Lightning Return Stroke to a Farm: Measurements and Simulations Using a Reduced Scale Model

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Abstract - This paper presents a reduced scale model developed to study lightning electromagnetic effects inside a farm. The reduced scale model (4-m long, 3-m wide and about 2-m high) was installed in a high voltage laboratory. An impulse Marx generator was used to inject a current in the roof of the farm model. The injected current has a risetime of 1 µs and a duration at half peak of 7 µs. Current along the lightning protection system (LPS) and induced voltages in the electrical installation of the reduced scale model were measured. In addition, the overall system was modeled using the Numerical Electromagnetics Code (NEC-2) and very good agreement was found between numerical simulations and experimental data.

Keywords: Lightning, lightning protection system, reduced scale model, current distribution, induced voltage, measurements.

I. INTRODUCTION

Lightning might represent a threat to sensitive electronic systems located inside a structure struck by lightning (e.g. [1-2]). In particular, flashovers between lightning protection system (LPS) and conductors of the electrical installation that might result in a fire should be avoided. To avoid the flashover, a galvanic connection (if not already available) can be installed between the 2 systems through the roof, but in that case the increased current in the electrical installation can generate an overheating and consequently a fusion with fire. A principle of "lightning protection zones (LPZ)" was developed by the committee IEC TC 81 and published in the International Standard Series IEC 61312 and 61024 [1-3]. This international standard gives some recommendations on lightning protection systems of buildings.

Lightning can interact with structures basically in two ways, direct strikes and nearby strikes. In this paper, we are considering only the direct strikes. In this case an impulse lightning current (ranging from 5 kA to 200 kA) is injected directly to the lightning protection system of the structures [2]. This high current flows through the down conductors generating an electromagnetic field which can induce currents and voltages in the electrical installations inside the structure. The magnitude of the induced currents and voltages can reach large values and can produce damages (fire) or electrical hazard to people and/or cattle too [4-6].

In this paper, we present a theoretical and experimental study of lightning electromagnetic effects inside a farm. The experiment is performed on a reduced scale model of a farm equipped with a lightning protection system (see Fig. 1). The model, 4-m long, 3-m wide and about 2-m high, was installed in a high voltage laboratory. An impulse generator was used to inject a current in the roof of the farm model. We will present current measurements performed along different metallic parts of the system, as well as induced voltages in a circuit (simulating the internal light cabling) inside the structure. We will also present simulations obtained using the Numerical Electromagnetics Code (NEC2) [7] and compare the computed results with experimental data.

II. EXPERIMENTAL SETUP - REDUCED SCALE MODEL

The scale structure we have built represents a farm with a reduction factor of about 1 to 5. A complete lightning protection system was installed into the model using copper conductors, and gutter- and drain-pipes (Fig. 1).

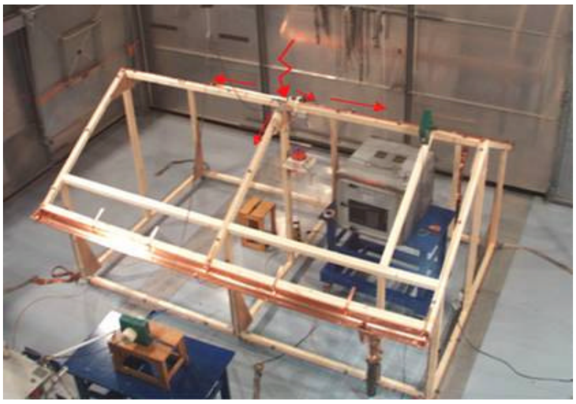


Figure 1– Top view of the scale model of the farm.

The whole electrical test structure (Fig. 2) is mounted on a wooden support and connected to the ground of the high voltage laboratory at its 4 corners.

The description of the materials and dimensions employed in the electric installations are presented in table 1.

An internal cabling is also considered in the model and shown in Fig. 2. The circuit is located inside isolated plastic pipes. It is composed of conductors representing the phase, neutral and ground wires. This circuit is employed in this study to observe induced currents and voltages.

