Lightning Overvoltages on Low Voltage Circuit Caused by Ground Potential Rise

S. Sekioka, K. Aiba, S. Okabe

Abstract-- The lightning overvoltages incoming from an overhead line such as a power distribution line and a tele-communication line, and an antenna to a residence are studied actively. However, a relation between a lightning hit to ground near the residence and the overvoltages on low voltage circuit in the residence is still unclear. The authors proposed a simulation method to estimate the lightning overvoltages in the residence due to ground potential rise by the lightning hit to the ground based on the Thevenin theorem. The method can be realized in the EMTP. This paper describes simulation results of the lightning overvoltages due to the ground potential rise and the radiation field generated by return stroke current.

Keywords: Lightning hit to ground, Ground potential rise, Lightning-induced voltage, Low voltage circuit, EMTP.

I. Introduction

It is very important to make causes of lightning damages in home appliances clear and to establish lightning protection methods for the reliability and quality of electric power system. The lightning damages are classified into three routes from which lightning overvoltages come:

(1) Distribution and telecommunication lines
(2) Antenna
(3) Ground potential rise (GPR) caused by lightning hit to the ground, a structure or a tree.

A number of papers discuss the lightning overvoltages coming from the overhead lines or from the antenna to home appliances [1-3]. However, any mechanism of the lightning damages in a low voltage circuit caused by the lightning hit to the ground is not clear. The authors proposed a method to simulate the lightning overvoltages on the low-voltage circuit in residence due to the GPR by the lightning hit to the ground [4]. The proposed method is obtained on the basis of the Thevenin theorem, and can be used in the EMTP [5].

This paper describes simulation results of overvoltages in a low voltage circuit in a residence when lightning strikes the ground near the residence. Two situations of the lightning hit to the ground to cause the overvoltages are considered. One is called lightning-induced voltage, which is generated by electromagnetic fields radiated from return stroke. The other is caused by the GPR. These overvoltages are simulated using the EMTP and are compared in the paper.

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II. Simulation Method of Lightning Hit to Ground

A. Ground Potential Rise

The GPR is dependent on the grounding resistance at the lightning-striking point. Assuming that lightning current flows into the ground uniformly through a grounding electrode or a tree as illustrated in Fig. 1, the GPR $V(x)$ at distance x from the lightning striking point is inversely proportional to x, and is given by

$$V(x) = \frac{V(0)}{x}. \quad (1)$$

B. Simulation Method of Lightning Overvoltages on Low Voltage Circuit Caused by Ground Potential Rise due to Lightning Hit to Ground Using the Thevenin Theorem

The Thevenin theorem is convenient to solve an electrical circuit including complicated or uncertain characteristics [6]. The theorem is represented by a circuit illustrated in Fig. 2 composed of a voltage source E at a terminal, which is obtained as the terminal voltage when the terminal is opened, impedance Z_e seen from an external circuit to the terminal, and impedance Z_c of the external circuit. The Thevenin theorem is applicable to analysis of lightning overvoltages on the low voltage circuit in the residence caused by the GPR due to the lightning hit to the ground [4]. The GPR at a grounding electrode in the residence can be regarded to be the voltage source E in the Thevenin theorem when the grounding electrode is not connected to any circuit. The grounding resistance is calculated by the sum of soil resistance of

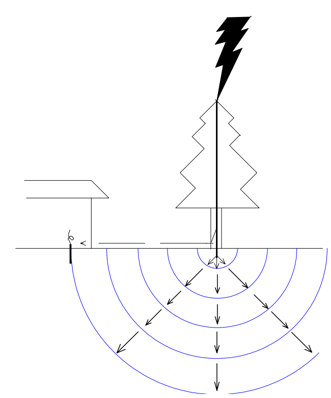


Fig. 1. A simplified model of lightning hit to ground associated with voltages in residence.

