Lightning-Generated Fields in Reinforced Concrete Buildings

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Abstract— This contribution presents a study, model and validation of the amplitudes of the residual fields inside a one-story building for different locations of lightning impacts. The special case where a second gridded structure exist inside the main building, forming a box-in-the-box configuration, is analyzed. We show also that formulas for magnetic field attenuation found in the relevant IEC documents are questionable, under certain conditions.

I. Introduction

When a lightning strikes a building (direct hit) or a nearby point, besides the abrupt change in local ground potential, an intense electromagnetic field radiates from the lightning channel. Even with a gridded concrete building like the one investigated here, the residual field inside can still induce transient voltages which can damage electronic equipment and electrical hardware. Although a large amount of data and standard documentation are available regarding conducted and radiated effects of lightning on steel-reinforced facilities, certain areas are not fully covered, like the case where a second gridded structure exists inside the main building, forming a box-in-the-box configuration. Generally, with ordinary facilities, a risk analysis is conducted, to balance the cost of the lightning protection measures versus the financial loss incurred if there was no protection. However in a case like ours, the cost of the systems installed in the building was such that a maximum risk coverage was requested. That is, we did not have to gamble about the fact that a worst lightning current *might* happen, but to take for certain that it *will happen*. The present article is a shortened version of our study, stripped of many calculation details and focusing mostly on the validation experiments carried on a representative 1/40 scale model. More details are available from the Author.

A. Structure *Under Study*

The building can be assimilated to a 40 m × 20 m × 4 m cubicle with reinforced concrete walls, ceiling and floor slab. Electromagnetic shielding is made by 0.50 m grid with 20 mm diameter steel bars, welded at intersections. The floor slab is resting on a soil of unknown conductivity, but goose leg-type earthing electrodes are evenly spread at 8m intervals on the perimeter, each one with an earthing resistance $\leq 10\ \Omega$.

Inside the building, at a 1.8m distance from the overall grid, few specific zones are protected by a second barrier with similar 0.50 × 0.50 grid, welded to the concrete floor armature. The access doors are metallic, with bonding contacts at regular intervals.

B. Lightning Parameters

IEC norms provide a precise formula for the time domain waveform $I(t)$of the stroke current, which is different from the usual double exponential, avoiding a singularity at the curve start-up, whereas the exponential would rise from a null to a finite slope in a zero time interval [1]. The essential features of these two waveforms are shown on Table 1 and Fig. 1.

TABLE 1. WAVEFORMS FOR THE TWO (SEVERITY CLASS ONE) LIGHTNING PULSES.

	First Stroke	Subsequent Stroke
Peak Amplitude	200 kA	50 kA
Rise time (10%–90%)	10 µs	0.25 µs
Average rising slope	20 kA/µs	200 kA/µs
Mid-amplitude Duration	360 µs	100 µs
Equivalent Frequency (Spectral domain)	30 kHz	1.2 MHz

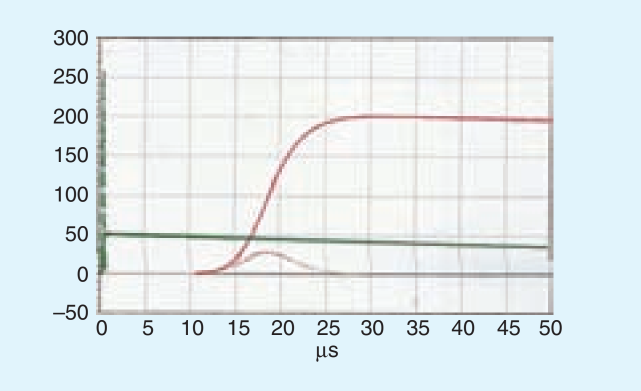

Fig. 1. Lightning Current Waveforms #1 and 2, with respective time derivatives (dotted lines, kA/µs) per IEC (Ref.1)

In the modelling analysis, these currents are regarded as ideal current sources, whose amplitude and slope are not altered by the target impedance (tower, down conductor, grid etc..). This assumption is totally valid with lightning.

The *dI/dt* rising slope has practically no influence on the current distribution in the grid elements of the target. This is an important aspect, because it allow for establishing this distribution once and for all, whatever the waveform. Yet, the slope plays a major role in the calculation of the voltage rise of various parts of the building versus the ground level, and the field-to-cable induced effects inside the building.

The subsequent fast stroke exhibits four times less amplitude than the initial "slow"one, but its derivative is 10 times greater. Thus, everything being equal, the induced effects by the subsequent stroke in a same structure will be 10 times worse than with the initial stroke, eventhough this latter is causing more conduction effects (voltage differences, Joule effect heating etc ..).

II. Summary Of Modeling Approach

A. Parameters, constraints and simplifications used

Each rise time defines an "equivalent frequency", allowing for quick results when calculations are easier to carry out in frequency than time domain. For a first order coupling mechanism, this equivalent frequency is taken as:

$F_{equ.} = 0.32/tm$ where t_m is the 10%–90% risetime. This will be used to define the penetration depth in the ground, skin effect in the steel rebars, Near-to-Far Field transition distance etc ...

