}\right)\sigma_h^2. \tag{26}$$

From Assumption (2), the peak value occurrence rate Q_p is found to be equal to the energy occurrence rate Q_e. Using (19) and (20), the time to zero value of the test surge is given by

$$t_0 = \mu_0 \exp(0.45\sigma_0^2). \tag{27}$$

From (25) and (27), the front time t_f and the time to half value t_h for the test surge are given by

$$t_f = \mu_f \exp\left[0.45\left(1 + \frac{\mu_f}{2\mu_h}\right)\sigma_f^2\right] \tag{28}$$

TABLE I
LINE CONSTANTS AND LENGTH OF THE CIRCUIT BETWEEN ONE WIRE OF THE BALANCED PAIR CABLE AND THE CABLE METALLIC SHEATH

Term	Constant
Line constants(line resistance R, inductance L, and capacitance C per unit length)	R=141 Ω/km L=0.64 mH/km C=59 nF/km
Line length	2 km

and

$$t_h = \mu_h \exp\left[0.45\left(1 + \frac{\mu_f}{2\mu_h}\right)\sigma_h^2\right]. \tag{29}$$

Equations (28) and (29) show that the front time and the time to half value are independent of the peak value occurrence rate Q_p and the energy occurrence rate Q_e. The test surge occurrence rate is then calculated from the peak value occurrence rate.

V. Determination of Test Circuit Parameters for the Equipment Connected to the Subscriber End in Japan

A. Impedance Parameters for the Test Circuit

As shown in Fig. 1(b), the impedance of the test circuit is determined by the equivalent impedance. From (17), the equivalent impedance depends on the line length and the primary constant of the line. These parameters have been determined using the mean subscriber line condition values for Japan and the maximum energy feeding conditions. The determined values are presented in Table I. Procedures used to determine the parameters are described below.

First, the line length was selected from the mean value of the subscriber line length in Japan [11]. Second, several connection types are considered when the equipment is connected to a telecommunications line. These types are further divided into three distinct groups, as shown in Fig. 7(a)–(c). In these three groups, two kinds of longitudinal surges are fed to the equipment. One propagates through the circuit between one wire of the balanced pair cable and the cable metallic sheath, as shown in (a), and the other propagates through the circuit between one wire of the balanced pair cable and the ground, as shown in (b) and (c).

The measured equivalent impedances of the circuits in Fig. 7(a)–(c) are shown in Fig. 8. Below 100 kHz, the equivalent impedance of the circuit in (a) is smaller than that of the other two circuits in Fig. 7(b) and (c). Since the energy spent on the equivalent impedance of the circuit(a) is smaller than the energy spent on the equivalent impedance of the other circuits, group (a) is selected to determine the equivalent impedance values based on maximum energy feeding conditions.

The line constants depend on the wire diameter of the balanced pair. The wire diameter mean value in Japan is 0.4 mm [11]. Measured line constants at 1 kHz were used for the calculation, and these values are shown in Table I. As a result of the measurement, these values are nearly constant in the region below 100 kHz.

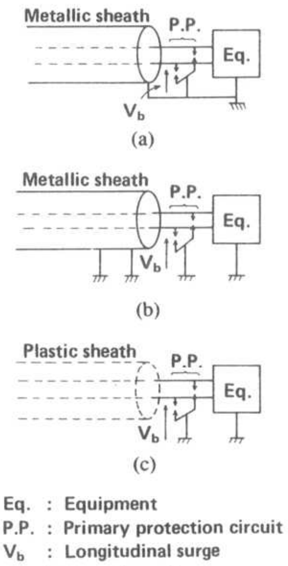

Fig. 7. Standard connecting configuration between the equipment and the telecommunication line. (a) Cable metallic sheath is connected to the equipment ground and P.P. ground. (b) Cable metallic sheath ground, equipment ground, and P.P. ground are separated. (c) Cable has no metallic sheath.

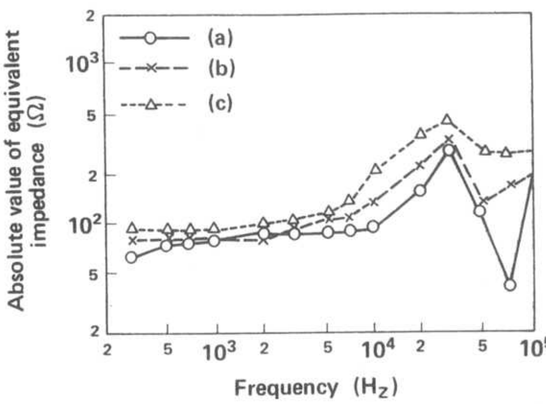

Fig. 8. Frequency characteristics of the measured equivalent impedance for Fig. 7(a)–(c).

Using constants shown in Table I, values R_i, L_i, C_i, and R_i' in Fig. 6 are calculated and summarized in Table II.

B. Test Surge Waveform for Equipment Connected to the Subscriber End

The test surge waveform can be determined from lightning surge observation data using (15), (19), (28), and (29). The procedures used to determine the waveform are described below.