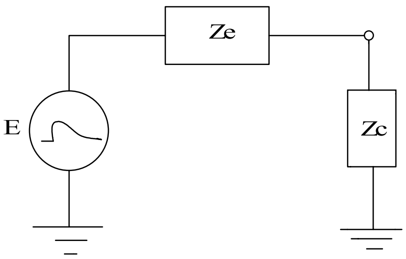


Fig. 2. Thevenin's theorem.

segment from the electrode surface to infinite point. Therefore, Z_e corresponds to the grounding resistance of the grounding electrode. The variables in Fig. 2 are obtained as follows:

1) Voltage source **E**: If the lightning striking point is modeled, the GPR at the striking point can be obtained. Then, the voltage sources are calculated using eq. (1). Assuming the lightning can be regarded to be current source, and the distance is very long, the voltage source is approximately given by

$$V(x) = R_m i = \frac{\rho}{2\pi x} i \qquad (2)$$

where R_m: mutual grounding resistance, ρ: soil resistivity, i: lightning current.

2) Backward impedance $\mathbf{Z}_e$: The backward impedance is expressed by self- and mutual grounding resistances of the grounding electrodes in the residence, and it is inserted between the voltage source and the external circuit models.

3) External circuit impedance $\mathbf{Z}_c$: The external circuit is the same as that used in the lightning surge analysis for the lightning hit to overhead lines, an antenna or lightning-induced voltages. The low voltage circuit can be realized by simulation models prepared in the EMTP.

Constants of the simulation models in the proposed method are easily calculated, and are used in the EMTP. Therefore, the lightning surge analysis for the lightning hit to the ground can be carried out by the EMTP.

C. Simulation Method of Lightning-Induced Voltage

The lightning-induced voltage is generated by electro-magnetic fields radiated from indirect lightning stroke. The lightning-induced voltage is simulated using a finite difference method implemented into an EMTP to solve line equations with external forces due to the radiation fields and transition points circuits simultaneously [7].

III. Simulation Circuit

A. Configuration of Lines and Low Voltage Circuit

Fig. 3 illustrates a configuration and dimension of a 6.6kV distribution line in Tokyo Electric Power Co. and a telecommunication line [1]. One phase of low-voltage line is grounded, and medium-voltage distribution lines in Japan adopt no grounding system.

A low voltage circuit in a residence is illustrated in Fig. 4. Three home appliances such as a facsimile, a television, and a ground type appliance, of which its case is grounded to prevent a person from electric shock, are considered. Impedances to represent the home appliances are not considered in this paper because line voltages are mainly determined by surge protective devices (SPDs). There are some grounding points for the home appliances and the SPDs in Japanese residences.

Fig. 5 illustrates a simulation circuit, where only right side of the circuit is drawn for simplicity. The residences except at No. 0 pole are represented by a simple circuit [8]. The ends of the line are terminated through characteristic impedance matrix of the lines. D_i and D_g are distance from the No. 0 pole and the house entrance, respectively.

