Induced Voltages to Wires Installed within a Building due to Direct Lightning

Naoto Nagaoka, Takaaki Kusuda, Yohei Iwakura, Akihiro Ametani

***Abstract*--Surge induced voltages to a grounding wire installed within a building due to a direct lightning strike are investigated by means of numerical simulations and experiments using a scaled model. It is confirmed from the results that the common grounding, which connects the grounding wire to the building structure, is not valid at all from the viewpoint of an insulation design of a system. The effect of a voltage-probe impedance on a measured result is investigated using numerical simulations by Finite Difference Time Domain (FDTD) method and the Electromagnetic Transients Program (EMTP).**

***Keywords*: Lightning surge, Building, Induced voltage, Grounding conductor, EMTP**

I. INTRODUCTION

A transient characteristic of a building struck by lightning is important for an insulation design of a power distribution system as well as of a communication system in a building [1], [2]. Induced voltages to wires installed in a building should be studied for its insulation design. An analytical investigation is impractical because of the complexity of the building structure. An experiment using an actual building is also unrealistic. The investigation of the induced voltage has to be carried out by experiments using a scaled model or by numerical simulations [2].

The frequency range of a measurement is shifted to a high frequency region if a scaled model is adopted. The measured result does not reflect a phenomenon to be investigated, because the impedance of an oscilloscope-probe affects the measured result in the frequency region. The effect of the measuring instrument on the measured result should be taken into account.

A numerical simulation is an alternative to the measurement. The simulation methods are roughly classified into a circuit analysis method and a field analysis method.

The circuit analysis method has been used for a lightning surge analysis, because it can easily express an electrical wire whose sectional area is far smaller than that of a building structure. The losses caused by the resistances of the building structures and wires are able to be taken into account. This is difficult to express by the electromagnetic field analysis method. The circuit analysis method, however, cannot take into account the retardation of mutual coupling between conductors.

The field analysis method, such as an FDTD method [3], [4], can easily express 3-dimentional structures including mutual coupling between conductors arranged perpendicularly, and the retardation of the mutual coupling is automatically included. Numerous computational resources are, however, required for the method. For a practical simulation, an electrical wire has to be represented by a thin wire model whose conductance and sectional area are neglected.

In this paper, induced voltages to a wire installed parallel to a pillar of a building due to direct lightning are investigated by means of an experiment and numerical simulations. The effect of the frequency characteristic of a measuring instrument is also investigated in this paper.

II. TWO-CONDUCTOR MODEL

A. Measurement and Simulation Model

A scaled model illustrated in Fig. 1 is used to investigate the transient induced voltage to a wire which models a grounding conductor. A pair of vertical copper wires on an aluminum plate expresses a pillar and a grounding wire. A current is injected by a pulse generator, PG, via a resistor R_i. Its return current flows into four wires installed on the corners of the aluminum plate. Table 1 shows the parameters of the circuit. The source of the experimental circuit can be assumed as a current source, because the resistance of the internal source is far higher than the pillar impedance [5].

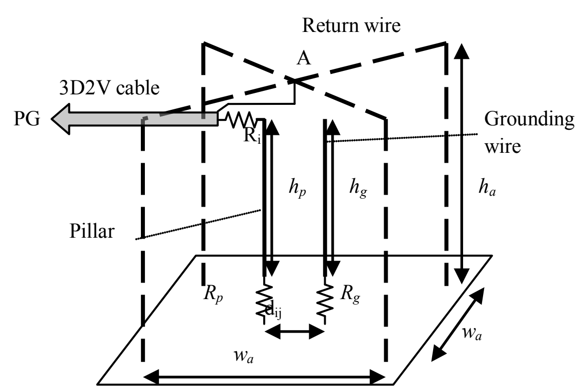

Fig. 1 Scaled model

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N. Nagaoka, T. Kusuda, Y. Iwakura and A. Ametani are with Doshisha University, Kyotanabe, 610-0321, Japan (e-mail of corresponding author: nnagaoka@mail.doshisha.ac.jp).

