

# An Experimental Investigation of Transient Voltages in an Intelligent Building due to Lightning with Special Reference to Grounding

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This paper has experimentally investigated transient voltages on floors in an intelligent building due to lightning with special reference to grounding of a lightning rod, the building and the floors by using an 1/10 scaled-down building model. It has been found that the floor voltages are the smallest in the case of the floors bonded to the building structure except the case of the structure being used as a lightning rod. The common grounding of all the floors causes very high floor voltages when the floor grounding is connected to the lightning rod grounding. Individual grounding of the floors, the building and the lightning rod produces rather high voltages on the floors. A voltage difference between the floors is significantly reduced by bonding the floors to the building structure or by the common grounding of the floors.

**Keywords:** grounding system, transient, intelligent building, EMI

## 1. Introduction

Electromagnetic disturbance (EMD) is an important subject when designing an intelligent building where a number of digital/electronic equipments are installed. For those equipments are sensitive not only to the EMI but also an overvoltage and the rate of the voltage rise ( $dv/dt$ ) during a transient due to lightning to the building, the lightning transient characteristic in the building needs to be carefully investigated<sup>(1)~(3)</sup>. Transient voltages and currents in building structures and an induced voltage to a loop circuit have been investigated experimentally by using a scaled model and numerically by a simulation tool EMTP<sup>(4)~(5)</sup>. In the investigations, grounding systems were not considered.

A transient voltage and a current are significantly dependent on grounding systems of a building. In principle, there are four systems to be grounded in the building, i.e. a lightning rod, electric power apparatuses, building structures (steel poles and beams) and floors (computers, communication network, etc.). The IEC recommends that the building grounding systems should be grounded at the same point, or are bonded to down-conductors and structures<sup>(3)</sup>, while the Japanese

Guide<sup>(6)~(8)</sup> has recommended independent grounding of the information technology (IT) related equipments, a lightning rod and electric power apparatuses. Thus, there are various grounding methods.

Considering the above, the present paper carries out an experimental investigation of the building grounding by means of an 1/10 scaled-down model of a building. Various arrangements of the grounding of a lightning rod, building structures and floors are examined to find an optimum grounding which results in the lowest floor voltages. Transient voltages and currents on every floor of the building are measured, when an impulse current from a pulse generator is applied at the top of the lightning rod or the building structure (pole). The current amplitude is restricted to be small enough (0.75 A) to avoid a nonlinear effect of ground.

## 2. Experimental Setup and Conditions

**2.1 Experimental Setup** Fig.1(a) illustrates an 1/10 scaled-down model of a building which has 3 floors with 4 rooms per floor. A room is of  $9175 \times 6400 \text{ mm}^2$  with the height of 4 m. The horizontal cross-section of the scaled model at the ground surface is shown in Fig.1(b). The relation of physical parameters between a real and a scaled-down model is explained in references<sup>(9)</sup> and<sup>(10)</sup>. It should be noted that the impedance of the scaled model is the same as that of the real one. Pillars of the real building are of the rectangular shape as shown in Fig.2(a). It is represented by a circular cylinder in the scaled model as in Fig.2(b) of which the inner and outer radii are determined so that

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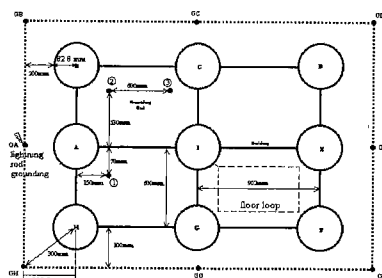
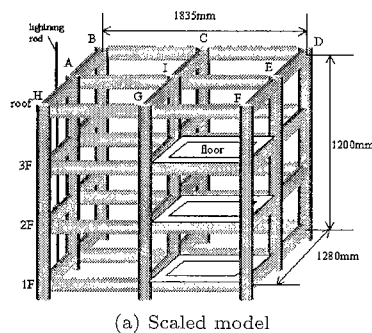
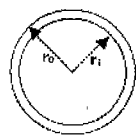
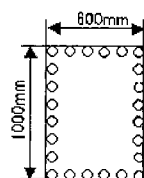


Fig. 1. An 1/10 scaled-down model of a building



$r_i = 261.5 \text{ mm}$ ,  $r_o = 509.3 \text{ mm}$

Fig. 2. A pillar and its equivalent cylindrical conductor

the impedance becomes nearly the same as the original one<sup>(11)</sup>. A reinforced wall of the original building is not considered in the scaled model.

