Magnetic Fields and Induced Voltages in case of a Direct Strike – Comparison of Results obtained from Measurements at a Scaled Building to those of IEC 62305-4

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Abstract: In the paper the results obtained from experiments at a modelled reinforced building in case of a direct lightning strike are compared with calculations. The comparison includes peak values of the magnetic field H_{max}, its derivative $(dH/dt)_{max}$ and of induced voltages u_{max} in typical cable routings.

The experiments are performed at a 1:6 scaled building and the results are extrapolated using the similarity relations theory. The calculations are based on the approximate formulae given in IEC 62305-4 and have to be supplemented by a rough estimation of the additional shielding effect of a second reinforcement layer.

The comparison shows, that the measured peak values of the magnetic field and its derivative are mostly lower than the calculated. The induced voltages are in good agreement. Hence, calculations of the induced voltages based on IEC 62305-4 are a good method for lightning protection studies of buildings, where the reinforcement is used as a grid-like electromagnetic shield.

Keywords: Direct lightning strike, electromagnetic shield, magnetic fields, induced voltages, calculations.

1. Introduction

The knowledge of magnetic fields and induced voltages inside a building in case of a direct lightning strike is crucial for the design of lightning protection measures. For the application of the concept of lightning protection zones (LPZ), the knowledge of the magnetic field attenuation by a spatial shield is necessary, especially at the interface of LPZ 0 and LPZ 1. On this basis, the determination of the induced voltages in cable loops inside the building is possible.

An effective method to form electromagnetic shields is to use existing metallic structural components, like the reinforcement of concrete. Especially in case of large industrial plants the concrete's reinforcement is widely used; usually it is the most cost effective measure to ensure the necessary protection of electrical and electronic systems against the lightning electromagnetic pulse (LEMP).

Such structural shields, of course, are leaky shields and therefore it is necessary to know about their effectiveness in reducing the electromagnetic environment. This task was widely investigated in the 1990ies with numerical simulations, leading to the results given in the international draft standard IEC 62305-4 [1]. The numerical simulations, however, were limited to a minimum mesh width of about 40 cm and had to be extrapolated for smaller mesh width (typical 15 cm for reinforcement of concrete). Furthermore the resistances of the current-carrying reinforcement rods and capacitive coupling were neglected. Therefore, frequency dependent effects as well as transient phenomena were disregarded for the approximate formulae of IEC 62305-4. So, always some uncertainties exist in the application of these formulae for real reinforcements of concrete.

Two experimental research campaigns were conducted at the High Voltage Laboratory of the University of the Federal Armed Forces to study the magnetic fields, the magnetic fields derivatives and the induced voltages within simulated buildings at a direct lightning strike:

- Model A was a grossly simplified building (size 2m x 2m x 2m) made of practical reinforcement grids, where the influence of a second layer of reinforcement and the different methods of the reinforcement's connections were investigated [2].
- Model B was a practical small industrial building with a scale factor of 1:6 (size 2m x 2m x 3m). Scaling the model's geometry necessarily means to also scale physical quantities, following the laws of the similarity relations theory [3]. Hence, an original two-layer steel reinforcement was replaced by a two-layer copper mesh with a mesh width of 2,5 cm. The influences of the type of lightning current, the point-of-strike, the bonding of typical cable routes and the

bridging of an expansion joint in the middle of the model were investigated [4].

The results obtained from the model experiments allow to investigate the accuracy of the formulae given in IEC 62305-4 also for practical reinforcement grids as natural shielding components.

In this paper the model B results necessary for the comparison with calculations are shown. This includes measurements for the magnetic field, the magnetic field derivatives and for induced voltages on typical cable routes. The model results are extrapolated to real lightning threat and to a real size (1:1) building. Then calculations according to IEC 62305-4 are performed for the magnetic fields, the magnetic field derivatives and the induced voltages on the cable routes of model B in a real (1:1) size environment. The influence of a second layer of reinforcement is considered. Finally model results and calculation results are compared and discussed. From that comparison we are able to define more accurately the limits of the calculation based on IEC 62305-4 if being applied to practical reinforced buidlings.