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TABLE 1 PARAMETERS OF EXPERIMENTAL CIRCUIT

Source resistance	R_i	4.7 kΩ
Grounding resistance of pillar	R_p	20 Ω
Grounding resistance of ground wire	R_g	20 Ω
Height of pillar	h_p	0.8 m
Height of ground wire	h_g	0.8 m
Height of return wire	h_a	1.2 m
Radius of pillar	r_p	1.6 mm
Radius of grounding wire	r_g	1.6 mm
Radius of return wire	r_r	1.6 mm
Distance between pillar and grounding wire	d_{ij}	0.1 m
Distance between return wires	w_a	1 m

A waveform recorder (Isolation System, DM-8000, Iwatsu Electric Co. Ltd.), which isolates between measuring circuits and a controller by optical fibers, is used in the measurements. A differential measuring method shown in Fig. 2 is employed to the voltage difference measurement. The GND terminals of the both probes have no external connection, but the terminals are connected to each other. The method reduces the effects of the induced voltages to the cables of the voltage probes.

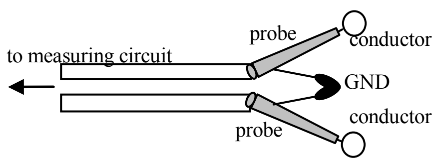


Fig. 2 Differential voltage measurement between a pillar and a grounding wire.

Numerical simulations in this paper are carried out using a program based on an FDTD method and the EMTP. In the EMTP simulation, the vertical conductors are modeled by a two-phase distributed parameter line whose propagation velocity is assumed to be the speed of light. Its characteristic impedance is obtained by the revised Jordan's formula proposed in [5]. Its approximated value can be obtained as a characteristic impedance matrix of a couple of horizontal conductors, whose height is middle of the vertical structure, by CABLE or LINE CONSTANTS in the EMTP. The current return wires are modeled by a single-phase distributed parameter line and the mutual coupling between the vertical conductors and the return wires are neglected.

In the FDTD simulation, each vertical conductor is modeled by a thin wire model, which assumes the wire's conductivity and sectional area are to be zero. The analysis region of the FDTD calculation is 1.6×1.6×1.496 m and is divided into 200×200×187 cells. The time step is 0.0153 ns which is determined by Courant's condition.

B. Measured and Calculated Results with Probes

Fig. 3 illustrates measured and calculated injected currents into the pillar model. The amplitude of the current is 20 mA and the rise time is about 4 ns.

The difference between the measured and calculated results is mainly caused by inaccuracy of the PG model. The oscillating frequency of 100 MHz observed in the measured current waveform cannot be reproduced by the simple source model employed in this paper.

Fig. 4 illustrates the measured and calculated voltage differences between the pillar and the grounding wire at the top, middle and bottom of the vertical structure. The maximum voltage becomes about 4.0 V (200V/A) at the top of the structure.

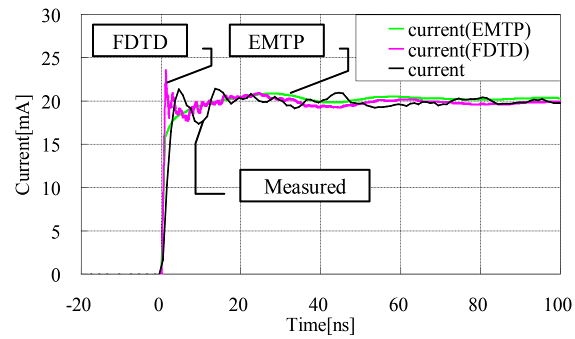
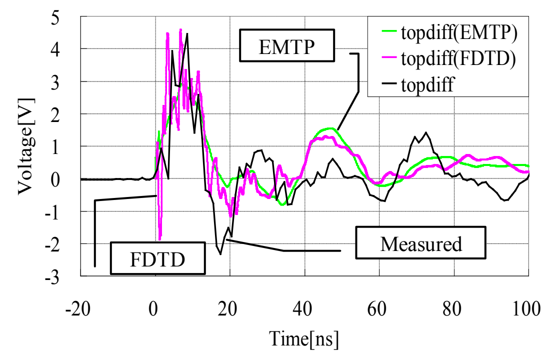