Fig. 3(a) illustrated the experimental setup. A pulse generator (PG) with the rated rise time of about 10 ns and the pulse duration of some  $10 \mu\text{s}$  is used as a current source representing a lightning current. A current lead wire is set at the height of 4 m above the ground with the separation of 20 m from the building model. A matching resistor ( $R = 500 \Omega$ ) is inserted between the PG and the lead wire to reduce traveling wave reflection at the PG. Applied current waveforms with the rise time of 7 ns to 290 ns representing various rise time of lightning currents measured at the top of the lightning rod are shown in Fig. 3(b). The former (7 ns) represents nearly a step function which produces a severe transient voltage (safety side), and the latter (290 ns) corresponds to a lightning impulse wave form with the rise time of about  $2 \mu\text{s}$ . The current dip observed at about  $t = 120 \text{ ns}$  in Fig. 3(b) is caused by negative reflection from the grounding wire of the PG. Because a transient voltage is determined dominantly by  $di/dt$  at the wave-front, the effect of the dip is minor. Also, the current waveform being the same in every measurement, the dip causes no effect on relative estimation of the transient voltages. The current is measured by a CT (Pearson

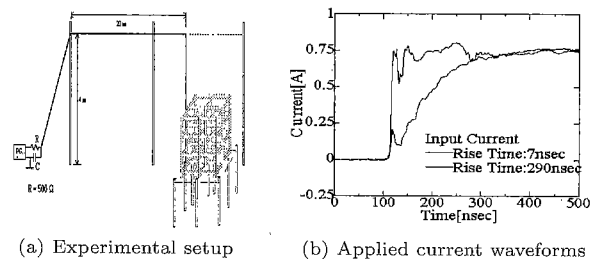


Fig. 3. Experimental setup

model 2877, bandwidth from 300 Hz to 200 MHz) and recorded by a digital OSC (Tektronix TDS 3054, bandwidth 500 MHz).

Transient voltages in the building are measured by a voltage probe (Tektronix P6139A, sampling time 500 MHz) between a measuring point and a voltage reference wire which is located perpendicular to the current lead wire and is grounded at 20 m far from the building. From the concept of equipotential bonding in IEC 1312-1<sup>(3)</sup>, the voltage should be measured between a measuring point (floor) and an earthing reference point. It however, is impossible to have a common earthing reference point in the series of experiments carried out in the paper. Thus, the voltage reference wire is adopted as a reference potential. The same approach has been widely adopted in measuring the surge impedance of a transmission tower<sup>(12) (13)</sup>. A rectangular loop conductor ( $450 \times 720 \text{ mm}$ ) is set in the building to measure a floor voltage as illustrated in Fig. 1(b) as "floor loop".

**2.2 Grounding Electrode** There are four grounding systems in a building i.e. a lightning rod, electronic equipments on a floor, building and electric power apparatuses. Each of them has to satisfy the conditions recommended by regulations and recommendations in Japan<sup>(6)~(8)</sup>. Because the grounding of the power apparatuses is rather different from those of the others, the grounding is not considered in the experiment.

The grounding resistance of a lightning rod has to be less than  $10 \Omega$ <sup>(6)</sup>. To achieve the condition in the scaled model of a building, the grounding electrode is composed of eight driven rods with the radius of 7 mm and the length of 1.4 m. The rods are connected circle-wise by a buried conductor with the depth of 0.1 m as shown in Fig. 1(b) by the dotted line GA-GB-...-GH-GA.