Each bar of the outer and inner grids are modeled as cylinders with length $l = 0.50$ m, and diam. $d = 20$ mm. Each wire is modelled by an impedance

$$Z = R_{ac} + j\omega L$$

with R_{ac} : resistance of the steel bar at frequency $F_{equ.}$, accounting for the skin effect and the decrease in relative permeability µr above hundred kHz

$R_{ac} = R_{dc} /(d/4\delta)$

R_{dc} (up to the beginning of skin depth regime)= $\rho l/s = 0.16$ mΩ

ρ : steel resistivity ≈ 10 µΩ.cm

δ : skin depth $= 0.3/\sqrt{f\text{kHz}}$ for steel up to hundreds of kHz

L : self-inductance of one 0.50 m *bar* $= 0.2\,\mathrm{Ln}(4l/d).0.50$ m $= 0.46$ µH.

Several buildings were foreseen in different locations, with ground resistivities varying from 30 Ω.m to 1000 Ω.m. However, since the earthing electrodes resistances were defined as a fixed parameter and considered as the only dependable link to the ground, essential calculations can be made without the need of ground resistivity.

All parameters used as modeling inputs are summarized in Table 2 and allow to validate some simplifications.

TABLE 2. ESSENTIAL MODELING PARAMETERS.

tm	10 µs	1 µs	0.25 µs
$F_{equ.}$	32 kHz	320 kHz	1.2 MHz
Wavelength in air, λ	9.4 km	940 m	240 m
Near-Far Field transition distance, λ/2π	1.5 km	150 m	37 m
Steel Bar Impedance			
ωL	0.046 Ω	0.46 Ω	1.84 Ω
Skin depth δ	0.05 mm	0.016 mm	0.01 mm
R_{ac}:	0.017 Ω	0.05 Ω	0.1 Ω
$Z = \sqrt{(R_{ac})^2 + (L\omega)^2}$	0.05 Ω	0.46 Ω	1.84 Ω
Penetration depth in ground (approxim.)			
sand, gravel	90 m	28 m	14 m
earth	16 m	5 m	2.50 m
Electrical Constants for Concrete			
Resistivity for a cement/sand ratio 1/5	300 Ωm		
Dielectric constant for concrete ε_r	= 10		
Absorption loss, for 1 m thick concrete	0 dB	0.5 dB	1 dB

B. Conclusion About Parameters

- Impedance of grid bars is dominated by self-inductance, even for the slow-rising front
- Inductance & Resistance of grid bars have no influence on the injected current amplitude and waveform, which are imposed by the quasi-perfect current source of the lightning phenomena.
- They have no effect either on the spread of currents in the grid members, since the current source and the 10 Ω earth rods have impedances much greater than those of the grid cells.
- The penetration depth in ground gives the distance of the image plane (virtual ground plane) where one can consider that the reflection of incident field will take place (Ref.6).
- All radiated couplings take place in the near-field, or quasi-static domain.
- the grid cell size (0.50 × 0.50 m) is such that concrete capacity and resistivity, that are shunting the steel bar impedance, can be neglected in calculations. We are also far below the self resonance of a concrete-buried cell (100 MHz).
- the cell dimension makes the bar-to-bar mutual inductance negligible. Two parallel bars can be seen as independent inductances, the current in one having no influence on the other.

C. Considerations on Lightning Couplings & Effects

Direct (radiated Effects)

The building height is small compared to its perimeter. During a direct hit, assumed to take place on the highest zones, lightning current will spread in the grid cells to reach the various earth electrodes. Current density will be higher in the grid region between the impact and the nearest earth rod, decreasing progressively as one move away towards farther cells. Beyond the 5th column of cells, less than 5% of the main current is found in the cell elements.

Major Effects are:

- voltage differences along the grid, caused by *I.R* and *L.dI/dt*
- a general rise of the building structure potential versus surrounding ground, caused by current sink through earthing
- a magnetic field (H) radiated by the whole network of bars taken as individual dipoles. This time-varying field is causing a time-varying flux in any loop area intercepting the H vector.

Indirect Hit, 20 m distance (Conducted & Radiated Effects)

With a 20 m distance stroke, as requested for the study, the current is mostly spreading in the ground, causing significant longitudinal ground voltages (tens to hundreds of kV) between the impact and other points around. These common mode voltages represent a serious threat for all services (power, fluids, signals etc...) entering the building.

In addition an intense magnetic field (Fig. 2) is radiated by the lightning channel, which, by an acceptable simplification (Biot & Savart law), will be regarded as a single vertical conductor

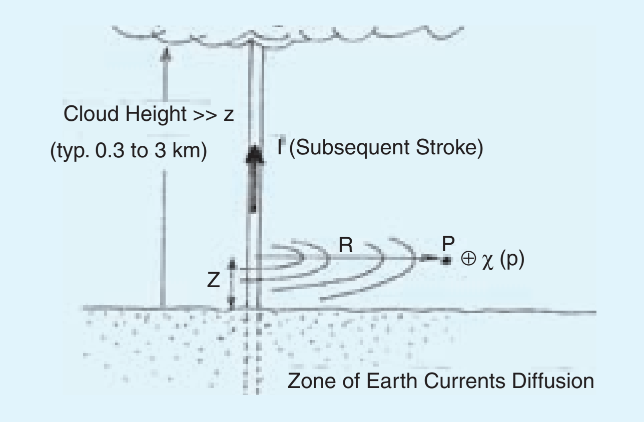

Fig. 2. Indirect hit.

connected to the ground. This semi-infinite wire, thanks to the image method, has the same radiating properties as an infinite vertical wire in free space. This H field is calculated as it would be received inside the building without any screening, then wire grid attenuation coefficients are applied, taking into account the near-field conditions. Finally, like for the direct effect, the flux can be used for deriving the induced voltage into exposed loops.