The lightning surge distributions observed at the subscriber end are needed to obtain the equivalent voltage-source distributions. These are shown in Figs. 9 and 10 [3]. In Figs. 9 and 10, the dotted lines indicate the observed lightning surge distributions V_b. K and p values in (12) and μ_f, μ_h, σ_f, and σ_h values in (13) and (14) are summarized in Table III.

The equivalent voltage-source distributions V_i are calculated from the observed data in Figs. 9 and 10 using (15). The calculated results are represented by solid lines in these figures as well. In the calculation, the surge waveforms are approximated with triangular waveforms and the Monte Carlo

TABLE II
LIGHTNING SURGE TEST CIRCUIT CONSTANTS FOR EQUIPMENT CONNECTED TO THE SUBSCRIBER END IN JAPAN

Term		Constant
Impedance		R_i=250 Ω, L_i=1 mH C_i=60 nF, R'_i=50 Ω
Test surge	Peak value	$V_p=(Q_p/K)^{(-1/p)}$ Q_p:Surge occurrence rate
	Waveform	t_f=28 μs, t_h=135 μs

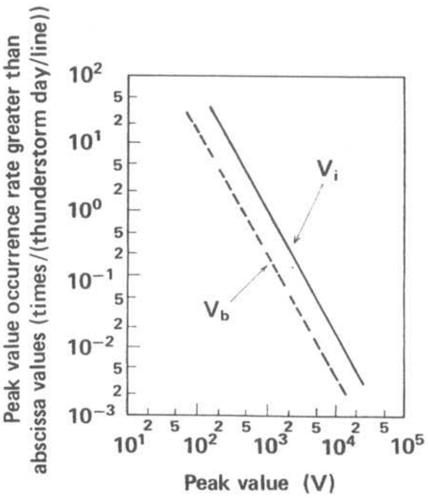

Fig. 9. Peak value occurrence rate greater than abscissa values of the observed surge V_b and the equivalent voltage source V_i at the subscriber end.

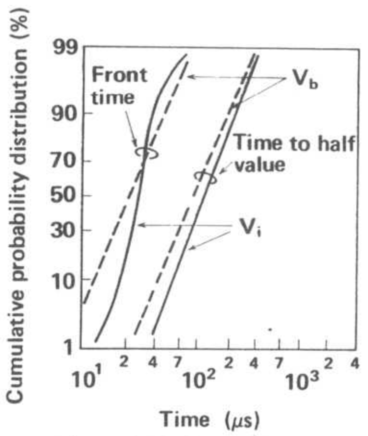

Fig. 10. Front time and time to half value distributions of the observed surge V_b and equivalent voltage source V_i at the subscriber end.

method is used. The detailed method for calculation is described in the Appendix.

The calculation constants are determined to be: 1) terminal impedance Z_b of 200 Ω based on the observed condition, 2) a random number of 1000 based on the convergence condition, and 3) other values used as constants in Table I. These figures show that distributions of the equivalent voltage source are almost completely represented by (12)–(14). The constants in these equations are summarized in Table III. Using (19), (28), (29), and the constants in Table III, the test surge waveforms are calculated; these values are also summarized in Table II.

TABLE III
PARAMETERS FOR OBSERVED LIGHTNING SURGE DISTRIBUTIONS V_b AND EQUIVALENT VOLTAGE-SOURCE DISTRIBUTIONS V_i

Term		V_b	V_i
Peak value	K value	0.6×10^5	2.5×10^5
	p value	-1.8	-1.8
Front time	Mean value(μ_f)	20μs	25μs
	Standard deviation(σ_f)	0.56	0.39
Time to half value	Mean value(μ_h)	100μs	118μs
	Standard deviation(σ_h)	0.56	0.51

C. Experiment

Block diagrams of the experimental setup for the test circuit are shown in Fig. 11. In Fig. 11, Z_i is the impedance of the test circuit in Fig. 6. These values and the test surge waveform are already shown in Table II. The 500-kV charged capacitor C, discharge gap G, inductance L, and resistances $R1$ and $R2$ make up the low output impedance test surge generator, and these values are C = 0.6 μF, L = 1 mH, $R1$ = 80 Ω, and $R2$ = 20 Ω. The earth resistances $R3$ and $R4$ are determined on the basis of typical values in Japan: these values are $R3$ = 100 Ω and $R4$ = 50 Ω. The primary protection circuit P.P. for the subscriber end is used.

The key telephone switching system with two telephones, which is designed to meet the voice communications needs of small businesses with two to six telephones, is used in this experiment. Five sets of the version I and II key telephone switching system were used, with version II incorporating improved lightning surge protection. In the experiment, the peak value of the test surge was measured when a malfunction occurred in a key telephone switching system. The mean value for version I is 25.7 kV and the mean value for version II is 40.3 kV. Using (19), the actual malfunction rate could be estimated from these values, and results are shown in Table IV.