Electronic and telecommunication equipments are basically bonded to each floor which is connected to a grounding electrode as illustrated in Fig. 1(b) by ① for the first floor, ② the second and ③ the third. The grounding resistance of each electrode is designed to be less than  $100 \Omega$  according to the Japanese standard<sup>(7)</sup>.

A reinforced concrete base of a building which is connected to the main structures of the building is buried into the ground. In the model building, the depth of the concrete base is 2 m. As a result, the building itself has a grounding resistance proportional to the concrete base and the ground resistivity. There is no standard of the building grounding resistance, i.e. the building grounding is said to be not well defined nor specified. Thus, each building has its own grounding system.

### 3. Preliminary Experiments

**3.1 Ground Resistivity** The ground resistance of the test yard was measured by means of Wenner's method using a specific earth resistance tester (Yokogawa Type 3244) by changing the depth. Then, the resistivity is evaluated from the resistance. The measured results are summarized in Table 1 which shows the average resistivity in the test yard to be 100Ωm. The resistivity corresponds to about 1000Ωm in a real building site considering the scale factor 1/10<sup>(9)(10)</sup>.

### 3.2 Steady-state Grounding Resistance

Steady state grounding resistances of the three grounding systems explained in the previous section were measured by applying a fall of potential method<sup>(14)</sup>. Average values of the measured resistances are given in Table 2. The grounding resistances of the lightning rod and the electronic (telecommunication) equipments are observed to satisfy the Japanese standard<sup>(7)</sup>. It should be noted that the grounding resistances are relatively low compared with the ground resistivity, and

Table 1. Measured results of ground resistivity

depth [m]	steady state grounding resistance [Ω]	ground resistivity ρ [Ω.m]
0.1	150.6	94.6
0.2	124.1	155.9
0.3	66.3	124.9
0.5	25.4	79.8
0.9	11.4	64.7
average 0.4	75.6	104.0

Table 2. Measured results of grounding resistance

grounding system	Grounding resistance [Ω]	Japanese standard
lightning rod $R_L$	10	10
building $R_B$	40	--
floor ① $R_f$	105	100
floor ② $R_f$	105	100
floor ③ $R_f$	103	100

thus the scaled model of the building is comparatively well grounded.

### 4. Experimental Results and Discussions

Various grounding conditions have been experimentally investigated. The grounding arrangement of floors is categorized into the following three groups.

- (a) case A: floors individually grounded, Fig. 4(a)
- (b) case B: floors commonly grounded, Fig. 4(b)
- (c) case C: floors bonded to building (pole I), Fig. 4(c)

There are six combination of grounding for a lightning rod (L), building structures (S) and floors (F) as follows:

- (1) case X-1: L, S and F individually grounded, where X=A, B and C in the above.
- (2) case X-2: L and S connected.
- (3) case X-3: S and F connected.
- (4) case X-4: L and F connected.

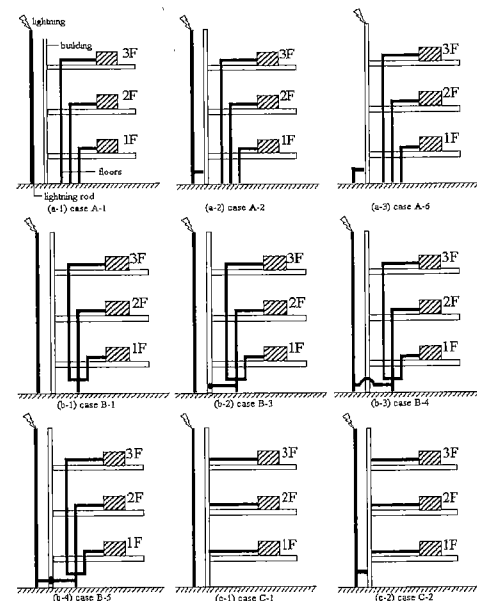


Fig. 4. Grounding configuration of a lightning rod, building and floors

Table 3. Experimental conditions and measured results for a current with  $T_f = 7$  ns