III. Hypothesis for Field Calculations and Mapping

A. *Zones Retained for H & E Fields Calculations*

In order to limit the number of elements, calculation domain has been limited to a +/−6m zone each side of the impact point, resulting in about 150 to 200 nets and 4 to 500 current dipoles. The areas of particular interest are those located 3 to 5 m away from the walls, where some critical facility elements can be installed. A sensitivity test was made to quantify the uncertainty introduced by these boundaries, compared to a closed or quasi infinite mesh. The pessimistic error in the current values, hence in the associated fields, was found acceptable since it affect mostly the zones farthest from the impact point, where the field amplitudes are lower.

For the direct impact, we neglect the field radiated by the upper portion of the current channel, between the roof and the storm cloud. Calculations and measurements [3] have shown that this contribution is negligible, compared to that of the currents in the building structure.

B. H field Waveform

Due to the near H-field conditions (see Table 2), we are in quasi-static conditions whereas time (or frequency) terms do not appear in the expression of the field. The waveform of the field is homologous to the injected current waveform. We have kept this assumption for the indirect stroke as well, considering that for such a short distance (impact at 20 m), the waveform distorsion in the ground layer can be neglected.

C. Arcing in concrete walls

The possible arcing inside the concrete walls, or side-flashing, has not been considered as an element that could change significantly the current distribution, but simply a risk of physical damage to masonry.

IV. Brief Description of the Calculation Routine

Simple formulas are available (IEC[1]) giving *H* field amplitude inside a gridded-type structure, but we they were not accurate enough for our needs, and had few shortcomings:

a) the values given for H (inside) are assuming implicitly that the building is uniformly connected to a perfect ground
b) the IEC Fig.A, Annex A, is bearing a wrong, misleading scale on the distance axis
c) In this same document, formula in Annex A.3, Table A.2 for the H field attenuation of a grid is announced for "plane wave", a condition never satisfied in critical lightning situations, where the lightning channel is typically at few tens meters from the grid.

Therefore we have preferred to conduct detailed calculations, taking into account the lumped nature of the earth connections.

A. *Calculation Routine, Direct Hit*

The current is injected on the grid, at selected top locations like building edges (because of the peculiar current distribution for such "suitcase corner" shapes), and other roof edge places, but *always above an earth rod location*, to emphasize the corresponding current concentration.

Individual currents in each grid bar are extracted from a R,L meshed network of the whole structure, treated by SPICE. From these current dipoles, the resulting *H* field is calculated by a specific MATHCAD program. It calculates for a given point P, the $H_{,xyz}$ projection from each individual dipole current. All contributions of individual currents are then superimposed, producing the three components of the total magnetic field in the x, y, z directions. The worst possible *H*-field amplitude is finally computed as the quadratic sum of total field components at point P. Field mapping is displayed as detailed numerical tables, or fancier 3-D colour plots. For some selected zones, the attenuation of the second grid, is applied to the relevant *H* field amplitude.

B. *Calculation of E field*

In conditions of intense, near *H* field, the knowledge of the true E field value is of little interest, since the *H* field term will always be the highest contributor to coupling in cables and equipments. Besides, while the *H* field close to a heavy current-carrying loop is easily calculated, it is not so for the *E* field component, because it implies a near field correction term $2\pi.r/\lambda$ which is continuously variable. Therefore, as a broad approximation, we have associated to the true *H* field value an average wave impedance Z'_w. This term is calculated for each point P, as a function of its distance to the grid and the current rise time. So, the average value of *E* is computed as $E = Z'_w.H$.This application of a virtual wave impedance is a gross estimate, but certainly closer to reality than an assumed far-field condition, with $Z_w = 377\ \Omega$.

V. Few Typical Prediction Results, Direct Impact

A. *Significance of the H (x),(y),(z) Terms in the 3-D Domain*

For each spatial point $P(x,y,z)$, the H field contributions of the discrete grid element are computed on the 3 planes (xOy, yOz, xOz) intersecting at point P. After summing up, the total Hx, Hy, Hz components are added quadratically:

$$H_{tot} = \sqrt{H_x^2 + H_y^2 + H_z^2}$$

So, the amplitude of this ultimate vector H_{tot} is always greater than the largest of its components, giving the worst possible exposure for the illuminated victim cable loops and equipments inside.

Results are shown in A/m for 1 kA injected in Fig. 4. From this, *H* can be extrapolated for any value of lightning current. For visibility, some true values of H have been also displayed for the 200 $kA/10\ \mu s$ and 50 $kA/0.25\ \mu s$ strokes.

Calculated values of *E* field are comparatively higher for the subsequent stroke than for the "slow" one, because of the front steepness (0.25 μs) forcing a higher wave impedance.

B. Example of Lightning Current Distribution in a Corner Zone

Fig. 3 give a partial overview of the way currents are spreading in the grid, for an impact at the top of the building corner. Although they are generally branching downward, some currents in the lower bars are changing directions, heading for the lesser impedance to the nearest earth rod. This aspect, caused by the lumped nature of the earthings, create a difference vs some published models [1, 3] where the contact is assumed as continuous via the building lower belt. So, our results are more realistic, eventually conservative. We verified that, beyond the sixth vertical column of cells, adding or deleting an earth electrode did not change the distribution of currents, hence associated fields, in the zone under study.