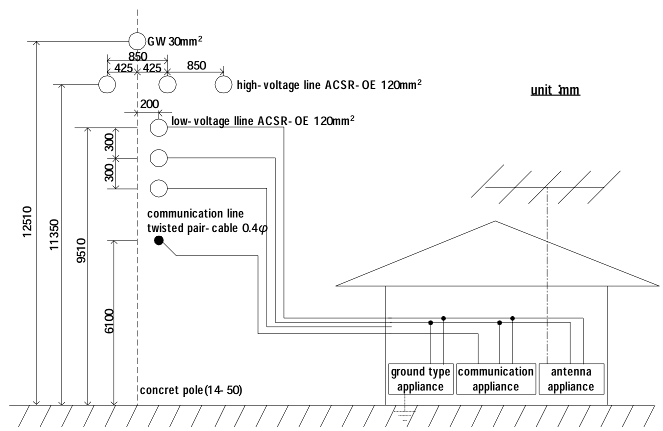


Fig. 3. Configuration of distribution and communication lines

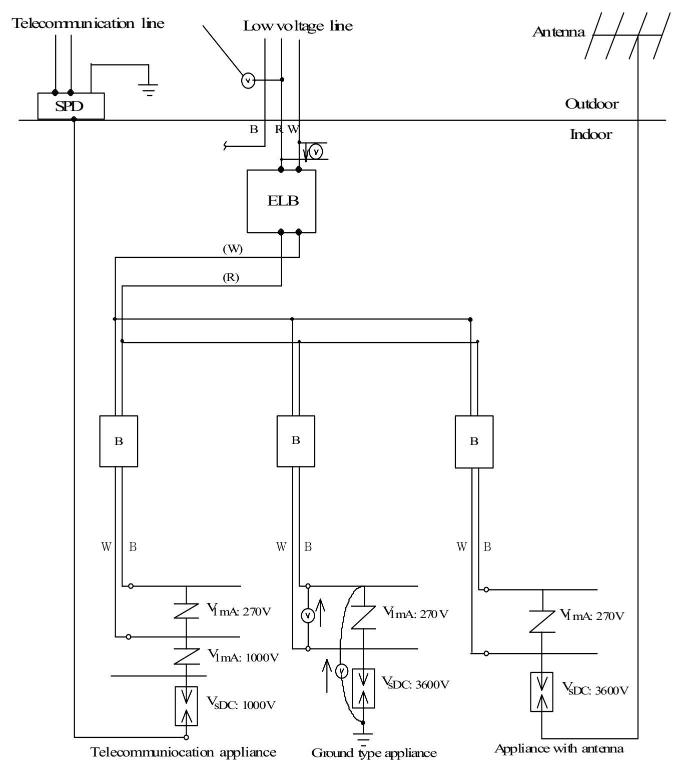


Fig. 4. Low voltage circuit in a residence

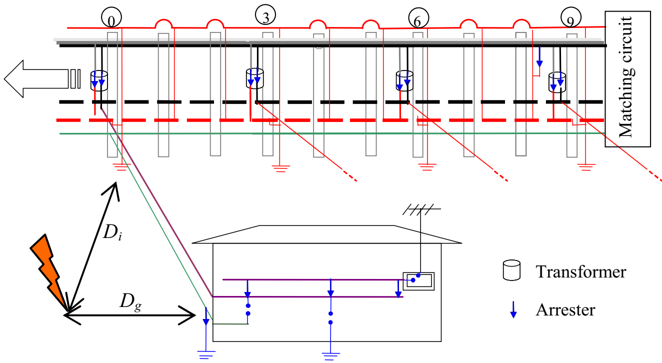


Fig. 5. Simulation circuit

B. Characteristics of Surge Arresters and SPDs

Two types of surge arresters are found in the distribution line. One is line arrester, and the other is one inside a transformer to protect the transformer against the lightning overvoltages. Voltage-current characteristics of the SPD for home appliances and the surge arresters are shown in Fig. 6. Breakdown in the home appliances are modeled by a voltage-controlled gap. The breakdown voltages are shown in Fig. 4.

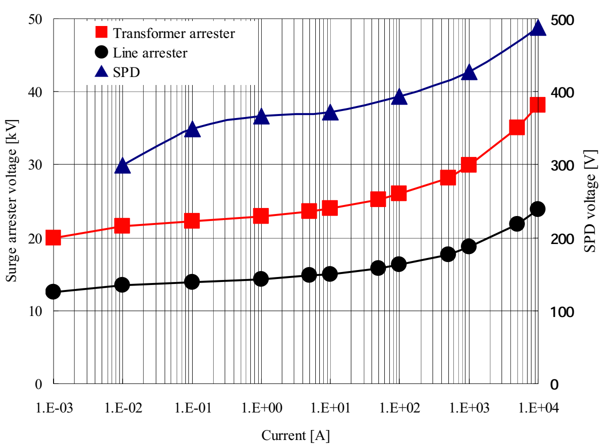


Fig. 6. Voltage-current characteristics of surge arresters and SPD

C. Simulation Conditions

Table I shows simulation conditions.

TABLE I
SIMULATION CONDITIONS

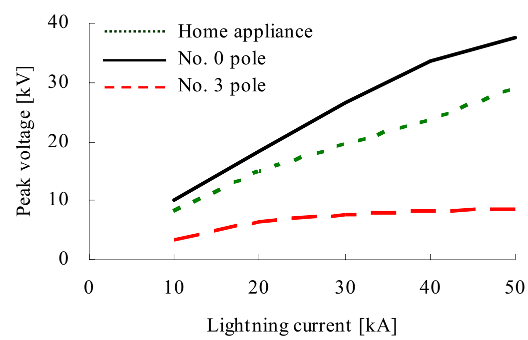
	Conditions
Waveform of lightning current	2/70μs, Ramp shape
Peak value of lightning current	10, 20, 30, 40, 50kA
Return stroke velocity	100m/μs
Lightning striking point	Lightning-induced incidence: D_i= 25, 50, 100 m from No. 0 pole GPR due to lightning hit to ground: D_g= 25, 50, 100 m from the house
Grounding resistance	Distribution line: 64.8Ω Home appliances: 95.4Ω
Soil resistivity	200Ωm
Distribution line	Span length: 35m No consideration of frequency dependence