A 4-stage Marx Generator, Haefely model SGS 400/12, 400kV-12kJ, was employed to inject the transient voltage on the roof of the model (Fig. 1). The transient currents were measured at different locations in the LPS and in the internal circuit using two Pearson sensors:

model 320 with a bandwidth of 160 Hz to 10 MHz, a gain ratio of 0.25 V/A and a maximum peak value of 2 kA, and model 3025 with a bandwidth of 7 Hz to 4 MHz, a gain ratio of 0.025 V/A and a maximum peak value of 20 kA.

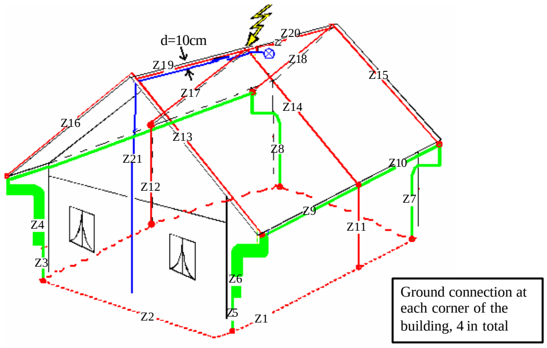


Figure 2– Description of the electrical system installed in the reduced scale model. Internal conductors are located at 10 cm from the lightning protection cabling in the roof.

Table 1– Electrical elements of the system installed in the scale model.

Element (see Fig.2)	Length [cm]	Diameter [mm]	Width [mm]	Surface [mm^2]
z1	405	8		
z2	245	8		
z3	52	6		
z4	70	120	0.8	
z5	55	6		
z6	70	120	0.8	
z7	166	6		
z8	175.5	6		
z9	201.5		0.5	12
z10	201.5		0.5	12
z11	175	6		
z12	170	6		
z13	193	6		
z14	194	6		
z15	192	6		
z16	184	6		
z17	185	6		
z18	185.5	6		
z19	197	6		
z20	198	6		
z21 (L+N+G)	376			3*1.5

The induced voltage was measured using passive high voltage probes Tektronix P6015A with a bandwidth up to 75 MHz, a reduction ratio of 1000 and a maximum voltage level of 20 kV. The measured voltages from the Tektronix probes were directly transmitted via a Thomson CSF adaptor V40 and fiber optic cables to a receiver which was connected to a Lecroy 8-bit digitizing oscilloscope operating at 100 Msamples/sec.

The overall operating frequency bandwidth of the measuring system, not including the oscilloscope, was 1 kHz to 130 MHz.

III. MODELING AND NUMERICAL SIMULATIONS

For the numerical simulations, the reduced scale model presented in Fig. 1 was reproduced using NEC-2 [7]. Fig. 3 presents the wire-representation of the reduced scale model implemented in NEC-2. All the conductors in this representation are considered to be lossless straight wires. The pulse generator is represented by an equivalent "Thévenin circuit" composed by an ideal voltage source (U_S) and its internal impedance (Z_{th} = 60 Ω). In the numerical model, an additional internal line (Fig. 3) located 10 cm from the lightning protection system represents the internal circuit.

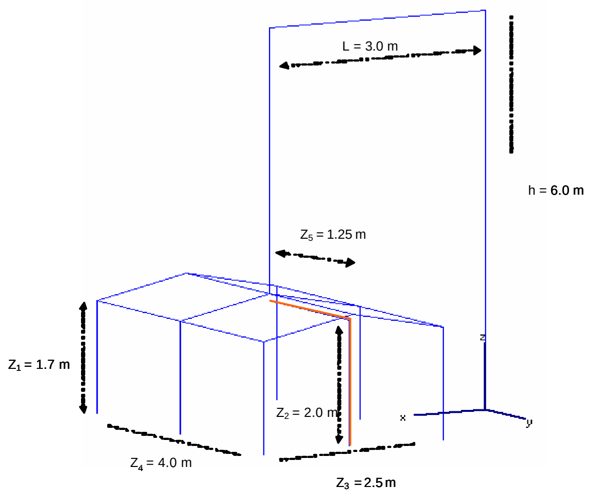


Figure 3 – Numerical representation of the reduced scale model using NEC-2

The computations in NEC-2 are performed in the frequency domain. The output results are converted into the time domain using inverse FFT routines.
The time-domain and frequency-domain parameters employed for the numerical calculations are presented in Table 2.