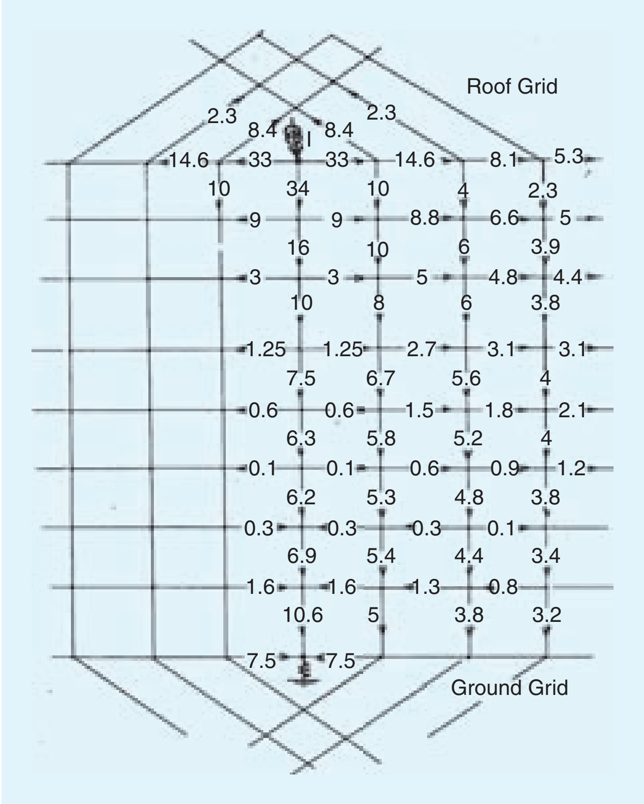

Fig. 3. Example (partial) of currents distribution in grid cells, seen from the inside, for injection at top of a corner zone. The 3-D configuration has been transformed in a 2-D schematic. Currents shown in % of total I injected. Notice the direction reversal of horizontal currents, from top to bottom.

C. Some Discrete Values of H

Impact at a corner

Field at point P_1 x = 3 m, y = 3 m, height z = 1 m :

Σ on each axis, (A/m)/kA Hx = 3.8 Hy = −3.8 Hz = $1.6.10^{-3}$

$H_{tot} = \sqrt{Hx^2 + Hy_2 + Hz^2} = \mathbf{5.3}$ (A/m)/kA

Application to:

	Wave #1,200 kA/10 μs	Waveform #2, 50 kA/0.25 μs
H_{tot}, bulk value:	1060 A/m	260 A/m
associated E field:	0.8 kV/m	7.4 kV/m
H_{tot} after attenuation (9 dB) of a second grid:	350 A/m	87A/m

b) Impact at Façade

Field at point P_2, facing the impact, y = 3m, height z = 1m

Σ on each axis, (A/m)/kA Hx = 9.65 Hy = 0 Hz = 0

$H_{tot} = \sqrt{Hx^2 + Hy^2 + Hz^2} = \mathbf{9.65}$ (A/m)/kA

Application to:

	Wave #1, 200 kA/10 μs	Wave #2, 50 kA/0.25 μs
H_{tot}, bulk value:	1930 A/m	480 A/m
associated E field:	1.7 kV/m	13.5 kV/m
H_{tot} after attenuation (9 dB) of a second grid:	640 A/m	160 A/m

D. General Remarks about Field Distribution (All Zones)

a) The field amplitudes are in general slightly higher than those published in some documents [1]. This can be due to the fact that:
   - we always assume the worst possible configurations
   - the building base is not in continuous contact with a perfect ground plane, but connected via scattered 10 Ω earth electrodes
   - all simplifying assumptions we used were made in a conservative sense

b) Although some papers in the literature seem to imply that corner zones are the highest field spots, we found that it is not always so. Inside locations facing a sidewall near a ground rod can exhibit *H* fields about 50% higher than a corner zone, at the same distance from the lightning impact.

c) The *Hx* component (parallel to wall plane and ground) is always the dominant one, this being coherent with general direction of largest current-carrying grid elements.

E. Expressing the Reduction Factor of the First Grid

An interesting criteria, constantly used in EMC, is the reduction factor, or shielding effectiveness (SE) for a given barrier. It is used here to quantify the benefit of the gridded envelope, compared to an ordinary wall. For a direct impact, we define it as follows:

- for a given stroke current I_0 , we retain the highest field value found behind the first barrier, for instance H_x, 3 m behind façade.
- we calculate the field amplitude H_0 that would be received by this same point, without the grid, if the full current I_0 was concentrated as a single vertical channel, centered on the impact

- the ratio H_0/H_x is the shielding effectiveness of the gridded envelope, or, in dB:

$$S.E = 20 \text{Log } H_0/H_x$$

Using Ampère's law, and normalizing calculations to 1kA and at distance R from impact, $H_0 = I/2\pi R$ (eg, $H_0 = 53$ A/m/kA at 3 m distance). Calculations indicate, for an impact centered on sidewall zone *(worst case)* and at the same 3m distance from the grid:

$$H_x \text{ at 3 m} = 9.6 \text{ A/m/kA (5.3 A/m/kA for corner)}$$

$$SE \text{ (dB)} = 20 \text{ Log } 53/9.6 \approx 15 \text{ dB (20 dB for corner)}$$