(a) Maximum and steady state floor voltages for all the cases (max/steady [V])

L, S, F condition Floors condition	-1	-2	-3	-4	-5	-6
	L, S, F individual	L-S connected	S-F	L-F	L-S-F	no L
A : individual ground	15.8/2.4	11.3/2.3	B-3	B-4	B-5	13.6/4.5
B : common ground	12.0/2.5	12.3/2.5	9.5/2.5	26.5/5.0	28.7/5.0	10.5/2.6
C : bonded to S	10.9/5.3	9.9/5.0	C-1	C-2	C-2	15.0/5.3

(b) Representative cases

Case no.	floors	S,L,F	Max voltages [V] / time[ns]			Fig. 5
			1F	2F	3F	
A-1	individual	individual	15.8/122	8.5/132	8.6/108	a
B-1	common	individual	11.7/122	12.0/124	11.7/122	b
B-5	common	L-S-F	26.1/118	27.8/120	28.7/122	c
C-1	bonded	individual	10.7/112	10.9/112	10.7/118	d
C-2	bonded	L-S	9.9/122	9.8/122	9.6/116	e
C-6	bonded	no L	14.2/114	14.3/114	15.0/112	f

- (5) case X-5: L, S and F connected.
- (6) case X-6: pole A used as a lightning rod (no L).

The rise time of an applied current in Sec. 4.1 to 4.4 is fixed to 7 ns to observe the severest transient voltage. Thus, it can be said that a real transient voltage is lower than the voltage measured in this experiment.

Table 3 summarizes the above mentioned experimental conditions and measured results of maximum floor voltages. (a) is for all the cases investigated, and (b) for representative cases.

It should be noted that the time axis is the same in each measured waveform, Figs. 5, 6 and 9, although the time  $t = 0$  has no physical meaning. Also, it has been confirmed that an induced voltage due to radiated TEM waves from the PG and the current lead wire is small enough in the measured waveforms.

#### 4.1 Case A: Floors Individually Grounded

Fig. 5(a) shows measured results of transient voltages on each floor for case A-1 where floors (F), building (S) and a lightning rod (L) are grounded individually as illustrated in Fig. 4(a-1). Thus, there are five grounding electrodes. The first, second and the third floors are connected to the grounding electrodes ①, ② and ③ in Fig. 1(b) respectively. A floor voltage is measured at a corner of the floor (represented by a rectangular closed loop) nearby the pole F in Fig. 1(b).

The first floor (1F) shows the highest voltage 15.8 V as given in Table 3(b) which appears at about 122 ns. All the floor voltages are the same until about 108 ns, and then a voltage difference becomes distinctive in Fig. 5(a). The initial part of the voltages is estimated to be induced by electromagnetic mutual coupling between the current carrying lightning rod, the building structures and the floors. Thus, all the floor voltages are nearly the same. The second part, where the voltage difference between 1F and 2/3F becomes distinctive, is caused by the voltages of the electrodes ① to ③ induced from

the grounding electrode of the lightning rod. Because the induced voltage is inversely proportional to the distance between two electrodes as indicated by Sunde's formula<sup>(14)</sup> as mutual resistance  $R_m = \rho/2\pi d$ , where  $d$  is the separation distance, the electrode ① voltage is estimated to be the highest. This might result in the highest voltage of the first floor. However, the second and third floor voltages are not noticeably different, since the grounding electrode of the lightning rod is installed circle-wise around the building.

After few 100 ns with multiple reflection between the building structures and the ground, the floor voltages reach a steady-state voltage of about 2 V as given in Table 3(a) which is roughly estimated by the applied current in the time region, i.e.  $I_s = 0.75$  A and by a mutual resistance  $R_m = 2 \sim 3 \Omega$  between the grounding electrodes of the lightning rod and the floors, i.e.  $R_m \cdot I_s = 2 \sim 3 \times 0.75 = 1.5 \sim 2.3$  V.