IV. Simulation of Lightning-Induced Voltages

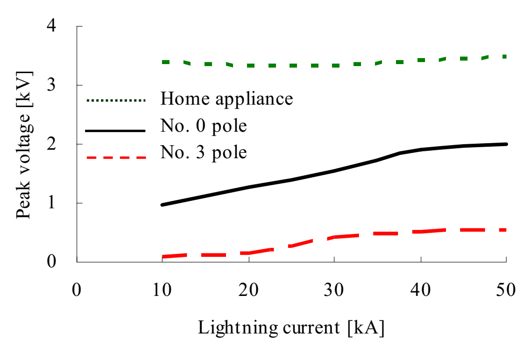
Electromagnetic fields from return stroke generate over-voltages on all conductors. This paper only considers induced voltages on the distribution line. The lightning current starts from the ground to cloud, and shows positive polarity.

Figs. 7 to 9 show crest values of potential and line voltage on the low-voltage circuit in an earth leakage breaker (ELB) at No. 0 and 3 poles, and at the ground-type home appliance caused by the lightning-induced incidence. The line voltage of the home appliance shown in the figures is defined as the B-wire potential minus the GPR at the appliance. An example of calculated waveforms of the potentials and the line voltages are shown in Fig. 10.

It is clear from Figs. 7 to 9 that the potentials become higher as the peak value of the lightning current is increased or the lightning location is closer to the line. The line voltages in the ELB show similar variation with the potential. The lightning-induced voltage is inversely proportional to the distance between the line and the lightning stroke [9]. The line voltage in the ground type appliance is suppressed by the breakdown in the appliance. Fig. 10 indicates the potentials have about 4μs period. The line voltage is suppressed by the SPD. High frequency oscillation of the waveform is caused by numerical instability of the finite difference method. The line voltage at the ground-type home appliance is suddenly decreased due to the breakdown, and the line voltages approximately take same variation by the SPDs.