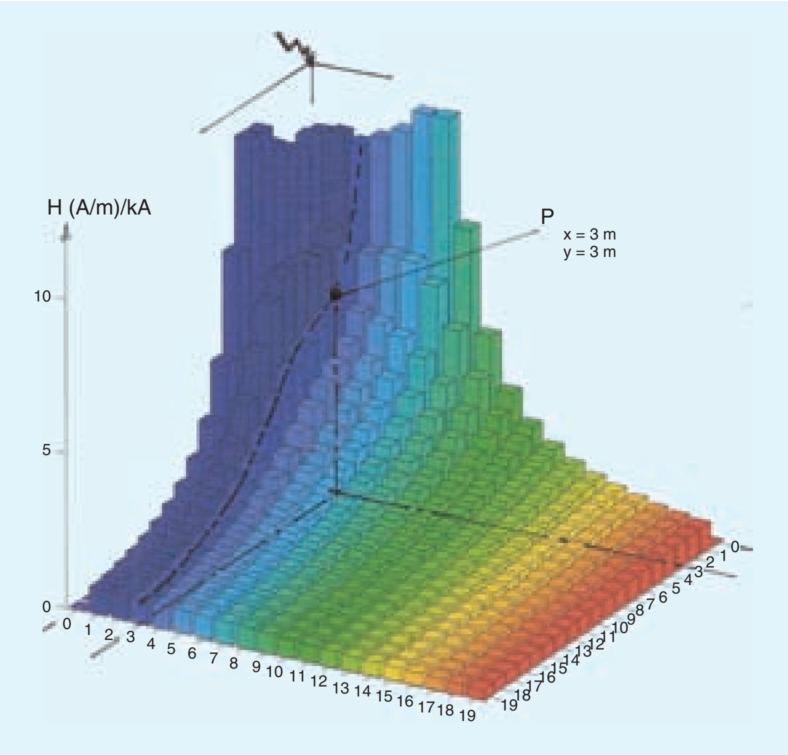

Fig. 4. Example of field distribution in a corner zone, for height z = 1.50 m. H-field values are normalized in (A/m)/kA.

These figures correlate fairly well with published results measured in actual buildings

F. Ground Voltage Rise within the Building Perimeter

Although this was not the main purpose of the study, the SPICE model of the grid network allowed a calculation of the voltage rise at some selected building locations. For instance, the voltage rise between the builing top belt and the floor slab was of particular interest. This voltage surge for Waveforms #1 & 2 are shown in Fig. 5. Thanks to the gridded structure, the combined *R.I* and *LdI/dt* effects are relatively moderate, not likely to cause a side-flashing. But yet, waveform #2 generate a ΔV of 35 kV (Fig. 5, curve C) , which can appear as a common mode voltage between an electrical device under the roof and its controlling equipment at ground level. For instance, if a remote device (floating sensor, actuator, luminaire etc...) is located near the ceiling, while its associated equipment is resting on the floor, the above 35 kV is a common mode emf impressed between the remote device and the frame of the master equipment.

VI. Lightning Impact at 20 m, Indirect Effect

This time, the effect is that of a field H_0 incident on the grid, instead of a current injection. The field inside the building is calculated by: $H_x = H_0$ x Shielding Effect (SE)

This S.E. value is not the same as the one found for the direct impact. The formula for the S.E. of a wire-type grid in Near H field is derived from Schultz in [5]:

SE(dB) = 20 Log (0.32 R/g)

with R = *distance from H field source,*

g = *largest dimension of grid.*

This simplified formula is based on the ratio of the incident wave impedance over the equivalent surface impedance of the wire grid. In our

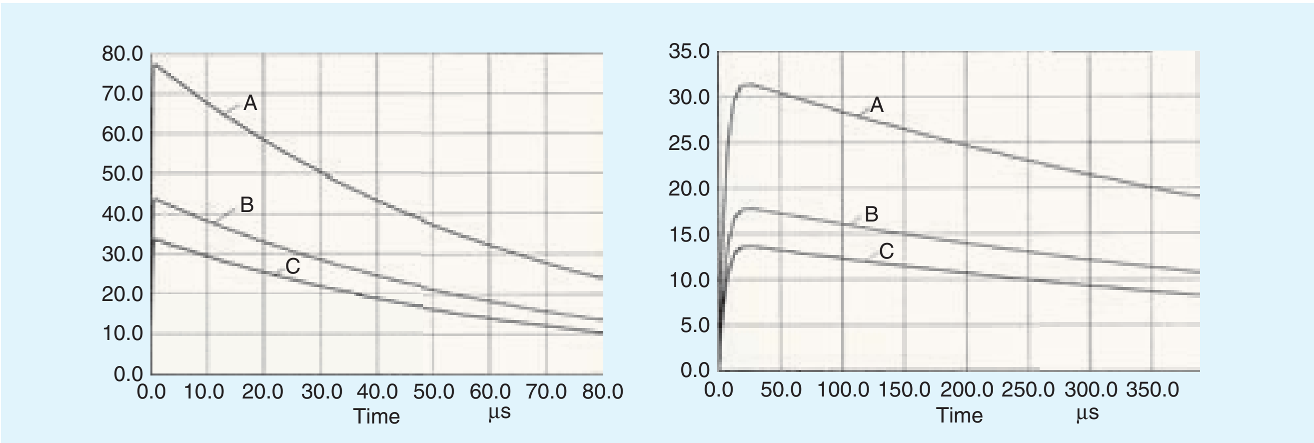

Fig. 5. Structural Voltages in kV, for waveforms #1, slow, 200 kA (top) and #2, fast 50 kA (bottom). Curve A: absolute value of grid voltage of building roof belt vs. remote ground reference. Curve B: absolute value of floor slab voltage vs. remote ground ref. Curve C: ΔV (A-B), ceiling-to-floor voltage gradient.