2. Used lightning currents

The similarity relations theory [3] allows to establish scale laws and scale factors from the differential equations describing a physical process without the need to solve these differential equations.

The geometrical scale factor of model B was selected to f_g = 1:6 [4]. From that directly the scale factors for the relevant physical quantities given in table 1 follow.

Table 1: Scale factors for model B

Physical quantity	Scale factor
Time	$f_t = f_g = 1:6$
Current	$f_I = f_g = 1:6$
Current derivative	$f_{dI/dt} = f_I/f_t = 1$
Magnetic field	$f_H = f_I/f_g = 1$
Magnetic field derivative	$f_{dH/dt} = f_I/f_g/f_t = f_I/f_g^2 = 6$
Voltage	$f_U = f_g = 1:6$

For the experiments the following lightning impulse currents were selected:

- the first lightning impulse current 200 kA 10/350 µs according to IEC 62305-1 [5];
- the first negative lightning impulse current 100 kA 1/200 µs according to the German standard KTA 2206 [6] valid for the erection of nuclear power plants.

Table 2 gives the main parameters of the selected impulse currents defined in the standards (scale 1:1), the down-scaled parameters for the 1:6 size environment and the parameters obtained in the model experiments [4].

It was the main aim of the experimental setup in the high voltage laboratory to achieve the time requirements of the standards as close as possible. The current peak values could not be achieved in the laboratory as required. However, this can be compensated by extrapolation of the model results.

Table 2: Test current parameters of model B.

		i_{max} (kA)	T_1 (µs)	T_2 (µs)
First impulse current [5]	Scale 1:1	200	10	350
	Scale 1:6	33,3	1,67	58,3
	Experiment	18	1,8	57
First negative impulse current [6]	Scale 1:1	-100	1	200
	Scale 1:6	-16,7	0,167	33,3
	Experiment	-5,5	0,25	12

3. Measurement results from the model B experiments

The results of the model B are described in detail in [4]. For four lightning attachment points on the roof measurements were collected for the magnetic field H and the magnetic field derivative dH/dt at four locations inside the model (fig. 1) and for the induced voltage u at three cable routings (fig. 2). The cable routings simulate typical cable runs on cable supporting structures as widely used in industrial plants and buildings.

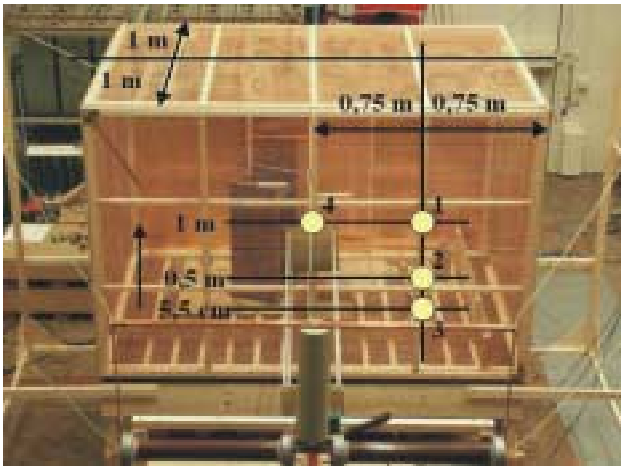

Figure 1: Model B with the four measurement locations of H and dH/dt [4].

The results depend essentially on the point of the lightning strike. For the investigation of this paper only the highest values obtained at one point or at one cable routing are taken into consideration. Furthermore the calculation based on IEC 62305-4 gives results for the peak values of the magnetic field or the induced voltage, resp. So for the measurements results also only the peak values are listed.

Table 3 shows the peak value of the magnetic field H_{max} at the four measurement locations and for both impulse currents. The magnetic fields are equal in the 1:6 model and in real size (f_H = 1). Only an extrapolation to the required current peak values is necessary:

- the model B data for the first impulse current [5] have to be multiplied by 1,85=33,3kA/18kA to take into account the reduced peak value of 18 kA in the experimental setup;
- the model B data for the first negative impulse current [6] have to be multiplied by 3,03= 16,7kA/5,5kA to take into account the reduced peak value of –5,5 kA in the experimental setup.