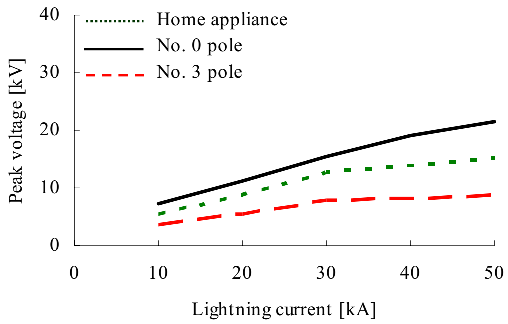


(a)Potential

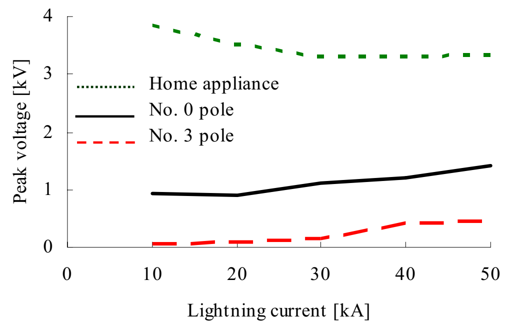


(b)Line voltage

Fig. 7. Simulation results of lightning-induced voltages in case of D_i=25m

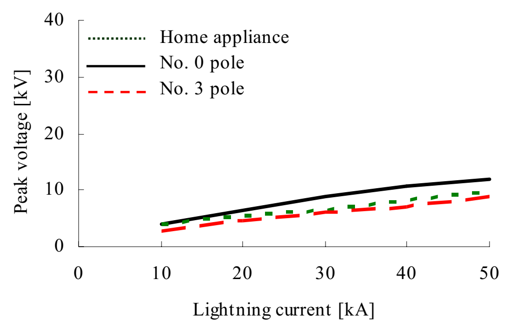


(a)Potential

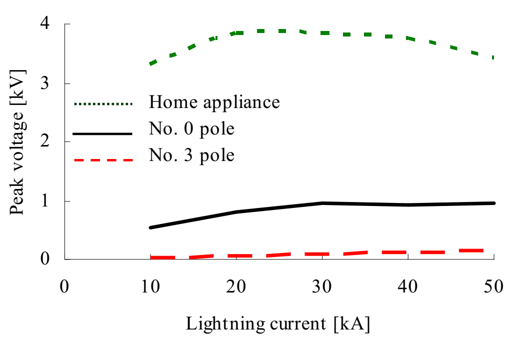


(b)Line voltage

Fig. 8. Simulation results of lightning-induced voltages in case of D_l=50m

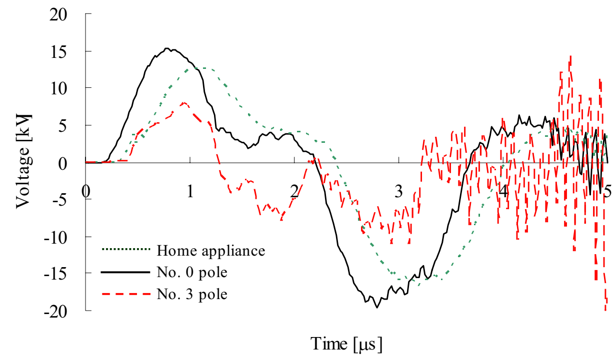


(a)Potential

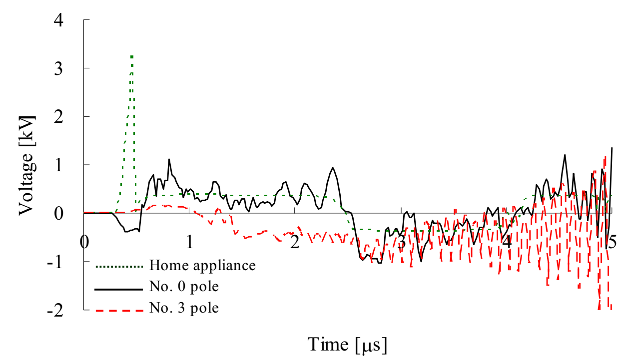


(b)Line voltage

Fig. 9. Simulation results of lightning-induced voltages in case of D_l=100m



(a)Potential



(b)Line voltage

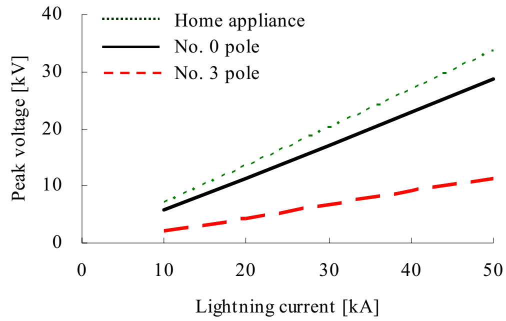
Fig. 10. Calculated waveforms of lightning-induced voltages in case of D_l= 50m and lightning current of 30kA

V. Simulation of Lightning Overvoltages due to GPR

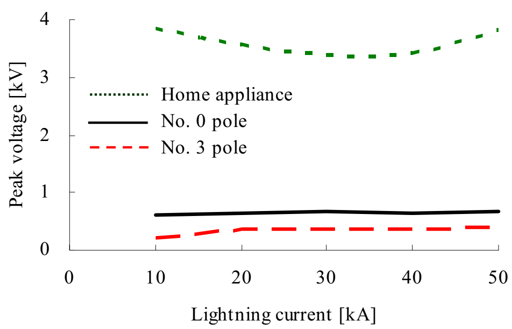
This chapter investigates the lightning overvoltages caused by the GPR due to the lightning hit to the ground. The lightning current is injected into an electrode, and shows positive polarity. For simplicity, the voltage waveforms of source voltage are assumed to be the same as the lightning current and the GPR at the lightning striking point. The source voltages are calculated using (2).