TABLE 3. SUMMARY OF ATTENUATIONS AND RECEIVED FIELD, 3M INSIDE, FOR INDIRECT IMPACT AT 20M.		
Basic received *H* field at 20 m + 3 m (Eq.1) :		
$H_0 = I_0 / 2\pi \times 23 = 0.007.\, I_0$		
Attenuation of 0.50 × 0.50 grid alone (Eq.2) : 22 dB (that is a 0.075 transmission factor)		
	Waveform #1	**Waveform #2**
H_0 at 20 m + 3 m	1380 A/m	350 A/m
Atten. of 1st grid (Eq.2)	0.075(22 dB)	0.075
Atten. of 2nd grid :	0.35 (9 dB)	0.35
Cumulated attenuation.	0.027 (32 dB)	0.027
Residual Field *HX:*	**37 A/m**	**9.5 A/m**

case, for $R = 20$ m and $g = 0.50$ m, SE = 22 dB.
For those specific indoor areas which are protected by a second grid, the additional attenuation has been evaluated at 9 dB.

VII. Scale Model Validation

The validation tests via a downscale model were an interesting part of the study. The design of this mock-up has been a trade-off between multiple constraints:

- the mock-up had to be lightweight, easy to carry and install, because it had to be moved to several places for quick demonstrations to facilities managers.
- the scale factor had to match the risetime of the kiloVolt pulse generator used for current injection, but also match with the grid size of the mock-up.
- the mock-up had to offer an optional, smaller mesh-grid box inside the main cage, with an easy mounting fixture
- calibrated H-field and current sensors had to be small enough to fit inside both boxes, without interfering significantly with the natural field-distribution
- the whole measuremen gear, coaxial cables, connectors and memory oscilloscope had to be enough decoupled/shielded, preventing the measurements from being corrupted by the strong kV and tens of Amperes pulse injection.

A. Description

A 1/40 scale factor was chosen, allowing for the injection of a down-scaled lightning pulse. It granted both an easy handling and the setting of the miniature H-field and current probes in various places. The entire mock-up, with a first meshed cage, representing the building envelope and the second cage inside, was mounted above a large ground plane (Fig. 6, 7). This scale factor was also a convenient trade-off considering that 1.25 cm steel meshes are available at ordinary hardware stores. The size reduction dictates a commensurate shrinking of the risetime, hence a corresponding increase in frequency and bandwidth of the selected instrumentation.

By contrast with the simulation set-ups mentioned in the reference studies, the floor grid of the mock-up cage is not in direct contact with the ground plane. It is elevated by a height equivalent to the ground penetration depth for the waveform #2, the only contact to ground plane being 12 × 10-Ωresistors.

TABLE 4. MOCK-UP SCALING PARAMETERS.		
	Actual Config.	**Mock-up**
Width	20 m	0.50 m
Length	40 m	0.80 m *
Height	7 & 4 m	0.10 & 0.17 m
Steel mesh	0.50 x 0.50 m	1.25 x 1.25 cm
Risetime	250 ns	6 ns (Waveform #2)
Required instrument Bandwidth	>1.2 MHz	>50 MHz
(*) a little too short, but at no prejudice for validation		

Fig. 6. General view of the mock-up.

B. Examples of Measured Results on Mock-up

A complete set of field measurements were conducted on the mock-up in both time and frequency domains, for validating our calculations for the actual building, and check that our dynamic range was adequate.

C. Summary of a Typical Measurement Routine

1) *Simulated Lightning:* current was injected via a wide metal foil stripe, for reducing self inductance of this feeder wire.
2) *H field measurement:* by a 40 mm diam. loop, shielded against E-fields (Moebius loop).
3) *Frequency-Domain Measurements:* a spectrum analyser and its tracking generator provided the current injection and *H* field reading. The input sensitivity (≈3 μV) allowed for a good dynamic range, even with only 5–10 mA of injected current.
4) *Time-Domain Measurements:* we used a TDS3054 sampling oscilloscope (500 MHz B W) and IEC 61000-4-4 fast transient generator, with 0.5 to 4 kV output, and 5–8 ns rise time, that matched well our down-scaling factor.

With this "miniature lightning" being a strong local disturbance, it is paramount to make sure that no parasitic response of the oscilloscope could obscure actual measurements of internal H field. This is checked by a "blank shot", all cables in place but without the field sensor.

5) *Closed cage Measurement, with inside field sensor in place* (for inst. at 7.5 cm from the wall, corresponding to 3m in reality). Collected data are $H(A/m)/I_{inj}$.
6) *Same measurement as 5) is repeated with the small cage inside.* New values of $H(A/m)/I_{inj}$ are collected.
7) *Reference Measurement, corresponding to lightning exposure for a totally unshielded building:* Current is injected on a 20 cm vertical rod

Fig. 7. Closer view on the second gridded cage, with Moebius loop field sensor.