Table 2– Time domain and frequency domain parameters for the numerical calculations

Time Domain		Frequency Domain	
Total simulation time (T_{max})	100 μs	Maximum value of frequency (f_{max})	10 MHz
Total number of points (Npts)	2000	Total number of points (Nf)	1000
Time resolution (Δt)	0.05 μs	Frequency resolution (Δf)	10 kHz

The segment length was selected to be $\Delta L = 0.1$ m and the radius of the segments was set to $r = 0.016$ m, in agreement with the NEC-2 recommendations:

$$\frac{c}{f_{\max}\times 10^3}\leq \Delta L\leq \frac{c}{f_{\min}\times 10} \quad \text{and}$$

$$r\leq \frac{\Delta L}{8} \quad \text{or} \quad r\leq \frac{\Delta L}{2\pi} \qquad (1)$$

in which c is the speed of light, f_{max}=10 MHz and $f_{min}=\Delta f$ = 10 kHz.

To reproduce the voltage source a double exponential function was used. The values for the parameters α and β ($12x10^4$ s^{-1} and $32x10^5$ s^{-1}, respectively) involved in equation (2) were obtained by trial and error. Fig. 4 shows the input voltage used in our study.

$$u_S\left(t\right)=U_{\max}\left(e^{-at}-e^{-bt}\right) \qquad (2)$$

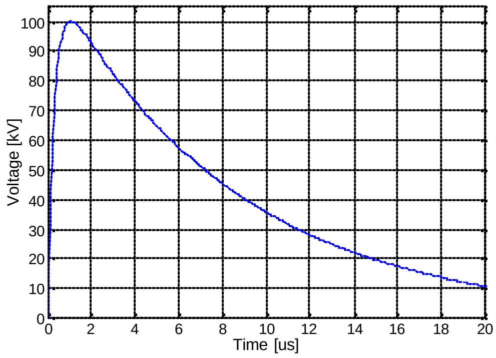


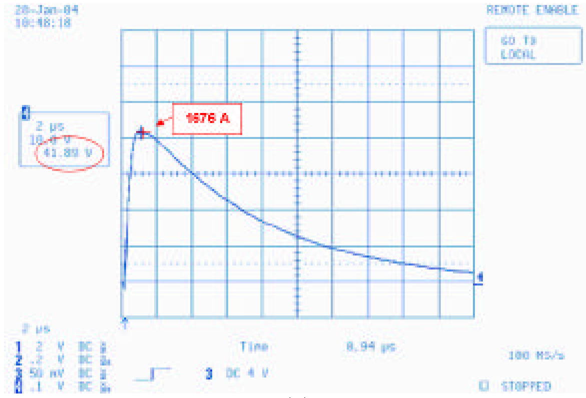
Figure 4 – Input voltage $u_S(t)$ in the time domain

IV. Comparison Between Experimental and Numerical Results

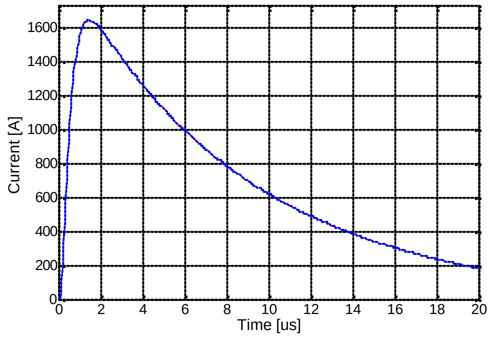
Two configurations are considered: (1) the internal circuit is isolated from the LPS, and (2) the internal circuit is connected to the LPS.

