Surge Voltages and Currents into a Customer due to Nearby Lightning

A.Ametani, K.Matsuoka, H.Omura, Y.Nagai

Abstract – This paper has carried out EMTP simulations of lightning surges incoming into a customer due to lightning to an antenna of the customer, a pole and a ground nearby the customer based on experimental results. The ground voltage rise is represented by a mutual resistance between grounding electrodes. EMTP simulation results have been observed to agree qualitatively with the measured results.

Keywords: lightning surge, grounding, distribution line, home appliance, EMTP

I. Introduction

Lightning overvoltages are important not only from the viewpoint of insulation coordination of transmission systems but also from the viewpoint of protection of customers' equipments and telecommunication systems. A number of disturbances of home appliances due to the lightning have been informed [1-5]. In a survey of the disturbances in a utility in Japan, nearly 100 disturbances per year are found to be caused by the lightning.

This paper investigates experimentally an incoming path of a lightning surge into a customer due to lightning nearby the customer [6, 7]. There exist four incoming paths: (1) low-voltage distribution line (feeder) through a distribution pole, (2) telephone line, (3) customer's TV antenna, (4) grounding electrode of a customer's electrical equipment. A lightning strike to a distribution line and an induced lightning voltage to the distribution line result in the path (1). Similarly a lightning strike to a telephone line and an induced lightning voltage result in the path (2), and the same is applied to the path (3). A lightning strike to a ground, a wood or a distribution pole nearby a customer results in a ground potential rise (GPR) due to a lightning current flowing into the ground [8, 9]. The current causes a potential rise to a grounding electrode of a customer's equipment which is the path (4).

Based on the measured results, modeling of electrical elements related to the above paths for a lightning surge simulations are developed, and EMTP simulations are carried out by the model. The simulation results are compared with the measured results and the accuracy of the modeling method is discussed.

II. Experiment of Incoming Surge into House

A. Experimental conditions

Kansai Electric Power Co. (KEPCO) has carried out a number of experiments to investigate lightning currents flowing into a house [6, 7]. An impulse current representing a lightning current is injected into an antenna, a distribution pole and a ground from an impulse current generator (IG, maximum voltage 3[MV], maximum current 40[kA]). Fig. 1 illustrates an experimental setup. An impulse current from 500[A] to 5000[A] is applied to

(a) an antenna: Fig. 1(A)
(b) a distribution pole: Fig. 1(B)
(c) a structure nearby a house: Fig. 1(C)
(d) a messenger wire of a telephone line: Fig. 1(D)

In a test-yard of the KEPCO, 3 distribution poles and 2 telephone company (NTT) poles are constructed and 6600/220/110[V] distribution lines with a pole transformer are installed as in Fig. 1. Also, a telephone line and the messenger wire are installed. A model house is built nearby the pole transformer, and a feeder line from the transformer is led in. In the model house, model circuits of an air conditioner and a Fax machine are installed as shown in Fig. 2. Those involve a surge protective device SPD, a kind of a surge arrestor (air conditioner: operating voltage 2670[V], Fax: 2800[V], NTT SPD: 500[V]). The poles, the transformer, the telephone line (NTT) and the air conditioner (home appliance) have their own grounding as in Fig.2.

Table 1 summarizes the test conditions and measured results of maximum voltages and currents through the grounding resistances.

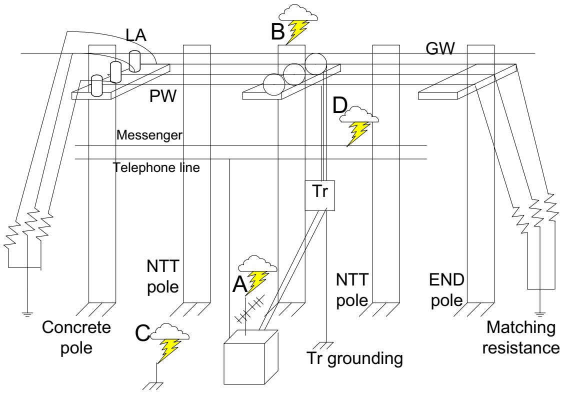

Fig. 1 Lightning and its path to a house

Lightning to A: antenna, B: pole, C: ground, D: telephone (messenger) line

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B. Experimental results

Fig. 2 illustrates the experimental circuit for various conditions corresponding to A to C in Fig.1. An impulse current is applied to (a) the antenna, (b) the top of the distribution pole and (c) a ground from the impulse current generator IG.