Fig. 3 Injected current



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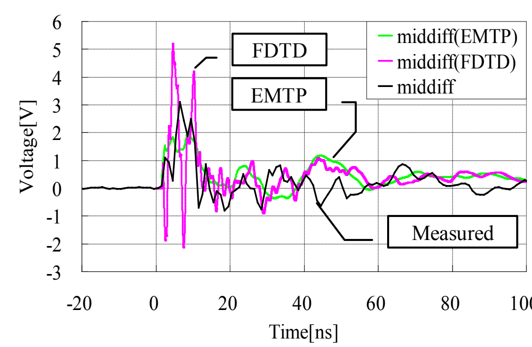
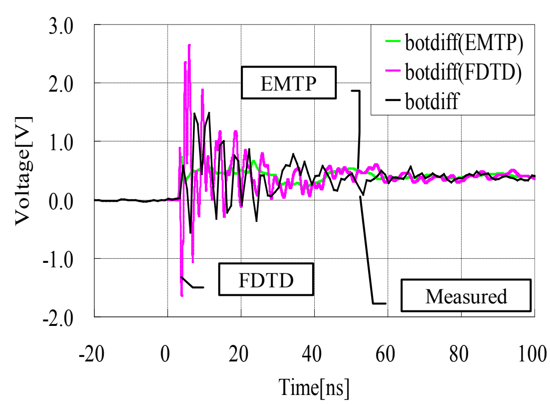


(b) middle

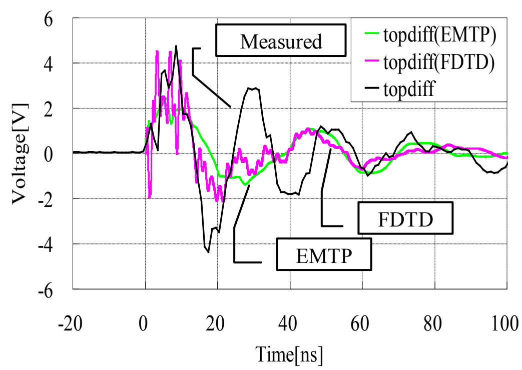


(c) bottom

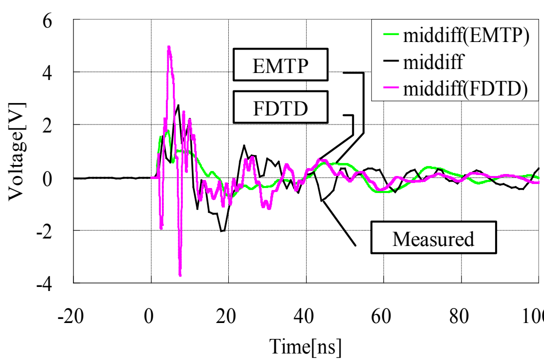
Fig. 4 Voltage difference (independent grounding)

The voltage at the bottom is approximately obtained by the injected current and the grounding resistance of the pillar ($=I\times R_p$). The steady state voltage at the bottom agrees with the theoretical value. The voltage at the middle is roughly given as an average of the top and bottom voltages.

Fig. 5 illustrates the voltage differences at the top and middle when the grounding wire is connected to the pillar at the bottom and the grounding resistor of the grounding wire R_g is removed. This condition expresses a common grounding method. In this case, there is no voltage difference at the bottom. The maximum voltages at the top is almost identical to that of the independent grounding case, and its value is 4.0 V (200 V/A). It is clear from the measured results shown in Fig. 4 and Fig. 5 that there is a minor difference between the results for the independent and common grounding case.



(a) top



(b) middle

Fig. 5 Voltage difference (common grounding)

The calculated results obtained by the EMTP and a program based on FDTD method are also illustrated in Fig. 4 and Fig. 5. The effect of the voltage probe impedance is unavoidable. The probe impedance is modeled by an *RC*-series circuit in this paper. The parameters of 12 pF (= C_p) and 150 Ω(= R_p) are obtained from a measured frequency characteristic of the impedance in a region at around 30 MHz.