Figs. 11 to 14 show simulation results of crest values and waveforms of the potentials and the line voltages using the ATP-EMTP. The values and the curves in these figures are same as those in Figs. 7 to 10.

From Figs. 11 to 13, the potentials become higher as the crest value of the lightning current is increased or the lightning location is closer to the line. This shows the same characteristic as the lightning-induced voltages. The line voltages are approximately independent of the lightning current. The potential in the ELB is lower than that on the ground type appliance. This relation is opposite to the lightning-induced voltages. As is shown in Fig. 14, the line voltage shows negative polarity and breakdown in the ground-type appliance occurs. The lightning surge comes from the ground. As a result, the potential is decreased along the low-voltage wire. The line voltage is suppressed by the SPD, and has long duration.

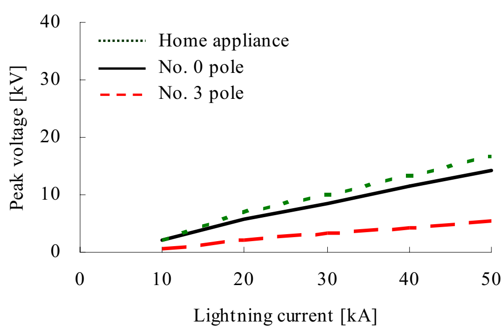


(a)Potential

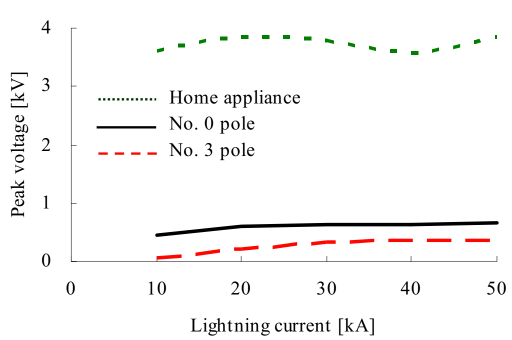


(b)Line voltage

Fig. 11. Simulation results of overvoltages due to GPRs in case of D_g=25m

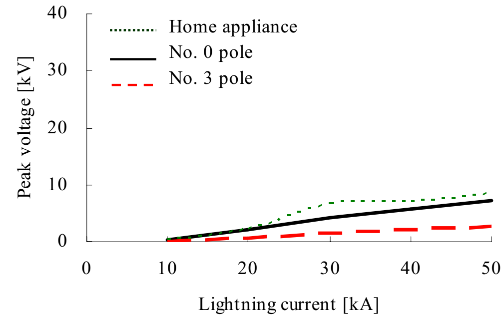


(a)Potential

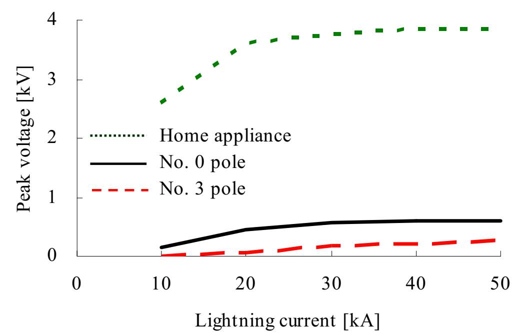


(b)Line voltage

Fig. 12. Simulation results of overvoltages due to GPRs in case of D_g=50m

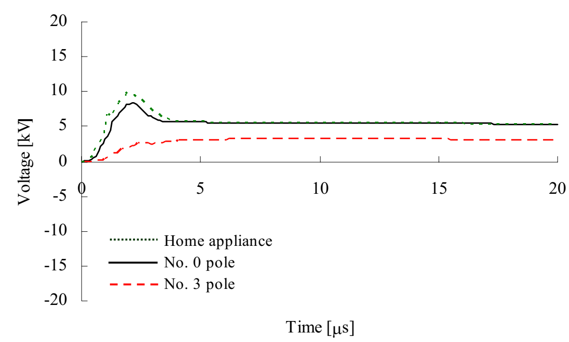


(a)Potential

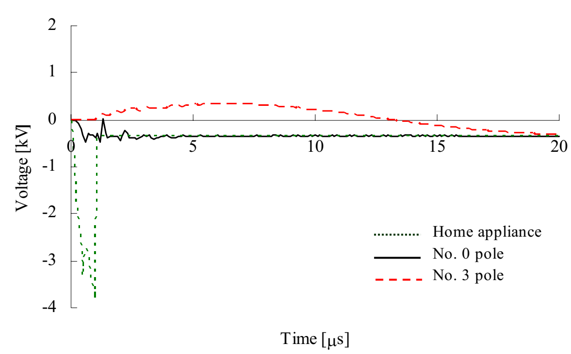


(b)Line voltage

Fig. 13. Simulation results of overvoltages due to GPRs in case of D_g=100m



(a)Potential



(b)Line voltage

Fig. 14. Simulation results of overvoltages due to GPRs in case of D_g=50m and lightning current of 30kA

VI. Discussion

Nearby lightning strokes generate the lightning-induced voltages on overhead lines. The nearby strokes are frequently observed. Therefore, overvoltages on a low voltage circuit in a residence sometimes appear, and malfunction and trouble in home appliances and computers occur. The peak values of the lightning-induced voltage on the low voltage circuit are not so different from those by the GPR due to the lightning hit to the ground comparing the simulation results. The waveform of the lightning-induced voltage shows oscillation, and that by the GPR has long duration. As a result, energy due to the GPR is much larger than that caused by the lightning-induced incidence. Therefore, the GPR is more dangerous for the home appliances than the lightning induced incidence due to the large energy.

The lightning-induced overvoltages are flown from the distribution line to the residence. On the other hand, the surges due to the GPR are flown from the ground into the distribution line via the home appliances. Thus, the direction of the lightning-induced voltage is opposite to the voltage by the GPR in spite of the same initiation of the lightning hit to the ground.

The simulation results lead to the following remarks.