The observed key telephone switching system malfunction rates are also presented in Table IV. Approximately 4000 Version I and 3000 Version II key telephone switching systems were monitored over a two-year period for malfunctions caused by lightning surges. The key telephone switching system malfunction rates were calculated using these data and the average thunderstorm days per year in Japan.

Though the test circuit design was based on the severest equipment conditions, estimated results were nearly identical to observed data, as shown in Table IV.

VI. Summary and Conclusion

This paper has described a new lightning surge test circuit that is capable of successfully predicting equipment malfunc-

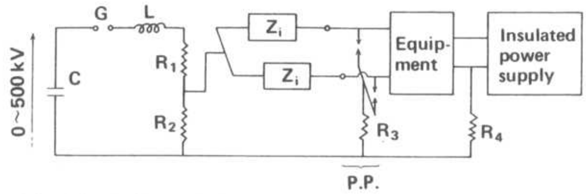

Fig. 11. Block diagram of the experimental set up for the test circuit.

TABLE IV
KEY TELEPHONE SWITCHING SYSTEM MALFUNCTION RATE (TIMES PER THUNDERSTORM DAY PER LINE)

Term	Observation	Estimation
Key telephone (Version I)	2.4×10^{-3}	2.9×10^{-3}
Key telephone (Version II)	0.8×10^{-3}	1.3×10^{-3}
Version II to I ratio	0.35	0.45

tion rates. The lightning surge that appeared between one wire of a balanced pair and ground at the line end was presented by an equivalent circuit, and the test circuit was designed through the use of an equivalent circuit. Results of the investigation for the design showed that the test circuit could be determined using three parameters: line constants, line length, and lightning surge observation data.

To demonstrate the validity of the test circuit, the test circuit parameter and the test surge waveform for the equipment connected to the subscriber line in Japan were determined, and test results were compared with observed data. The test circuit parameters for the equipment-connected subscriber end were $R_i = 250\ \Omega, L_i = 1$ mH, $C_i = 60$ nF, and $R_i' = 50\ \Omega$. The surge waveform parameters were $t_f = 28\ \mu$s and $t_h = 135\ \mu$s, and the peak values were determined from the lightning surge occurrence rate. The equipment malfunction rates estimated from the tests were almost identical with the observed data.

This test circuit will be useful in the design of circuits for the protection of equipment against lightning surges.

APPENDIX

CALCULATION METHOD FOR EQUIVALENT VOLTAGE-SOURCE DISTRIBUTIONS

This appendix presents the method for calculating the equivalent voltage source. A triangular waveform with constant peak value is randomly selected from front time and time to half value distributions using a random number. The equivalent voltage-source waveform is calculated using (15).

The ratio of the peak value of the equivalent voltage-source waveform V_p to the peak value of the observed surge $V_{bp}(V_p/V_{bp})$, and front time and time to half value distributions are obtained, as these values are independent of the observed peak value. The peak value distributions are calculated from the peak value ratio distributions.

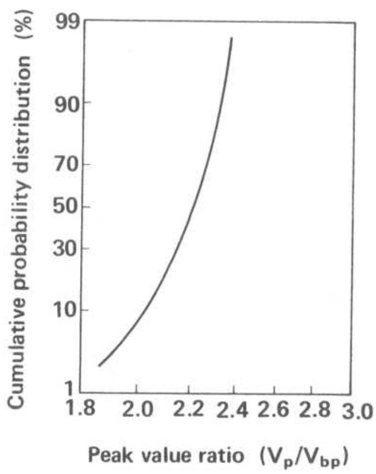

Fig. 12. Cumulative probability distributions of the peak value ratio (V_p/V_{bp}).

The peak value ratio (V_p/V_{bp}) distributions of the equivalent voltage source are shown in Fig. 12. When these distributions are approximated with a log normal distribution, they are given by

$$n(A) = \frac{1}{\sqrt{2\pi}\sigma_a} \exp\left[\frac{A - \ln(\mu_a)}{\sqrt{2}\sigma_a}\right]^2 \quad \text{(A1)}$$

with

$$A = \ln(a) \quad \text{(A2)}$$

where a is the peak value ratio V_p/V_{bp}, μ_a is the mean value of the peak value ratio distribution, and σ_a is the standard deviation of the peak value ratio distribution.

In the region between A and $A + dA$, the peak value ratio is constant. From (12), the peak value occurrence rate greater than abscissa value $N(V_p)$ is given by

$$N(V_p) = K\left(\frac{V_{bp}}{\exp(A)}\right)^{-p} \quad \text{(A3)}$$

where K and p are constants in Table III.

From (A1) and (A3), $N(V_p)$ is given by

$$N(V_p) = \int_{-\infty}^{\infty} K\left(\frac{V_p}{\exp(A)}\right)^{-p} n(A)\, dA. \quad \text{(A4)}$$

Integrating (A4), the peak value distributions are given by

$$N(V_p) = KV_p^{-1.8} \exp(1.62a_a^2)\mu_a^{-1.8}. \quad \text{(A5)}$$

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