The dominant transient responses of the voltage difference between the vertical conductors are reproduced by the EMTP. The FDTD method is able to express high-frequency oscillation observed at the wavefront. The difference between the circuit analysis and the FDTD method would comes from the mutual coupling between the vertical conductors and the current return wires, which is neglected in the EMTP simulation. The difference becomes small as time passes. The circuit analysis method, i.e. EMTP is a practical simulation tool from a viewpoint of the computational time and the data creation time.

C. Calculated Results without Probe Model

The effect of the probe impedance can be eliminated by a numerical simulation. Calculated results without the probe models expressed by the *RC* series circuits are illustrated in the following figures with the measured results. The injected current is illustrated in Fig. 6. The calculated current waveforms in Fig. 6 contain much high-frequency components than those shown in Fig. 3, because the capacitive impedances of probes bypasses the high-frequency components.

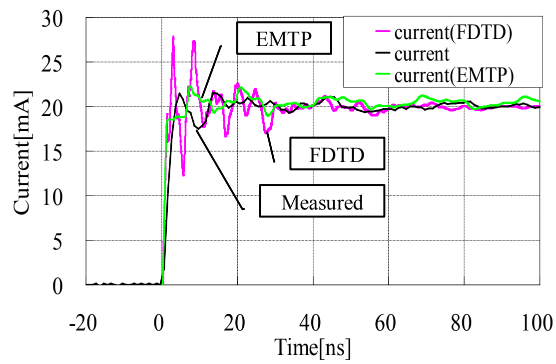
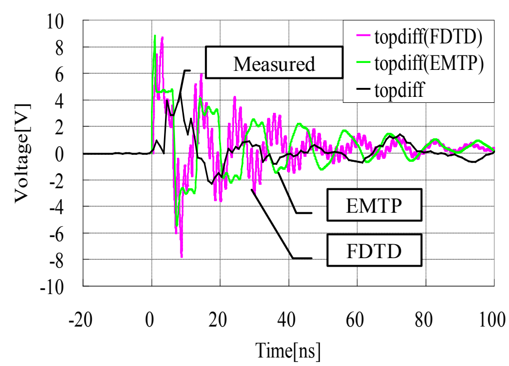
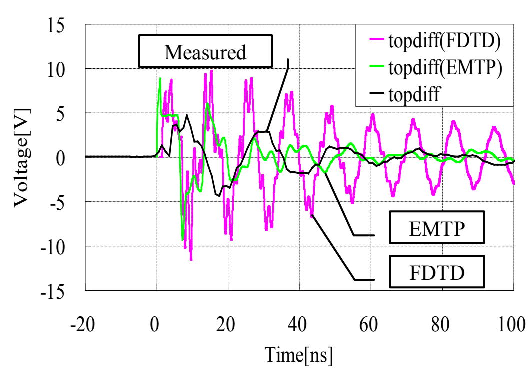


Fig. 6 Injected current



(a) independent grounding



(b) common grounding

Fig. 7 Voltage difference at the top of the vertical structure without probes (The measured results includes the effect of the voltage probes)

Fig. 7 illustrates the simulated voltage differences between the pillar and the grounding wire at the top of the vertical structure. The calculated results of the independent grounding and the common grounding case are illustrated in Fig. 7 (a) and (b), respectively. The difference between the results shown in Fig. 4, Fig. 5 and Fig. 7 indicates the effect of the voltage probe.

The removal of the probe model doubles the oscillating frequencies. The oscillating frequency of the case with the probe model is mainly determined by the capacitance of the probe and the inductance of the vertical conductor. The frequency of the case without the probe is determined by four times of the traveling time of the vertical conductor, 4τ ($\tau=h_g/c_0$=0.8 m/0.3 m/ns=2.7 ns). In the case with the probe model, the dominant oscillating frequency and the attenuation obtained by the circuit analysis method (EMTP) are almost identical to those by the FDTD simulation. The probe impedance also affects the attenuation of the oscillation. In the case without the probe model, the oscillating frequency obtained by the FDTD method slightly higher than that by the EMTP. The difference comes from the difference of the travelling velocity including numerical error. Although the velocity difference is small, the phase difference between these results increases as time passes. A resonance between the vertical conductors and a multiple reflections along the conductors are notable in the case of common grounding. The thin wire model of the FDTD method cannot take into account the resistance of the conductor. This is a reason that the attenuation of the common grounding case obtained by the FDTD method is smaller than that by the EMTP.