(1) The lightning overvoltages on the low voltage circuit in the residence caused by both the lightning-induced voltage and the GPR due to the lightning hit to the ground are suppressed by the SPDs.

(2) The lightning overvoltages caused by the lightning hit to the ground are spread from the lightning striking point. Accordingly, the lightning damages occur in a large area. Considering the GPR due to the lightning hit to the ground becomes higher as the soil resistivity is larger, the soil resistivty should be taken into account for the GPR as well as deformation of the electromagnetic fields radiated from return stroke [10].

(3) The peak value of the lightning-induced voltage in the low voltage circuit is not so different with that of the voltage caused by the GPR. The duration of the lightning-induced voltage is sufficiently shorter than that of the voltage by the GPR. Accordingly, the voltage by the GPR greatly affects the lightning damages in the low voltage circuit.

VII. Conclusions

This paper has discussed overvoltages in a residence due to lightning hit to the ground. This paper has concerned two types of the voltages, which depend on mechanism to cause. One is lightning-induced voltage generated by electro-magnetic fields from return stroke. The other is caused by ground potential rise, and is simulated using the proposed method on the basis of the Thevenin theorem. A series of the simulations have been carried out by the EMTP. The simulation results have showed the lightning overvoltages on the low voltage circuit in the residence are suppressed by surge protective devices, and the peak value of the lightning-induced voltage in the low voltage circuit is not so different from the voltage caused by the ground potential rise. The paper has pointed out the soil resistivity is very important for lightning analysis of the lightning hit the ground.

VIII. References

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IX. Biographies

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Kiyoshi Aiba was born in Chiba, Japan on June 1, 1967. He received the B. Eng. and M. Eng. degrees from Keio University, Japan in 1991 and 1993 respectively. He joined the Tokyo Electric Power Company in 1993. Presently he is a researcher of the High Voltage and Insulation Group at the R & D center of the Tokyo Electric Power Company. He is engaged in research of lightning protection.

Shigemitsu Okabe was born on September 18, 1958. He received the B. Eng., M. Eng. and Dr. degrees in electrical engineering from the University of Tokyo in 1981, 1983 and 1986, respectively. He has been with the Tokyo Electric Power Company since 1986, and is presently group manager of the High Voltage & Insulation Group at the R & D center. He was a visiting scientist at Technical University of Munich in 1992. He has been involved in several research projects on transmission and distribution equipment. Dr. Okabe is a member of IEEE and IEE of Japan.