Fig. 5 presents the measured current (Fig. 5a) and the calculated current (Fig. 5b) at the injection point. The injected current is characterized by a risetime of about 1 μs and a duration at half peak of 7 μs. Fig. 6 presents measured and simulated current waveforms for the case (1) for which the internal circuit is isolated from the LPS. Figure 7 presents similar results for case (2) when the internal circuit is connected to the LPS. Finally, figure 8 presents the corresponding current in the internal circuit.

To summarize, table 3 presents a comparison between measured and calculated current peak values for the considered configurations. The peak values observed experimentally and those calculated numerically are in good agreement. The smallest and largest differences between measured and simulated peak values are 2 % and 24 %, respectively.

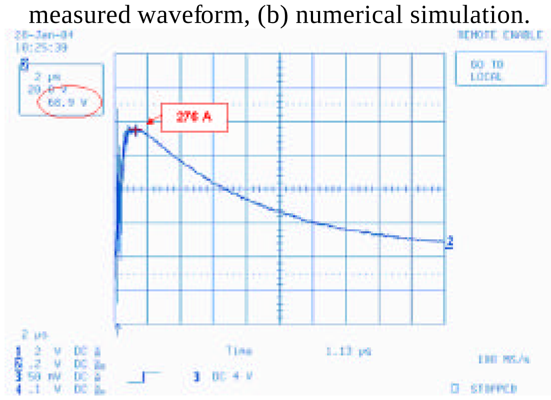


(a)

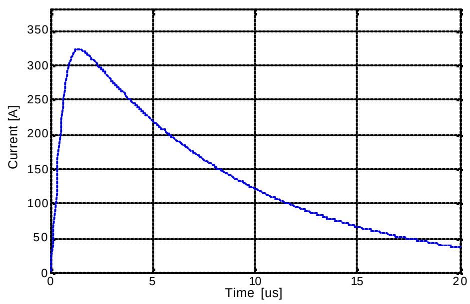


(b)

Figure 5 – Current at the injection point, internal circuit not connected to the lightning protection system: (a) measured waveform, (b) numerical simulation.

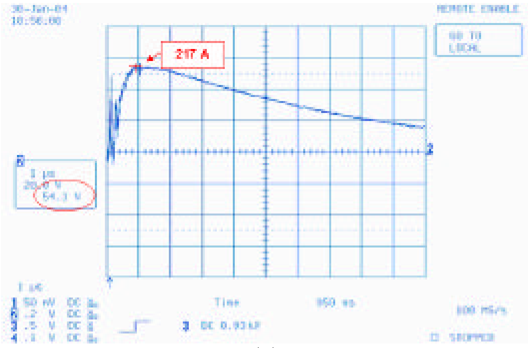


(a)

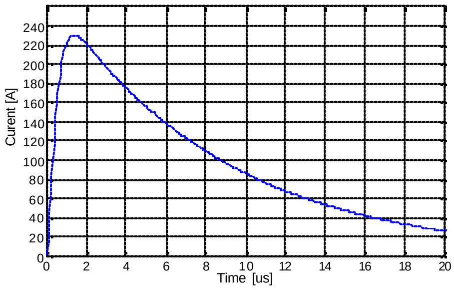


(b)

Figure 6 – Current in the conductor of the LPS, internal circuit not connected to the lightning protection system: (a) measured waveform, (b) numerical simulation.

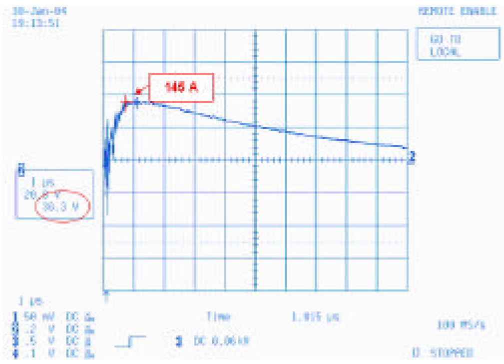


(a)

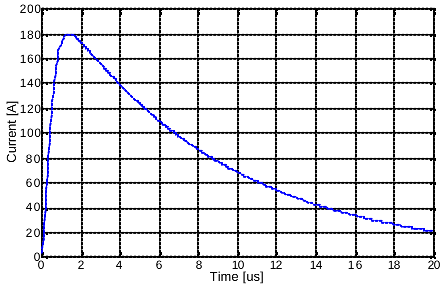


(b)

Figure 7 – Current in the conductor of the LPS, internal circuit connected to the lightning protection system: (a) measured waveform, (b) numerical simulation.