Fig. 3 shows experimental results for the conditions in Fig.2 (a) to (c). From the experimental results, the following observations have been made.

B1. Lightning to antenna

When lightning strikes the antenna of a house in Fig.2(a), the lightning current flows out (1) to a distribution line I_1 (I_n, I_t) through feeders in the house, and (2) to the earth I_2 (I_a, I_{np}) through grounding electrodes of home appliances. The ratio of I_1 and I_2 is dependent on the grounding resistances (1) seen from the house feeder to the distribution line, (2) seen from the house to the telephone line and (3) of the grounding electrodes of the home appliances. In the experimental results one of which is given in Fig.3 (a) with the applied current I_0=739[A], about 85 [%] of the current into the antenna flows out to the distribution line. The remaining 15 [%] is estimated to flow into the other houses. A large current 543[A] flowing into the distribution pole is caused by a flashover between the transformer grounding lead and the steel of the pole and the low grounding resistance of the pole.

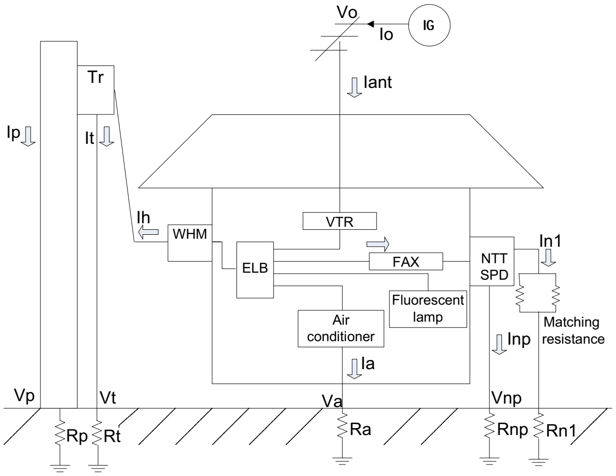
B2.Lightning to distribution pole

Fig.3 (b) shows a measured result when I_0 is 2416 [A]. In this case, 8.1% of I_0 flows into the grounding resistances R_t of the transformer neutral, 8.5% flows into the grounding resistance R_a of the air conditioner, and 2.8% to the grounding resistance R_{np} of the telephone line SPD.

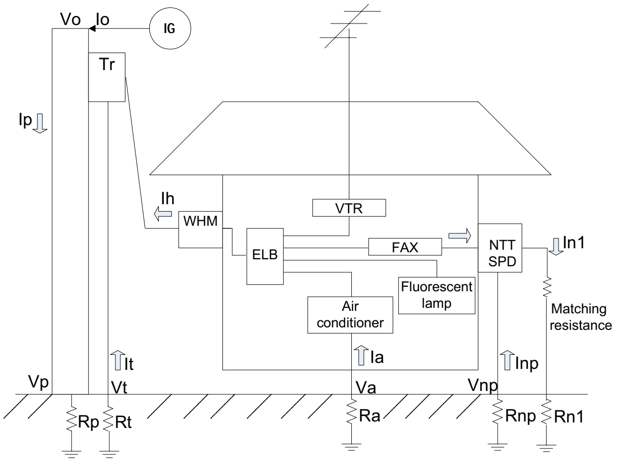
B3. Lightning to grounding

A part of the applied current I_0 flows into the air conditioner ($I_{a\ max}$=58.2[A] for I_0=2815[A]) and the NTT SPD ($I_{np\ max}$=56.6[A]) in Fig. 3 (c), case C1. The current flowing into the air conditioner flows out to a distribution line. The current into the NTT-SPD protector flows out through the telephone line. No current flows into the Fax, because the operating voltage 2800[V] of a surge arrestor within the Fax is higher than the voltage across the Fax, i.e. the voltage difference between the feeder line in the house and the telephone line.