The amplitude of the transient voltage is increased by the removal of the probe models. The calculated result with a probe model is indispensable to confirm the accuracy of the calculation.

III. Building Model

Induced voltages to a grounding wire installed in a scaled building model illustrated in Fig. 8 are investigated in this chapter. A grounding wire is installed along the center pillar. The scale ratio to a practical building is 1/25.

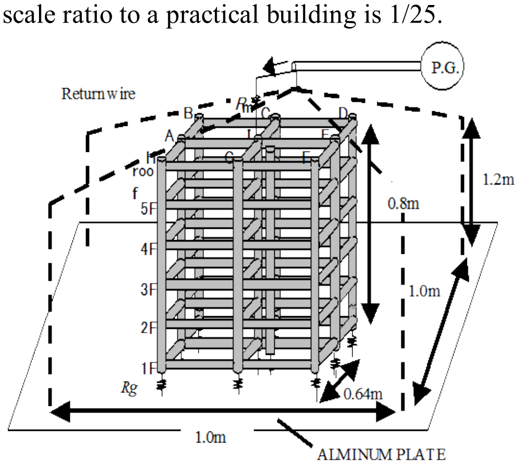


Fig. 8 Building model

Fig. 9 illustrates a measured and calculated injected current into the building model and a voltage difference between the top and the center of the current return wires, i.e. the applied voltage. The rise time of the injected current is 4 ns, and it corresponds to 0.1 µs (=4ns×25) for a practical building.

The voltage is measured by a probe, i.e., without the differential measurement. The high-frequency oscillation of 150 MHz is assumed to be caused by an induced voltage to the probe cable. The results show that the differential measurement is indispensable even if the isolated measuring instrument is used.

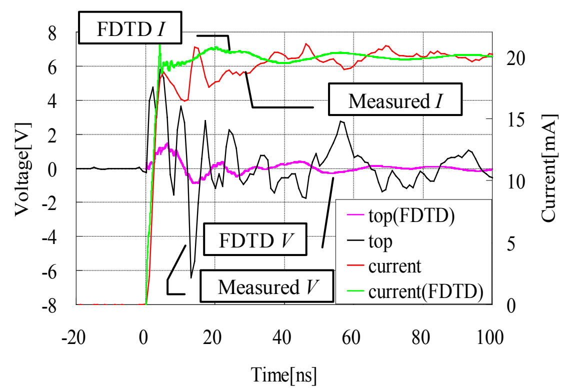


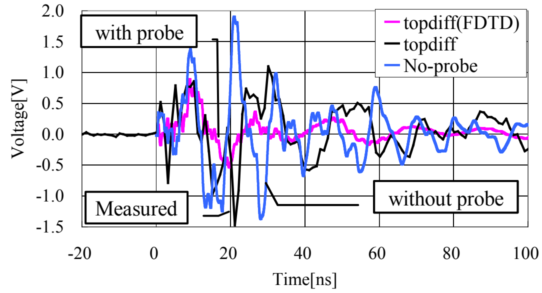
Fig. 9 Pillar voltage at the top and an injected current

Fig. 10 illustrates the measured and calculated voltage differences between the pillar and the grounding wire at the top, middle and bottom of the vertical structure.

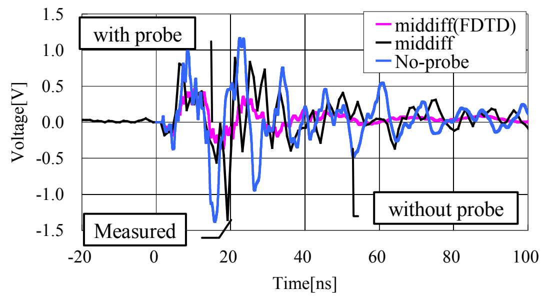
If the independent grounding system is adopted, the maximum voltage measured from the nearest pillar (center pillar) is about 0.8 V (40V/A) at the top of the building. The voltage is smaller than that of the two conductor model because the lightning current is divided by the pillars and the current of the center pillar is smaller than that of the two-conductor model. If the high-frequency oscillations of 250 MHz are removed from the measured result, the maximum voltage agrees with the calculated result by the FDTD method.