(a)



(b)

Figure 8 – Current in the internal conductor, internal circuit connected to the lightning protection system: (a) measured waveform, (b) numerical simulation.

In the case where the internal circuit was isolated from the LPS, we have also measured the induced voltage between the LPS and the inner conductor extremity. Fig. 9 illustrates the gap along which the voltage was determined. The length of this gap was about 10 cm.

The observed measured voltage presents a very high frequency signal (Fig. 10a). It was filtered using the 2 bits enhanced resolution of the oscilloscope. This function is similar to smoothing out the signal. The resulting waveform is presented in Fig. 10b together with the observed current at the injection point, for an input lightning voltage of 100 kV.

Table 3 – Comparison between measured and calculated current peak values.

Current Peak Values	Measured [A]	Calculated [A]	Difference %
Internal circuit isolated			
Injection	1676	1643	2
LPS	276	323	17
Internal circuit connected			
LPS	217	230	6
Internal conductor	145	180	24

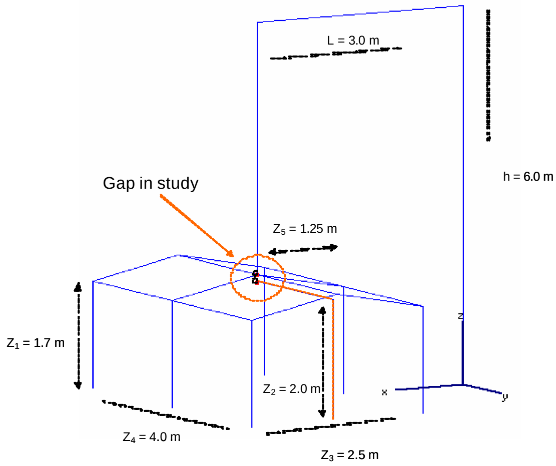


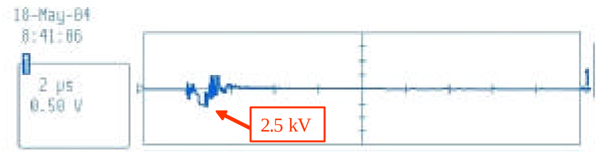
Figure 9 – Induced voltage between the internal conductor's extremity and the LPS.

The numerical evaluation of the induced voltage cannot be obtained directly in NEC-2. This voltage is determined by integrating the electric field computed by NEC-2 along the considered gap (see Fig. 9)

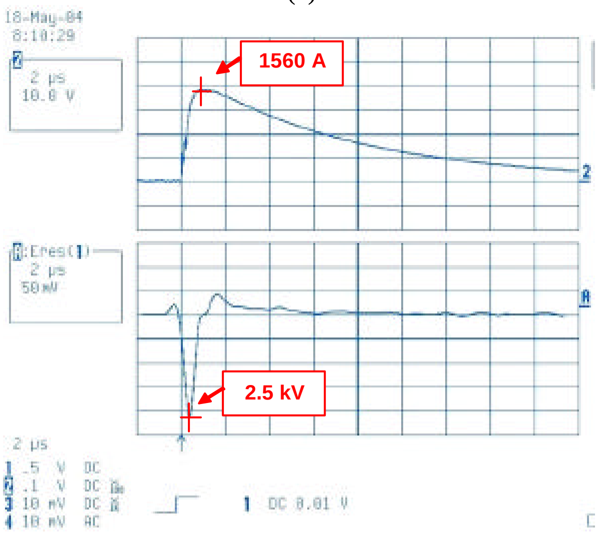
$$V_{Ez} = \int_a^b E_z dl \cong \sum_{n=1}^{N} E_{z_n} .\Delta l \qquad (3)$$

where a and b are the limits of integration (the two extremities of the gap), N is the number of segments in which the gap is divided to and for which the electric field is evaluated, and Δl is the length of each segment of the gap. In our calculations, we have used the following values for these parameters: $N = 5$ and $\Delta l = 2$ cm.