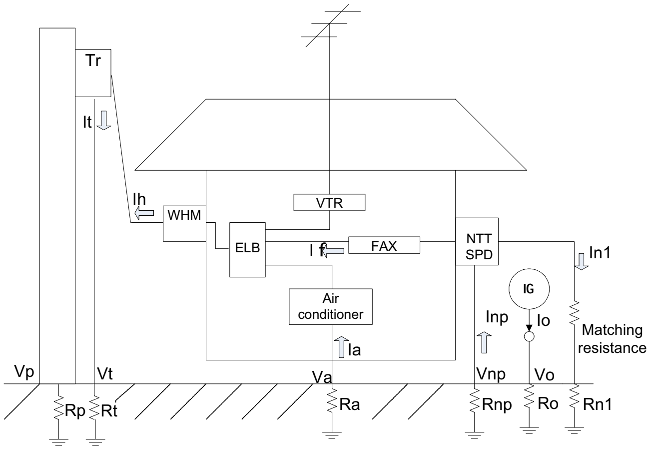
Compared with case C2, no air conditioner grounding, the currents flowing into the house increases heavily.



(a) Lightning to an antenna



(b) Lightning to a distribution pole

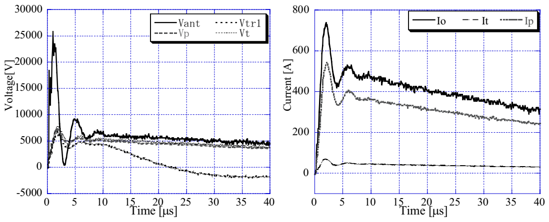


(c) Lightning to a ground

Fig. 2 Experimental circuit and lightning current path

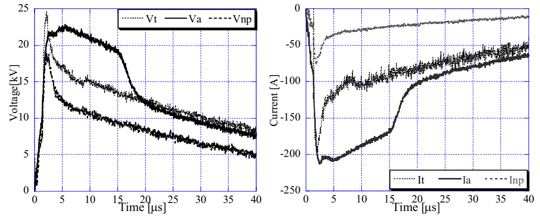
TABLE 1 Test conditions and results

case	grounding resistance[Ω]					measured voltage[kV]					current[A]						
	Rp	Rt	Ra	Rnp	Rn1	Vo	Vt	Vp	Va	Vnp	Io	Ip	It	Ih	Ia	Inp	In1
A	17	89	830	900	153	25.9	7.7	7.5	….	…	739	543	69	…	…	…	…
B	19	75	100	300	150	37.6	25	…	23	19.1	2416	…	197	…	206	68	…
C1	19	85	140	380	100	122	4	…	3.1	4.97	2815	…	…	58	58	57	56.6
C2	19	85	…	380	100	122	2.5	…	…	4.5	2845	…	…	30	…	84	56.4



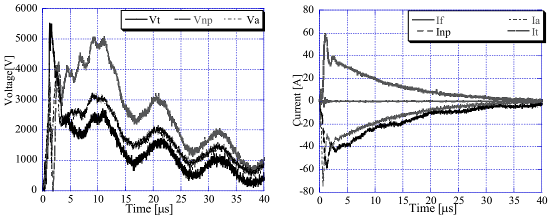
(1) Voltage (2) Current

(a) Lightning to an antenna (case A)



(1) Voltage (2) Current

(b) Lightning to a distribution pole (case B)



(1) Voltage (2) Current

(c) Lightning to ground (case C1)

Fig.3 Experimental results of transient currents and voltages

III. Modeling and Simulation of Incoming Surge

A. Modeling

The distribution line, the pole and home appliances in the house in Fig. 2 can be readily represented by horizontal and vertical distributed line models and lumped-parameter circuits [10, 11]. The grounding electrodes of the pole, the telephone line SPD and the home appliances if those are grounded are modeled by a combination of a distributed line and a lumped-parameter circuit to simulate the transient characteristic [12]. This paper, however, adopts a simple resistance model of which the resistance value is available from the experiments explained in references [12, 13], because the vertical grounding electrode used for a home appliance is short and the transient period is far smaller in the phenomenon investigated in this paper. A protective device installed in a home appliance and the NTT SPD are represented simply by a time controlled switch prepared in the EMTP [14].