When the pole A of the building is connected to the lightning rod at the bottom (case A-2), the waveshapes of the floor voltages are similar to those in case A-1, Fig. 5(a), but the highest voltage becomes smaller as shown in Table 3(a). The reason for this is that the total grounding resistance of the lightning rod is decreased by the parallel grounding resistances of the lightning rod and the building, and thus the ground voltage rise becomes smaller than that in case A-1.

**4.2 Case B: Floors Common Ground** Fig. 5(b) shows transient voltages in case B-1. In this case, the voltage on each floor is nearly the same because all the floors are commonly grounded. The highest voltage is smaller by about 20% than that in case A-1: floors individually grounded. The steady-state voltage is nearly the same as that in case A-1. No significant difference is observed between case B-1, B-2 and B-3. Case B-3 shows the smallest floor voltage among cases B.

Fig. 5(c) shows transient voltage waveforms in case

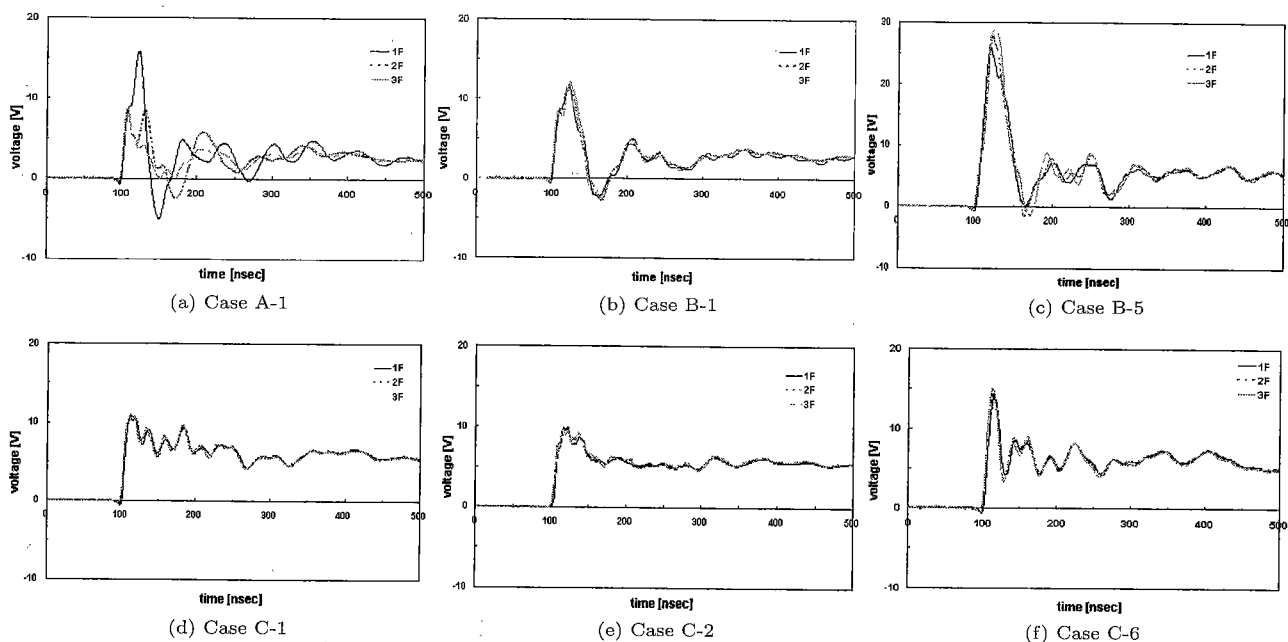


Fig. 5. Measured voltage waveforms for current rise-time 7 ns

B-5 which are similar to those in case B-4. The floor voltages are much higher than those in any other case as observed in Table 3(a). The high voltage is a result of the short circuit of the lightning rod and the common grounding lead of the floors, i.e. the ground voltage rise at the lightning rod grounding is directly transferred to the floors due to the short circuit. Thus, it may be recommended the common grounding of the floors not be connected to the lightning rod grounding.