Figure 11 presents the vertical electric field waveforms along the considered 5 segments of the gap, calculated with NEC-2. The resulting induced voltage (original and low-pass filtered waveforms) along the gap obtained using (3) is presented in Fig. 12.



(a)



(b)

Figure 10 – (a) observed induced voltage before filtering, (b) current at the injection point and induced voltage after filtering (using the 2 bits enhanced resolution function).

The numerical vertical electric fields and the resulting induced voltage exhibits high frequency oscillations, similar to those observed in the experimental waveforms. The calculated peak value for the induced voltage was around 1.1 kV (without filter) and 860 V (filtered). The rise time was about 0.25 µs and the half wave duration 0.56 µs.

Despite a very good agreement between measured and simulated waveforms, the measured peak is about 2.5 times larger than the calculated one. The difference can be attributed to simplifications in the computation of the voltage and also to possible experimental errors.

V. DISCUSSION AND CONCLUSIONS

We presented in this paper a reduced scale model developed to study lightning electromagnetic effects inside a farm. The reduced scale model (4 m long, 3 m wide and about 2 m high) was installed in a high voltage laboratory. An impulse Marx generator was used to inject a current in the roof of the farm model. The injected current has a risetime of 1 µs and a duration at half peak of 7 µs. Current along the lightning protection system (LPS) and induced voltages in the electrical installation of the reduced scale model were measured. The overall system was modeled using the Numerical Electromagnetics Code (NEC-2) and the numerical simulations were found to be in very good agreement with measured waveforms.

Additional work is needed to better evaluate the induced voltage between the internal cabling and the LPS.

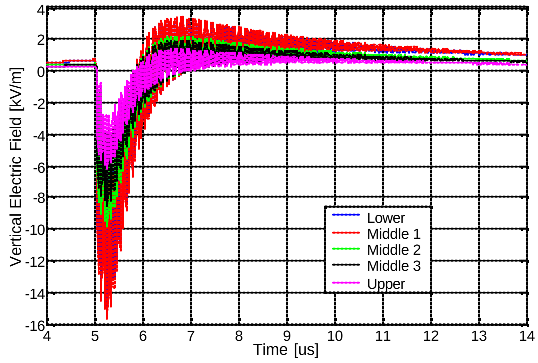
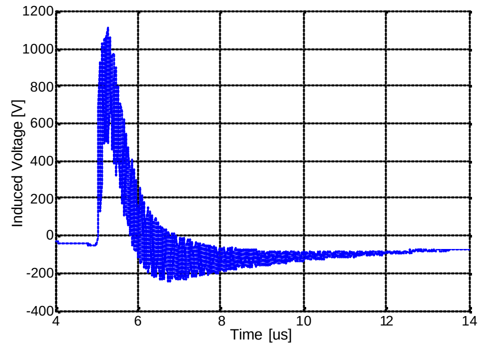
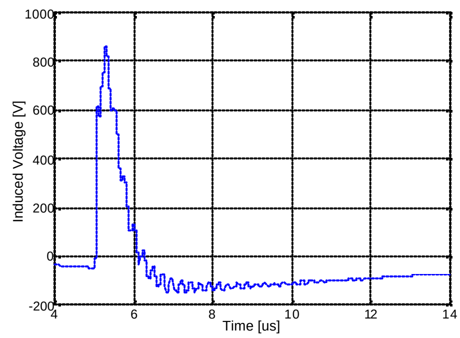


Figure 11 – Calculated vertical electric field waveforms in the gap region.



(a)



(b)

Figure 12 – Calculated induced voltage. (a) Without filter and (b) low-pass filtered.

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