Table 3: Measured and extrapolated peak values of H_{max} in A/m for model B.

Current	Measurement location	Model B data	Extrapolated results
First impulse current [5]	1	8,27	15,3
	2	12,5	23,1
	3	13,5	25,0
	4	12,6	23,3
First negative impulse current [6]	1	0,657	1,99
	2	0,508	1,53
	3	0,687	2,08
	4	0,622	1,88

Table 4: Measured and extrapolated peak values of $(dH/dt)_{max}$ in A/m/µs for model B.

Current	Measurement location	Model B data	Extrapolated results
First impulse current [5]	1	0,763	0,254
	2	1,03	0,343
	3	1,10	0,367
	4	1,09	0,363
First negative impulse current [6]	1	3,19	2,42
	2	2,66	2,02
	3	4,27	3,24
	4	2,46	1,87

Table 4 shows the peak value of the magnetic field derivatives $(dH/dt)_{max}$ at the four measurement locations and for both impulse currents. The time derivatives of the magnetic field are 6 times higher in the 1:6 model compared to real size. Furthermore the experimental data have to be extrapolated to the required impulse current derivatives:

- the model B data have to be multiplied by 1:6 ($f_{dH/dt}$ = 6);
- the model B data for the first impulse current [5] have to be multiplied by 2,0=33,3kA/18kA* 1,8µs/1,67µs to take into account the reduced peak value of 18 kA and the slightly reduced front time of 1,8 µs in the experimental setup;
- the model B data for the first negative impulse current [6] have to be multiplied by 4,55= 16,7kA/5,5kA*0,25µs/0,167µs to take into account the reduced peak value of –5,5 kA and the reduced front time of 0,25 µs in the experimental setup.

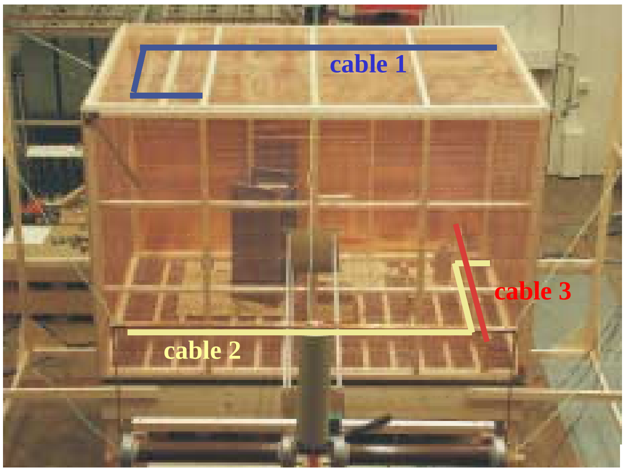

Figure 2: Model B with the three typical cable routings [4].

Finally table 5 shows the peak value of the induced voltages u_{max} at the three cable routings (fig. 2) and for both impulse currents. The experimental data are extrapolated to the real size (1:1) and to the required current:

- the model B data have to be multiplied by 6 (f_U = 1:6);
- the model B data for the first impulse current [5] have to be multiplied by 2,0=33,3kA/18kA* 1,8µs/1,67µs to take into account the reduced peak value of 18 kA and the slightly reduced front time of 1,8 µs in the experimental setup;
- the model B data for the first negative impulse current [6] have to be multiplied by 4,55= 16,7kA/5,5kA*0,25µs/0,167µs to take into account the reduced peak value of –5,5 kA and the reduced front time of 0,25 µs in the experimental setup.

Table 5: Measured and extrapolated peak values of u_{max} in V for model B.

Current	Cable routing	Model B data	Extrapolated results
First impulse current [5]	1	0,302	3,62
	2	0,308	3,70
	3	0,457	5,48
First neg. impulse current [6]	1	0,814	22,2
	2	0,741	20,2
	3	1,050	28,7

4. Calculations according to IEC 62305-4

The fundamentals for the calculation of magnetic fields, magnetic field derivatives and induced voltages in case of a direct strike to a building with a grid-like electromagnetic shield are given in Annex A of IEC 62305-4 [1].