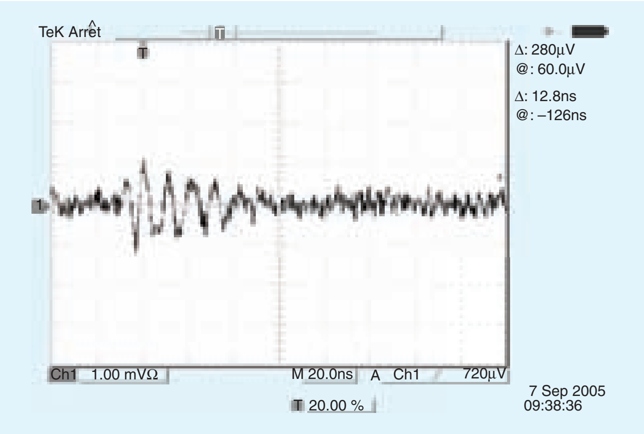

Fig. 8. Pulse measurements. Parasitic signal picked-up by the set-up, without field sensor.

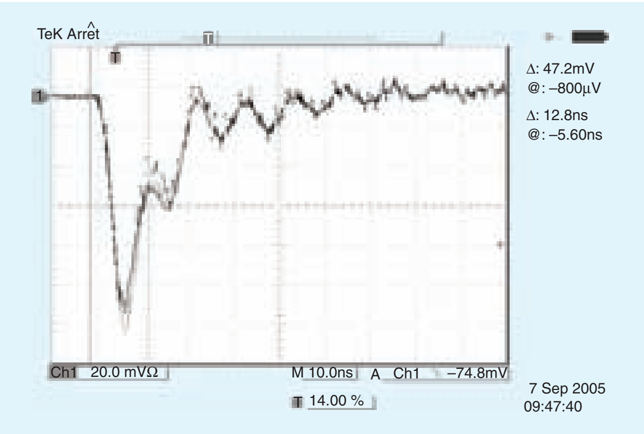

Fig. 9. Pulsed field. Sensor 7.5 cm inside. Only one grid. Scale : Ch.1 : 20 mV = 100 mA/m. The overshoot after the first peak is deemed to be the reflected pulse bounced-back after its two-way trip.

representing the lightning channel. The H-field sensor is located 7.5 cm outside the cage, at the same height than for 5 or 6).

Notice that this current injection is somewhat asymmetrical, because of our single-side arrangement of the feeder stripe, from the generator to the injection structure. *This does not correctly replicates reality, since it creates an opposite H-field. With actual lightning,*

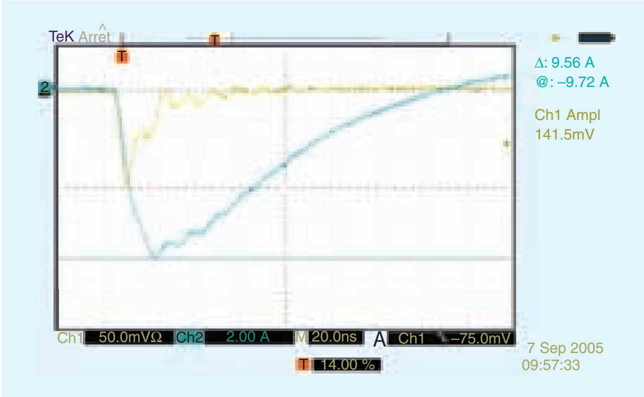

Fig. 10. Same as Fig. 9, but with the second trace showing the injected current (Ch. 2: 2A/div).

the "feeder wire" is the whole cloud-and-earth system. Other experiments (Metwally, Ref.7) used a coaxial structure where the feeder is concentric to the injection wire. Although this make a symetrical injection, it creates artificially a strong horizontal E-field (perpendicular to the injected current path) that we preferred to avoid.

A few typical results (Injection on façade, sensor 7.5 cm inside)

a) Frequency sweep, 10–60 MHz

F(MHz)	I inj.	H in the x direction, (one grid) dBµA/m(*)	mA/m	H with 2nd grid dBµA/m(*)	S.E, 2nd grid
10	6 mA	62	1.2	50	12 dB
20	5 mA	60	1	50	10 dB
30	4 mA	58	0.8	46	12 dB
40	3.5 mA	56	0.7	48	8 dB
50	2.6 mA	54	0.5	44	10 dB

(*) After taking into account the loop antenna factor.

H-field/ Current ratio, averaged on sample size:

0.2 (A/m)/Amp

For extrapolating this H field-to-current ratio to the full size building, we must account for the 40/1 scaling factor (see rationale in Annex A), shifting the 7.5 cm results to 3 m, and convert into A/m/kA, so: 0.2 A/m × 1000/ 40 = (5 A/m)/kA

Our calculations, for an impact on façade were giving 7.6 to 9 A/m/kA, depending on wether the measurement point is exactly aligned with a grid member, or half-pitch shifted.

b) Pulse Injection, 500 V, *I peak = 8 A*, rise time 7.5 ns.

The calibrated time-domain response of our small loop sensor for such rise time is 13.5 dB, that is 4.8 A/m/V

Result with 1st grid only: 0.1 $(A/m)/Amp$

Result with 2nd grid: 0.022 A/m (a four times improvement)

Reference with sensor outside, at 7.5 cm from rod: 1.5 $(A/m)/Amp$

Hence the corresponding reduction factors:

1st grid only: 1.5/0.1 = 15 $(23.5\ dB)$

With 2nd grid added: 1.5/0.022 = 68 $(37\ dB)$

VIII. Summary & Conclusions

A set of equivalent networks, representing the various zones of the gridded enclosure allowed for an accurate mapping of all current segments. Each current segment was used to calculate the internal