A model circuit for an EMTP simulation is shown in Fig. 4. In the figure, Z_p is the surge impedance of a distribution pole which is represented by a lossless distributed line with the propagation velocity of 300[m/μs]. The surge impedance is evaluated by the following formula of a vertical conductor [10].

$$Z_p=60\cdot\{\ln(h_p/r_p)-1\}[\Omega] \qquad (1)$$

where h_p: height of the pole, r_p: radius of the pole

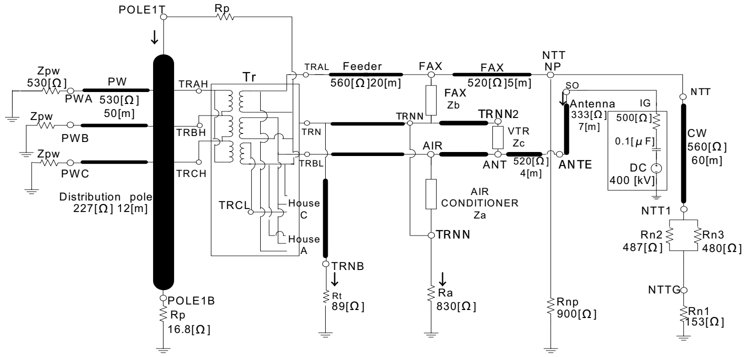
R_p=17 to 19[Ω] is the grounding resistance of the pole. The value is given by a utility [6, 7]. Tr is a pole mounted distribution transformer which is represented by an ideal transformer with the voltage ratio 6600:110[V] and stray capacitances.

TRN-TRNB is a grounding lead of the transformer represented by a lossless distributed line of which the surge impedance is explained in reference [15]. R_t is the grounding resistance of the transformer grounding lead and is given as in Table 1 by a utility [6, 7]. PW is a phase wire of a distribution line and is modeled by a lossless distributed line with the surge impedance Z_{pw}=530[Ω].The other end of PW1 is terminated by the matching impedance $Z_{pw.}$

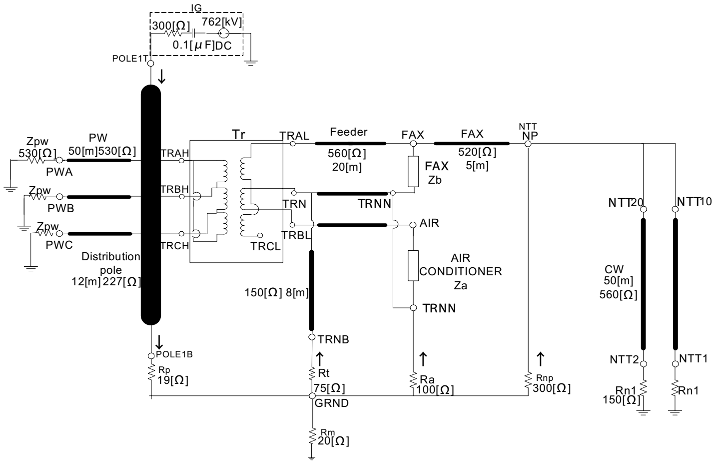
TRAL-FAX and -HOME1 are a feeder line from the pole transformer to a house. For the transformer, A is for phase A and N for neutral. The steady-state AC voltage between the phase A to the neutral is 114[V] in Japan. In the case of lightning to an antenna, case A, a flashover between the transformer grounding lead and the steel of a distribution pole was observed. The flashover is modeled by short circuiting those by resistance Rp in Fig.4 (a).

The feeder line is represented by a lossless distributed line with the surge impedance of 560[Ω] and the velocity of 300[m/μs]. R_a is the grounding resistance of an air conditioner of which the value is given is Table 1 [6, 7]. Z_a represents the air conditioner expressed by a lead wire inductance 1[μH] and by a time controlled switch representing a surge arrester operating when the voltage exceeds 2670[V] in parallel with the resistance. Z_b represents a Fax machine. It is expressed in the same manner as Z_a except that the other terminal of Z_b is connected to a telephone line through an NTT SPD, a surge arrester valve with the operating voltage of 500[V] represented by a time controlled switch. The telephone line is represented by a lossless distributed line with the surge impedance of 560[Ω] and he propagation velocity of 200[m/μs] and the other end is terminated by the matching resistance with the grounding resistance of 153[Ω].