The equations further used in this paper are only valid, if the distance from the point considered or from the cable routing to the wall or the roof is at least one mesh width of the electromagnectic shield. IEC only considers single layer shields. This has to be taken into account in the further investigations, because the reinforcement simulated in the model B is a double layer (section 5).

The peak values of magnetic fields H_{max} within LPZ 1 (fig. 3) can be estimated as:

$$H_{\max} = k_h \cdot i_{\max} \cdot \frac{w}{d_w \cdot \sqrt{d_r}} \qquad (1)$$

where:
- k_h configuration factor (k_h = 0,01 $m^{-1/2}$);
- i_{max} peak value of the lightning impulse current;
- w mesh width of the grid-like shield of LPZ 1 (here: w = 0,15 m);
- d_w shortest distance between the point considered to the wall of shielded LPZ 1;
- d_r shortest distance between the point considered and the roof of shielded LPZ 1.

The peak values of magnetic field derivatives can be easily calculated in a first approximation using:

$$\left(\frac{dH}{dt}\right)_{\max} = \frac{H_{\max}}{T_1} \qquad (2)$$

where: T_1 front time of the lightning impulse current.

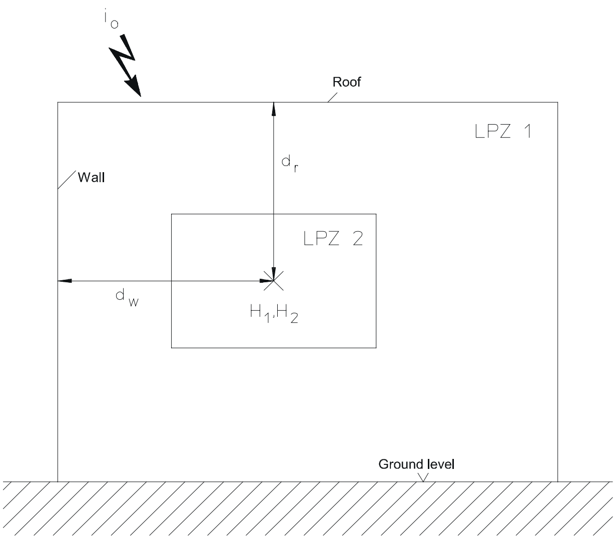

Figure 3: Magnetic fields within a building directly struck by lightning [1].

Using the data from table 2 for the peak values i_{max} and the front times T_1 of the lightning impulse currents and the data from fig. 1 for the shortest distances from the points considered to wall d_w and roof d_r (up-scaled to 1:1 size) for eq.(1) and eq. (2), the values given in table 6 are obtained for the peak values of the magnetic fields H_{max} and the magnetic field derivatives $(dH/dt)_{max}$.

The calculations of the induced voltages are performed for open circuits. Then the peak value of the open circuit voltage for a loop (fig. 4) can be estimated as:

$$u_{d/\max} = \mu_0 \cdot b \cdot \ln\left(1 + \frac{l}{d_{l/w}}\right) \cdot k_h \cdot \frac{w}{\sqrt{d_{l/r}}} \cdot \frac{i_{\max}}{T_1} \qquad (3)$$

where:
- μ_0 = $4\pi*10^{-7}$ Vs/Am;
- b width of the loop;
- l length of the loop;
- $d_{l/w}$ distance of the loop from the wall of the shield;
- $d_{l/r}$ average distance of the loop from the roof of the shield;
- k_h configuration factor (k_h = 0,01 $m^{-1/2}$);
- w mesh width of the grid-like shield of LPZ 1 (here: w = 0,15 m);
- i_{max} peak value of the lightning impulse current;
- T_1 front time of the lightning impulse current.