**4.3 Case C: Floors Bonded to Building** Fig. 5 (d) and (e) show transient voltage waveforms in cases C-1 and C-2 respectively. All the floor voltages are nearly the same in each case as observed in Table 3(b). The highest voltage is 10.8 V in case C-1 and 9.9 V in case C-2, which are smaller by about 30% than that in case A-1. The voltage waveforms are quite different from those in case A and B. If compared with that in case A-1, Fig. 5(a), the wavefront (rising part) in cases C-1 and C-2 are the same as initial part upto about 9 V in Fig. 5(a). Then, the voltage starts to decrease, i.e., the highest voltage is determined by the initial part in cases C-1 and C-2 and becomes rather flat, while the voltage in case A-1 still increases upto 15.8 V and starts to oscillate. A similar tendency to the latter (case A-1) is observed in cases A and B. The difference comes from the fact that the floors are bonded to the building pole I in cases C-1 and C-2. Because the radius of the pole is far greater than those of the grounding leads of the floors in cases A and B and the lightning rod, the surge impedance of the pole is far smaller than those of the grounding leads. It is estimated that the lower voltage in cases C-1 and C-2 is caused by negative reflection at the pole due to its lower surge impedance, but this needs a further investigation.

The steady-state voltage in a time region after 300 ns is about 5.1 V in cases C-1 and C-2 which is about a twice of those in cases A-1, A-2, B-1 to B-3 as observed

in Table 3(a). The voltage corresponds nearly to the product of the total grounding resistance  $R_g$  given by the parallel circuit of the grounding resistances  $R_L$  and  $R_B$  of the lightning rod and the building and the applied current  $I_s$  in the time region, i.e.  $R_g \cdot I_s = 8 \times 0.75 = 6 \text{ V}$ ,  $R_g = R_L // R_B = 10 // 40 = 8 \Omega$ .

**4.4 Case C-6(X-6): Building Pole A used as a Lightning Rod** Fig. 5(f) shows voltage waveforms in case C-6 where the pole A of the building is used as a lightning rod and thus no lightning rod is installed. It is observed that the waveshape becomes similar to those in cases A and B, but differs from those in cases C-1 and C-2, Fig. 5(d) and (e). Accordingly, the highest voltage of the floors is far greater than those in cases C-1 and C-2, and is nearly the same as that in case A-1. The reason for this is readily explained. The initial part of the floor voltage in all the cases (cases X-1 to X-5) in the previous sections is an induced voltage from the current carrying lightning rod by mutual coupling between the lightning rod and the floors, while it is the voltage itself on the current carrying pole A in case C-6 because the floors are bonded to the pole. Fig. 6 shows the pole A voltage in case C-6. It is clear that the initial part of the floor voltage in Fig. 5(f) is nearly the same as the part in Fig. 6. Thus, it is easily understood that the floor voltage is higher, in principle, in case X-6 than the other cases, and that a building structure should not be used as a lightning rod in general.

A similar waveshape to that in case C-6 is observed in cases A-6 and B-6 although the figures are not given. The highest voltage in cases A-6 and B-6 is lower by 30 to 15% than that in case C-6. This is due to the fact that the initial part of the floor voltage in cases A-6 and B-6 is an induced voltage from the current carrying pole A, while that in case C-6 is the voltage itself on the pole A as explained above.