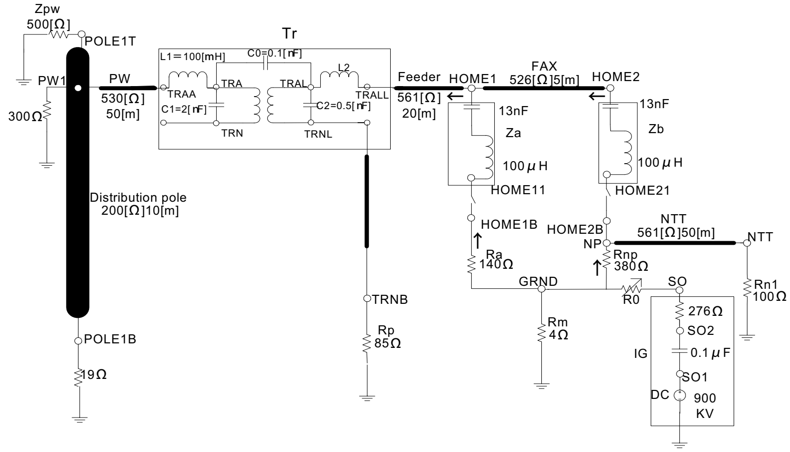
IG is an impulse current source used in the experiment and is represented by a charged capacitance and a resistance [6, 7]. R_m is a mutual grounding impedance between various grounding electrodes, and the value of 2 to 10[Ω] is adopted [9, 13].



(a) Lightning to an antenna



(b) Lightning to distribution pole



(c) Lightning to ground

Fig.4 Model circuits for EMTP simulations

PW: power line, CW: communication (NTT) line

B. Simulation results

Table 2 summarizes simulation conditions and results, and Fig. 5 shows simulated voltage and current waveforms corresponding to the measured results in Fig.3. From the simulation results in comparison with the measured results, the following observations are made.

(1) In Fig.5 (a) when lightning strikes the antenna, simulation results of transient voltages and currents agree well with the measured results in Fig.3 (a) except the wavefront of the applied current and voltage at the top of the pole and the voltage at the primary winding on the transformer.

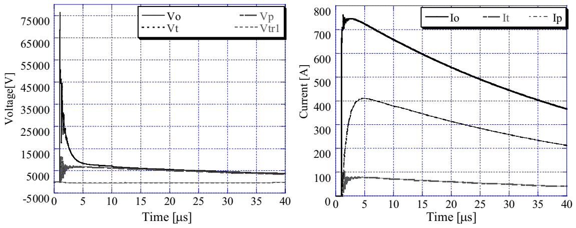
(2) In the case of lightning to the pole top in Fig.5 (b), voltage differences between the top and the bottom of the pole and at the air conditioner grounding electrode are observed to be smaller than those of the measured results in Fig.3 (b). Otherwise the simulation results show a reasonable agreement with the measured results. The node voltages in Fig.5 (b) are analytically investigated at around t=5 [μs] in Appendix and the result shows

TABLE 2 Simulation results corresponding to the TABLE 1

case	Voltage[kV]					Current[A]						
	Vo	Vt	Vp	Va	Vnp	Io	Ip	It	Ih	Ia	Inp	In1
A	76.4	9.1	11.4	…	…	761.1	409.5	102	612	…	…	…
B	17.6	29.1	17.6	30.6	23.6	1533	1533	108	-183	75.9	50.1	…
C1	12.2	2.5	…	10.3	6.2	2593	…	…	32.4	32.3	20.6	20.6
C2	12.2	…	…	…	6.2	2564	…	…	0	…	20.8	20.7