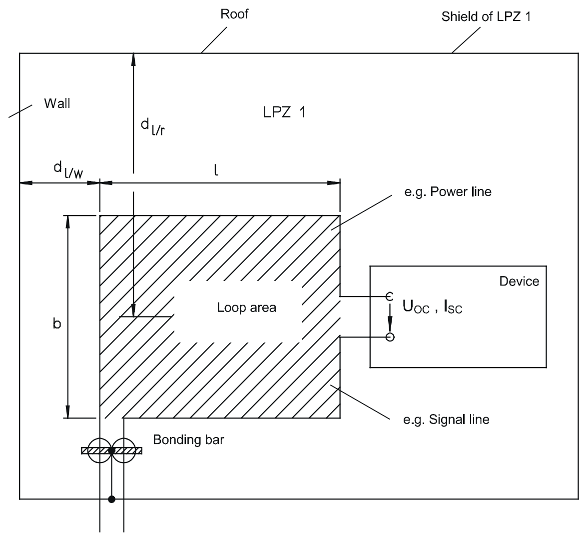

Figure 4: Voltages and currents induced in a loop within a building directly struck by lightning [1].

Table 6: Calculated peak values of H_{max} and $(dH/dt)_{max}$.

Current	Location	H_{max} (A/m)	$(dH/dt)_{max}$ (A/µs)
First impulse current [5]	1	27,2	2,72
	2	40,8	4,08
	3	371	37,1
	4	20,4	2,04
First negative impulse current [6]	1	13,6	13,6
	2	20,4	20,4
	3	186	186
	4	10,2	10,2

In case of real cable routings (like the examples of model B) it is essential to separate the entire routing into different sections having constant “geometrical quantities”. The partial voltages are calculated based on eq. (3) for each section and then the partial voltages are added. This is a strong worst-case assumption because dependent on the orientation of the induction loop the partial voltages may also compensate each other partly. However, the orientation is usually unknown, therefore a simple addition seems to be correct.

For the three cable routings shown in fig. 2 the induced voltages are calculated. All dimensions have to be up-scaled by the reciprocal geometrical scale factor $f_g^{-1} = 6$. The details of the cable routings are given in the tables 7 – 9, the lightning impulse current parameters come from table 2. The width of the induction loop (cable on supporting structure) is estimated to 10 cm.

For the cable routings 1 and 2 the entire routing is separated into three sections. The first section is always at the cable entrance to the model B. Then the sections follow each other until the cable end. The peak values of the induced voltages at all three cable routings and for both lightning impulse currents are given in tables 7 – 9.

Table 7: Calculated peak values of u_{max} in V at cable routing 1.

Section	b (m)	l (m)	$d_{l/w}$ (m)	$d_{l/r}$ (m)	First imp. curr. [5]	First neg. imp. curr.[6]
1.1	0,1	16,5	0,15	10,5	5,4	27,4
1.2	7,5	0,1	1,5	6,5	7,2	35,8
1.3	0,1	3	1,5	3	2,4	12,0
Sum:					**15,0**	**75,2**

Table 8: Calculated peak values of u_{max} in V at cable routing 2.

Section	b (m)	l (m)	$d_{l/w}$ (m)	$d_{l/r}$ (m)	First imp. curr. [5]	First neg. imp. curr.[6]
2.1	0,1	1,5	0,15	10,5	2,8	14,0
2.2	7,5	0,1	1,5	6,5	7,2	35,8
2.3	0,1	9	1,5	3	4,2	21,2
Sum:					**14,2**	**71,0**

Table 9: Calculated peak values of u_{max} in V at cable routing 3.

Section	b (m)	l (m)	$d_{l/w}$ (m)	$d_{l/r}$ (m)	First imp. curr. [5]	First neg. imp. curr.[6]
3.1	12	0,1	1,5	6	**11,9**	**59,6**

5. Consideration of a second reinforcement layer

Model B should represent a real building made of reinforced concrete. Therefore the reinforcement was built by two layers. The calculations described in chapter 4 are performed for a single layer grid-like shield.

The influence of a second layer of reinforcement was already investigated for the 1:1 size model A [2]. The second layer leads to a reduction compared to a single layer arrangement, which is different for the magnetic field and the magnetic field derivative. Furthermore the reduction factor depends on the front time of the impulse currents. Table 10 gives the mean values for reduction factors R for both impulse currents and for the magnetic field and its derivative obtained from the prior measurements [2].