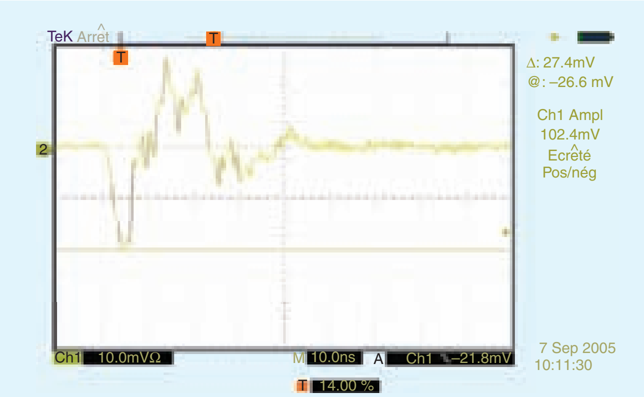

***Fig. 11.** Same as Fig. 9, but with second grid added. Channel 1: 10 mV 5 50 mA/m.*

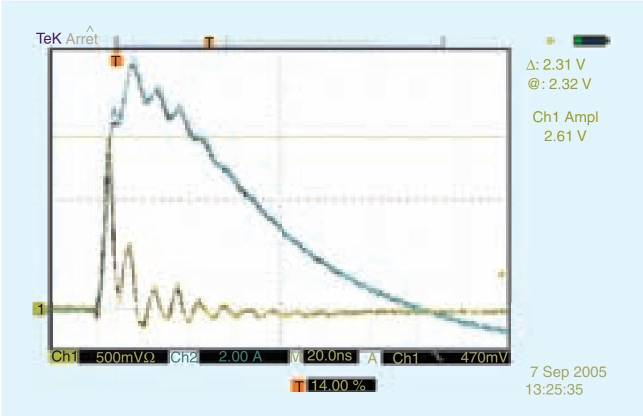

***Fig. 12.** Reference measurement, outside the box. Chan. 1: Field radiated with current injected on an external,vertical rod, simulating the lightning channel. Chan. 2: injected current.*

H fields in x, y, z directions, and their vectorial combination. *Considering that our calculations were made with several worst-case assumptions, they correlate fairly well with both published results and the 1/40e scale model results, the latter ones showing approximately 8 dB margin.* The external 0.50 × 0.50 m grid provides a minimum H-field reduction factor of 15 dB. An additional 9 dB is obtained by a second, internal, gridded cage.

Thanks to this combined attenuation of two enclosures, the H-field, 3 m inside for the most exposed case (impact at façade, ground with poor conductivity) remains <640 A/m and <160 A/m for waveform #1 and #2, respectively. Yet, waveform #2 remains a bigger threat because of its *dH/dt* derivative. For instance, residual *H* field wave #2 will induce 850 V (open circuit) per sq.meter of exposed loop, assuming maximum flux intercept. This is still significant, but it can be reduced 100 to 1000 times by conventional EMC techniques like cable routing/shielding, transient suppressors and filters.

It is always the H_x component, parallel to the façade where impact occurs, which dominates.

The earth rod resistances have no effect on the *H*-field values, but they do influence the voltage rise of various structural points versus the ground. The number of earth rods has some influence, since a larger number helps spreading the currents around the building footprint.

Indirect Impact at 20m

Because of the distance factor increasing the wave impedance, the attenuation of the first and, eventually, the second grid are slightly higher, resulting in indoor *H*-field values of 37 A/m and 9.5 A/m for waveforms #1 and 2, respectively. The main danger with indirect hit comes from the coupling with external lines (overhead or moderately buried) penetrating the facility.

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Annex A. Scaling factor for H-field extrapolation

In Par. VIII.B, the mock-up scaling factor has been also applied to the measured H-field values. Given that the 1/40 downscaling had been applied to dimensions and rise-time, one might argue that there is no need to adjust the results for the field sensor-to-grid distance, since the grid-to-target viewing angles are unchanged.

However, we must remember that it is the H_x-field (in the « x » direction) that is dominant, which means the major contributors are the vertical current-carrying wires. At close distance from such conductors, the H-field is that of a quasi-infinite wire, with a 1/D dependency (Ampère's Law). Therefore, at 7.5 cm distance, a given current will always produce an H-field 40 times larger than at 3 meters.

Biography

***Michel Mardiguian**, IEEE Senior Member, a graduated electrical engineer with BSEE and MSEE degrees, was born in Paris, 1941. After military service in the French Air Force, he worked for Dassault Aviation from 1965 to 1968. Then he moved to the IBM R&D Lab near Nice, France, and worked in the packaging of modems and digital PABXs. He started his EMC career in 1974 as the local IBM EMC specialist, having close ties with his US counterparts at IBM in Kingston, USA. From 1976 to 1980, he was also the French delegate to the CISPR Working Group on computer RFI, participating in what was to become CISPR 22, the root document for FCC 15-J and European EN 55022. In 1980, he joined Don White Consultants (later renamed ICT) in Gainesville, Virginia, becoming the Director of Training, then VP of Engineering. He developed the market of EMC seminars, himself teaching more than 160 classes in the US and worldwide. In 1990, he established a private consulting firm in France, teaching EMI/RFI/ESD classes and working on consulting tasks from EMC design to firefighting. One top assignment involved addressing the EMC of the Channel Tunnel with his British colleagues at Interference Technology International. He has authored eight widely sold handbooks, two books co-authored with Don White, and 28 papers published at the IEEE and Zurich EMC Symposia, as well as at various conferences. He is also a semi-professional musician and bandleader of the CLARINET CONNECTION Jazz Group.*