**4.5 Effect of Current Rise Time** The previous observation was for the case of a steep front current (rise time  $T_f = 7 \text{ ns}$ ) corresponding to a real current with the rise time of 70 ns which is too steep as the lightning current. Fig. 7 shows measured results of floor voltages with various rise times. It is clear from the figure that the floor voltage decrease as the rise time increases as expected. Fig. 8 shows the relation between the maximum floor voltage and the rise time  $T_f$ . The maximum floor voltage is inversely proportional to the rise time of the applied current. Thus, the highest voltage observed

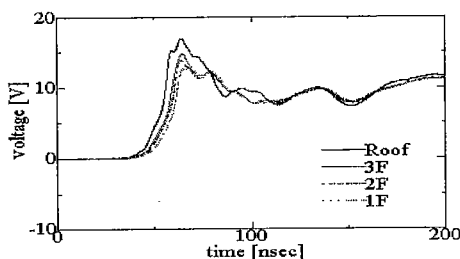


Fig. 6. Pole A voltage in case C-6

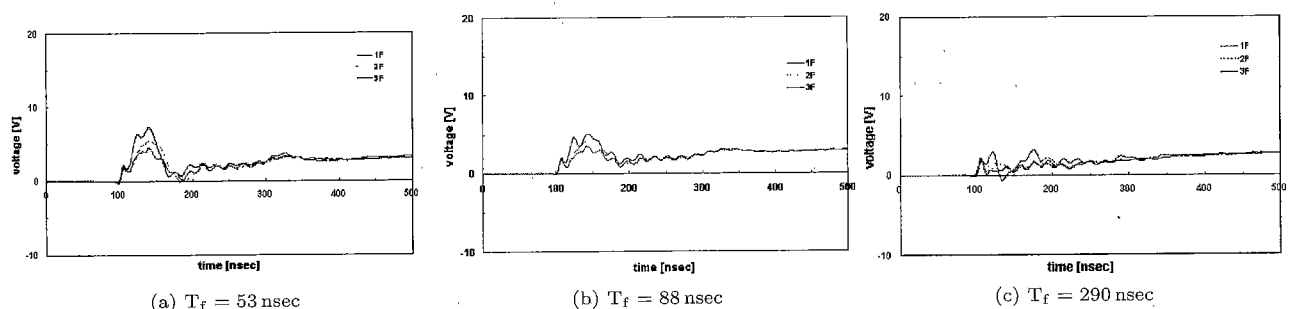


Fig. 7. Effect of the rise time  $T_f$  on the floor voltages

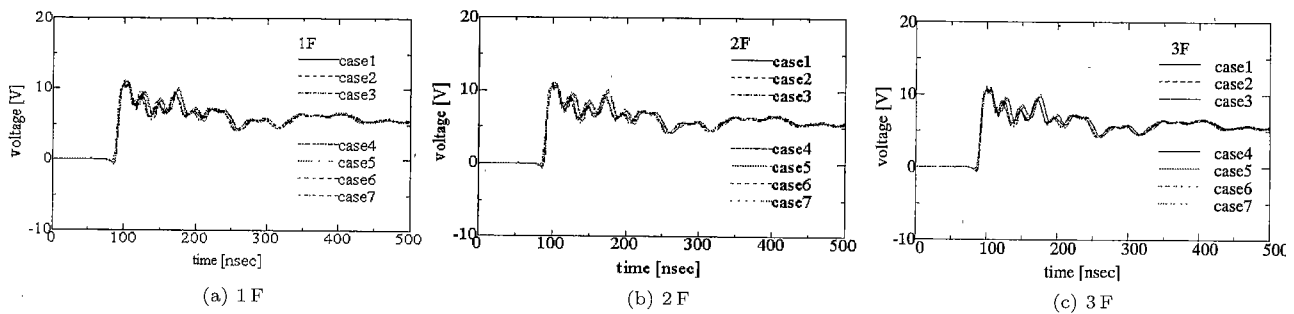


Fig. 9. Effect of floor bonding

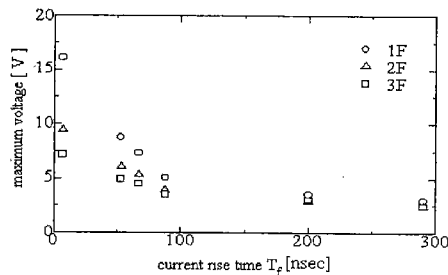


Fig. 8. Maximum floor voltage vs rise-time of applied current

Table 4. Floor bonding conditions and maximum voltages

(a) Case C-1

case	bonded poles	3F	2F	1F
case 1	I	10.8	10.7	10.6
case 2	G	10.9	11.0	11.1
case 3	E	10.8	10.7	10.6
case 4	F	11.1	11.0	11.1
case 5	I, F	11.0	10.9	10.8
case 6	I, E	11.1	11.2	11.3
case 7	I, E, F, G	10.4	10.5	10.6

(b) Case C-2

case	bonded poles	3F	2F	1F
case 1	I	9.60	9.79	9.89
case 2	G	9.42	10.3	10.3
case 3	E	9.52	9.65	9.85
case 4	F	9.66	9.49	10.3
case 5	I, F	10.1	10.7	9.84
case 6	I, E	10.3	10.6	10.3
case 7	I, E, F, G	9.72	10.3	10.3

in the previous sections is said to be the severest case which is on the safety side from the viewpoint of the insulation of electronic/digital equipments on the floors.

No significant variation of the floor voltages due to the different bonding conditions of the floors is observed in Table 4 and Fig. 9. This observation suggests a further investigation of the bonding position and the number of bonding points of a floor from the practical application viewpoint.

**4.6 Voltage Difference between Floors** A transient voltage on each floor has been investigated in the previous sections. In an intelligent building, a voltage difference between floors becomes significant because various electronic/digital equipments are connected across the floors through a communication line,

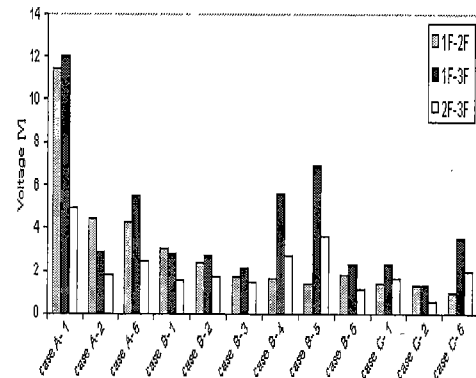


