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EMC ASPECTS OF A LIGHTNING SURGE GENERATOR AND ITS MEASURING SYSTEM

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Abstract

Adequate EMC techniques can make digital measurements in high-voltage engineering as straightforward as they are in low-voltage electronics. We demonstrate that for the case of a 2.4 MV lightning surge generator. Interference currents in grounding structures and coaxial cables have been measured. With an EMC-cabinet and a differentiating/integrating measuring system the effects of these interference currents can be suppressed far enough to obtain clean records of the high voltage waveform on a digital oscilloscope.

1. Introduction

Accurate digital measurements of high-voltage (HV) waveforms generated for instance by a lightning surge generator, require first of all good solutions for the EMC-problem (Electromagnetic Compatibility). To study this problem we measured during shots of the generator the common mode (CM) interference currents which flow in the grounded elements, such as the braids of signal cables. Currents up to 50 A peak value have been observed; frequency analysis revealed components up to 50 MHz and higher. These large currents firstly present a threat to the registration equipment, which thus has to be protected properly. An EMC-cabinet provides a detour for the CM currents around the equipment via a well designed path; such a cabinet has been described earlier [1]. Secondly, through the transfer impedance of the cable a differential mode (DM) interference signal may be coupled in into the measuring channel. We consider two solutions for this second problem:

- Use a large amplitude signal. The signal source normally is the low-voltage (LV) arm of a high-voltage (HV) divider, 1:2000 in our case. The amplitude of this signal is of the order of 1 kV; this signal can be sent directly to the EMC-cabinet and be attenuated there. In a differentiating/integrating (D/I) measuring scheme [2] the signal from the HV-divider is differentiated by means of a small capacitor C_d connected to a 50 Ω signal cable. The cable is terminated by its characteristic impedance at the entrance of the EMC-cabinet; the signal is then restored by analogue integration. Larger values for the input signal are obtained when the input capacitor is connected to a larger fraction of the full high voltage. We also employed a measuring capacitor (C_m) connected to the full high voltage and an E-field sensor (the Knight, Kn) looking at the HV-divider at about 40 percent of its height. The E-field sensor is described in more detail by Wolzak [3].
- Use a cable with a better braid, in severe cases a cable with a solid outer conductor. One may also place the signal cable in a conduit [4]; the braid must be connected to the conduit at both ends; the conduit then carries most of the CM-current. Here the results for three cables will be presented.

The DM interference voltages were measured together with the CM currents. Their ratio corresponds with the (measured) transfer impedance of the signal cables; this indicates that the interference sources and paths are well understood. The final interference voltage can be made as low as 10 mV at the input of the digital oscilloscope; surge signal voltages in our setup are at a signal level of 4 V or 1000 V, depending on the measuring system employed. More than sufficient signal to interference ratio is thus obtained.

An extensive study on surge generators has been carried out in a number of HV-labs, in order to assess the level of screening needed [5]. Both E- and H-fields have been measured at many places around the equipment to characterize the "EM-environment" eg. near the leads and the digitizers [5,6]. We feel that this concept of an EM-environment is not very useful. On one hand the EM-field has a very complicated structure since it is strongly modified by metal. Therefore the E/H ratio can vary wildly inside a laboratory. On the other hand, metal can be used to improve the local "EM-environment" wherever that is needed.

The metal housing of equipment can carry currents caused by the local E- and H-fields. In most cases the housing is only a small, and therefore inefficient antenna. Larger interference currents are carried to the equipment by the leads (signal, power, grounding, etc.) which are long antennas. To divert these CM interference currents away from the vulnerable equipment we used the above mentioned EMC-cabinet, which provides a path for the interference currents with a very low transfer impedance with respect to its interior. We finally demonstrate that with these prescriptions a correct registration of the lightning surge waveform is possible.

2. Experimental setup

We use a lightning surge generator with 12 stages of 0.125 μF capacitance which can each be charged up to 200 kV. A minimum distance of 4.5 m to the wall of the shielded HV-lab ensures that no flash-over occurs at the highest charging voltage used (12 x 180 kV, 2.16 MV). A 500 Ω resistor couples the Marx generator to the HV-divider, which is composed of six stages of 3600 pF//7.8 kΩ, in series with a LV-arm of 1.2 μF//24 Ω. In Fig. 1 the position of the components in the HV-lab is shown.

2.1 Grounding system

The low voltage side of the generator is connected to the base of the HV-divider by a brass tube of 5.6 m, 42 mm od. The low voltage end of the divider is connected directly to the conducting floor of the lab, thus forming a "single grounding point".

A measuring HV-capacitor (C_m, 57.7 pF, max. voltage 800 kV), is placed close to the HV-divider; its frame is also connected to the divider by a copper braid. Finally, a free standing E-field sensor (the
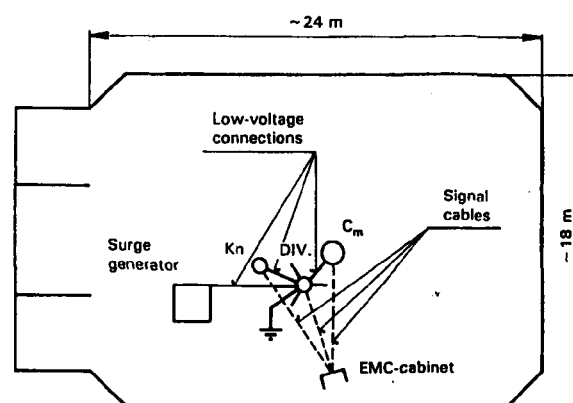