Table 10: Reduction factor R for H_{max} and $(dH/dt)_{max}$ for a double layer reinforcement compared with a single layer.

	H_{max}	$(dH/dt)_{max}$
First impulse current [5]	1,4	3,1
First negative impulse current [6]	1,7	3,5

The reduction factor for the induced voltages is assumed identical to the reduction factor for the magnetic field derivatives, because the induced voltages measured in [2] were dominantly proportional to the current derivatives.

6. Comparison of model and calculation results

Following, the results of the model experiments (chapter 3) and of the calculations according to IEC 62305-4 (chapter 4) are compared. Tables 11 – 13 show these comparisons for the peak values H_{max}, $(dH/dt)_{max}$ and u_{max}. All results of the calculation are reduced by the reduction factors R described in chapter 5 to account for the additional shielding by a second layer of reinforcement.

Table 11: Comparison of model and calculation result for H_{max} in A/m.

Measurement location	First impulse current [5]		First negative impulse current [6]	
	Model	Calculation	Model	Calculation
1	15,3	19,4	1,99	8,0
2	23,1	29,1	1,53	12,0
3	25,0	265	2,08	109
4	23,3	14,6	1,88	6,0

Table 12: Comparison of model and calculation result for $(dH/dt)_{max}$ in A/m/µs.

Measurement location	First impulse current [5]		First negative impulse current [6]	
	Model	Calculation	Model	Calculation
1	0,254	0,88	2,42	3,89
2	0,343	1,32	2,02	5,83
3	0,367	12,0	3,24	53,1
4	0,363	0,65	1,87	2,91

Comparing the peak values of the magnetic field H_{max} and the magnetic field derivatives $(dH/dt)_{max}$ it is found, that the calculations according to IEC mostly lead to higher results, i.e. they give results on the safe-side. For the measurement locations 1, 2 and 4 the differences between model experiment and calculation are moderate. Considering the simplifications implied in the IEC formulae, differences by a factor of up to 5, or so, had to be expected.

For the measurement location 3 however, which is very close to the wall, the differences are significantly higher. It seems that increase of the magnetic field close to a reinforced wall is less dramatic than the IEC-formula suggests. Also in [7] it is stated "The results .... show that it is indeed not possible to calculate the complicated field distribution near the shield by a simple formula ..."

Table 13: Comparison of model and calculation result for u_{max} in V.

Cable routing	First impulse current [5]		First negative impulse current [6]	
	Model	Calculation	Model	Calculation
1	3,62	4,84	22,2	21,5
2	3,70	4,58	20,2	20,3
3	5,48	3,84	28,7	17,0

The induced voltages u_{max} in the cable routings correspond remarkably well. The differences of the calculations related to the model results are usually below 20%, the maximum deviation is about 40%.

7. Conclusions

The paper compares calculations based on the formulae given in IEC 62305-4 for the determination of electromagnetic quantities inside a grid-like shield to measurements at a modelled building consisting of two layers of reinforcement.

The grid-like electromagnetic shield as the basis for the calculations in IEC 62305-4, Annex A [1] consists of one layer only. Technical grid-like shields like reinforcements have at least a second layer which has to be taken into account.

At locations not too close to the wall the peak values of the magnetic fields and the magnetic field derivatives in the experiment are within reasonable agreement with the calculation results. Only the H and dH/dt peak values very close to the wall differ considerably. The calculated values, however, are on the safe-side in almost all cases studied. The calculated and measured induced voltages in typical cable routings within the grid-like shield correspond remarkably well.

If a lightning protection study for the electrical and electronic system within a reinforced building is to be performed, usually the knowledge of the voltages induced in the cabling is the most important item. These voltages can be estimated as follows:

- As a 1st step a calculation based on IEC 62305-4, Annex A is performed with the mesh width of the (outer) layer of the reinforcement.
- In the 2nd step the influence of a second layer of reinforcement is taken into account using the reduction factors described in table 10 [2].

8. References

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