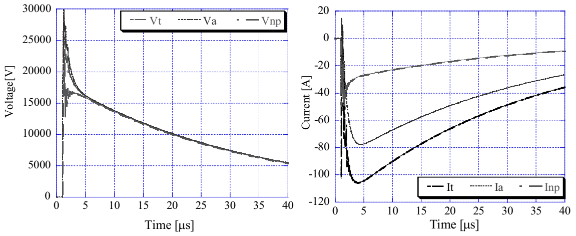
that the node voltages Vt, Va and Vnp become nearly the same. This explains the result in Fig.5 (b) and indicates that the model circuit in Fig.4 (b) is not good enough to represent the experimental circuit in Fig.2 (b). Thus a further improvement is required

(3) When lightning hits ground nearby a house, the simulation results in Fig.5 (c) shows a qualitatively satisfactory agreement with the measured results in Fig.3 (c) and thus the proposed approach to deal with a ground voltage rise by means of a mutual impedance is confirmed to be adequate.



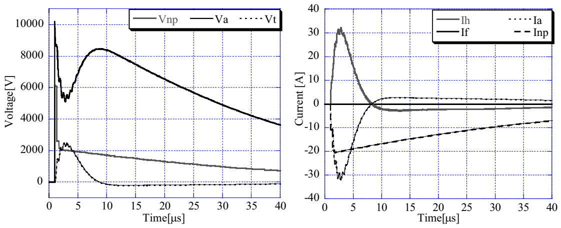
(1) Voltage (2) Current

(a) Lightning to an antenna



(1) Voltage (2) Current

(b) Lightning to a distribution pole



(1) Voltage (2) Current

(c) Lightning to ground

Fig.5 Simulation results

It, however, requires a further improvement of the overall simulation method to achieve a quantitative agreement with a measured result. For example, a surge protecting device has to be carefully represented based on its circuit and the nonlinear characteristic. Also, a grounding impedance should be modeled considering its transient characteristic rather than a simple resistance adopted in this paper.

IV. Conclusions

This paper has shown experimental and EMTP simulation results of a lightning surge incoming into a house due to lightning nearby the house. The simulation results agree qualitatively with the experimental results, and thus the simulation models in the paper are said to be adequate. The measurements being carried out in different time periods for three years, the experimental conditions such as the earth resistivity, a voltage probe used and a reference voltage line for each measurement are different, and the difference is not considered in the simulations. Some oscillations observed in the measured results are estimated to be caused by mutual coupling between the measuring wires and feeder lines in the experiments. Also, a grounding electrode may have coupling to the other electrode. A further improvement for modeling the experimental circuits is required to achieve a higher accuracy in comparison with the measured results.

Lightning surge voltages in a customer and lightning currents flowing out to a distribution line can be made clear based on the experimental and simulation results. The results are expected to be applied to protection coordination of SPDs for customers and a telephone line, and to investigate the necessity of home appliance grounding.

V. References

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VI. Appendix:steady –state voltages in Fig.5 (b)

At around t=5 [μs], Fig.5 (b) is rewritten as Fig. A-1. It is clear is Fig. A-1 that the voltages Va, Vt and Vnp are the same.

$$Va=Vt=Vnp=Vg*Z_3/(Z_2+Z_3)=16\ [kV]$$

where $Vg=E_0-(R_0+Rp)\ I_0=31\ [kV]$

$$I_0=E_0/Z_0=1940\ [A],\ Z_0=R_0+Rp+Z_1=335\ [\Omega]$$

$$1/Z_1=1/(Z_2+Z_3)+1/Rm,\ 1/Z_2=1/Ra+1/Rt+1/Rnp$$

$$1/Z_3=1/Rh+2/Rn1$$

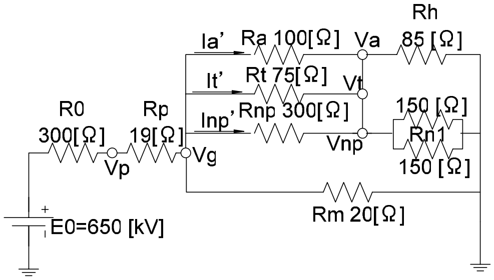

Fig. A-1 Equivalent circuit of Fig.5 (b) at around 5[μs]

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