The maximum grounding wire voltage measured from the center pillar at the middle of the building is about 0.4 V (20 V/A), and it is about half of the voltage at the top. The voltage at the bottom which is mainly determined by the grounding impedance of the structure and the lightning current flowing through the impedance is smallest.

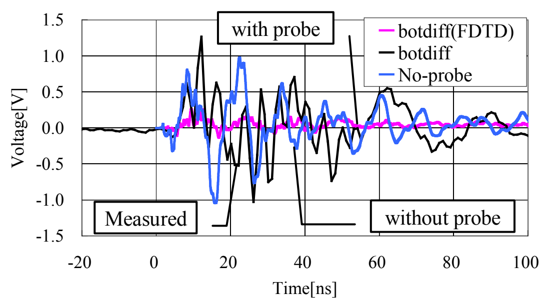
The first peak voltages of the calculated results without the *RC* circuit expressing the probe model increase by 40 % at the top and middle of the building model. The differences of the second peak voltages are much greater than those of the first peak. The second peak voltage is much affected by the current return wires.



(a) top

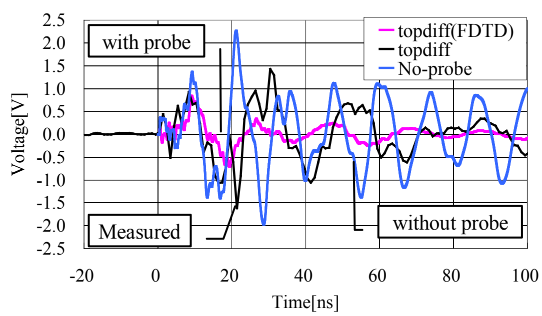


(b) middle

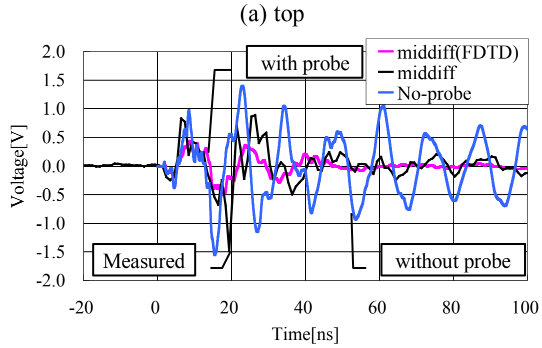


(c) bottom

Fig. 10 Calculated voltage difference by FDTD method. (independent grounding)



(a) top



(b) middle

Fig. 11 Calculated voltage difference by FDTD method. (common grounding)

Fig. 11 illustrates the voltage differences at the top and middle of the building when the grounding wire is connected to the bottom of the center pillar, i.e. a common grounding method is employed. There are minor differences between the results of the independent and common grounding system.

The results indicate that the common grounding method is effective for reducing the voltage difference between grounding wire and the structure at the bottom. The efficacy is decreased as increasing the height of the measuring point.

IV. Conclusions

Surge voltages on a grounding wire for a power distribution system and/or a communication system installed within a building caused by a direct lightning strike are investigated by means of numerical simulations using a circuit analysis method and an FDTD method. The accuracy of the results is confirmed to be satisfactory by experiments based on a scaled model.

The effect of a voltage-probe on a measured voltage is unavoidable. The probe impedance decreases inversely proportional to the frequency by the input capacitance of the probe. A measured transient voltage is found to be generally smaller than an actual voltage. Experimental results obtained by a scaled model cannot be directly used for an insulation design of the power and/or communication system. The experimental results are, however, valuable for a confirmation of the accuracy of numerical simulations. A numerical simulation is indispensable for an accurate estimation of the transient induced voltage. A field analysis by the FDTD method and a circuit analysis by the EMTP are powerful simulation tools for estimating the transient response of the building to a direct lightning. From a viewpoint of computational time, the circuit analysis method is practical, although the FDTD method gives an accurate result.

From the investigations in this paper, it is confirmed that the common grounding, which connects the grounding wire to the building structure, is not valid at all for a fast transient.

V. References

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