Fig. 10. Maximum voltage difference between floors

and thus the voltage difference across the floors can cause a trouble to the equipments. Fig. 10 shows the voltage difference, which is evaluated arithmetically as a difference of the measured voltage waveforms of the three floors, for all the cases explained in Table 3(a). It is observed that the voltage difference is small when the floors are commonly grounded (case B) or bonded to the building (case C) except the case of the grounding leads of the floors connected to the lightning rod (cases B-4, B-5). The individual grounding, case A, shows, a significant voltage difference, and thus it should not be adopted.

## 5. Conclusions

Based on the experimental investigation of floor voltages from the viewpoint of grounding, the following remarks have been obtained.

- (1) The floor voltages are the smallest when each floor is bonded to the nearby pole of the building structure except the case of the structure being used as a lightning rod.
- (2) Connecting the floor grounding to the lightning rod grounding may result in a very high voltage when lightning strikes the rod.
- (3) Individual grounding conventionally adopted in existing buildings produces rather high voltages on the floors.
- (4) The floor voltages are inversely proportional to the rise time of an applied current.
- (5) A voltage difference between the floors is large when the floors are individually grounded. The difference is significantly reduced by bonding the

floors to building structures as recommended by the IEC 1312-1 or by the common grounding of the floors.

The experimental results in the paper requires a further investigation especially from the viewpoint of an absolute voltage rather than a voltage difference to a voltage reference wire. This can be done by adopting a numerical simulation tool such as the EMTP and a FDTD approach.

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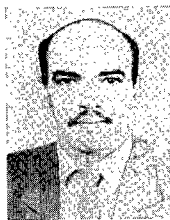
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