Fig. 1: Layout of the measuring setups in the HV laboratory of the Eindhoven University of Technology. Kn - the Knight; DIV.- HAEFELY voltage divider; C_m - HV measuring capacitor
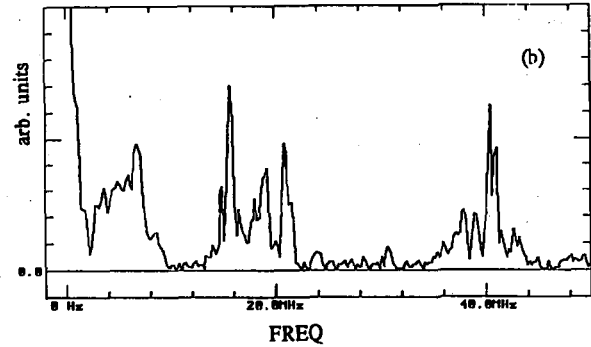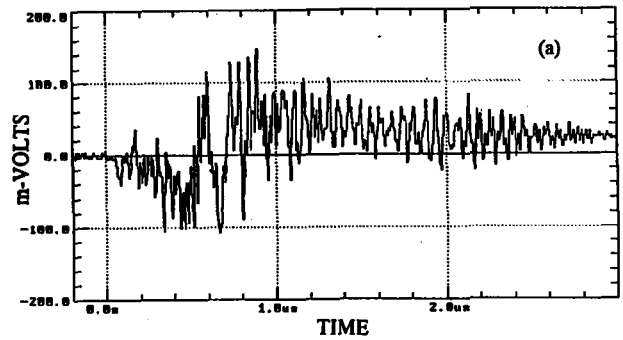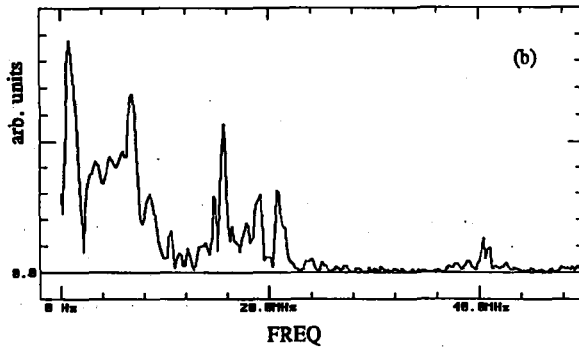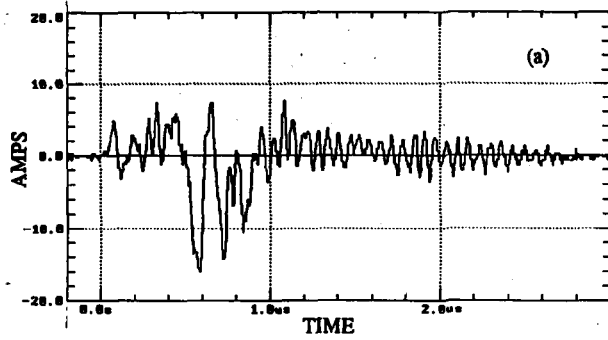
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Fig. 3: Common mode current in the shield of the signal cable RG 214, caused by the 1.58 MV shot [Q16, U_c=2.16 MV, see Table 1] of the lightning impulse generator. The signal cable, connected directly to the measuring system, was short-circuited and grounded at the source end and was lying on the floor.
a) current waveform; b) Fourier transform

Fig. 4: Differential mode voltage at the registration end of the signal cable RG 214, for the same shot as in Fig. 3.
a) voltage waveform; b) Fourier transform

Table 1: Interference currents and voltages at the registration end of different signal cables and setups

Signal cable Position/Grounding Structure		Measurement		U_c [kV]	I_{CMp} [A]		U_{DM} [mV]	Interference frequencies [MHz] of I_{CM} through the cable braid.
		system	shot number		cable braid	cond-uit		
H V - D I V I D E R	RG 58 on floor/ SC & G at HV-divider	Direct	Q08 Q09	800 2160	7.4 10.8	- -	2700 4300	7.0, 16.6-20.9, 43-46, 65-72, 92 3.5-6.8-7, 17-18-21.5, 24, 43-36, 69, 92
	RG 58 in conduit/ SC & G at HV-divider	Direct	Q07 Q06	800 2160	0.6 0.7	20.4 32.5	142 201	3.7-8.4, 17.6-20.9-22, 44-48-50, 68 3.1-7.0, 17.6-19.7-21.5, 45-45.7-48, 66
	RG 214 35cm above floor/ SC & G at HV-divider	Direct	Q18 Q17	800 2160	18 31.8	- -	165 275	6.8, 17.7, 20-22, 25-32, 47-51-58, 93 3-6.4-8, 25-30, 47-51-55, 80-83
	RG 214 on floor/ SC & G at HV-divider	Direct	Q15 Q16	800 2160	10 16	- -	136 147	3-6.4-8, 13.6-15.2-22, 38-43 2-6.8-10, 13.6-15.6-22, 38-43
	RG 214 in conduit SC & G at HV-divider	Direct	P14 P15	800 2160	1.4 1.7	19.3 31	15.2 20.	3-8, 15-18.4-20.7-22, 45-50, 63.3 0-8, 17-17.9-19.9-25, 45-48, 63-64.8-68
	RG 214 on floor/ SC & G at HV-divider	D/I C_d=1nF	Q19 Q20	800 2160	8.6 14.5	- -	7.9 9.6	3-7-8, 15-20.7-22, 40-43, 75-78, 98 3-6.4-10, 13-18.4-21
	RG 214 in conduit SC & G at HV-divider	D/I C_d=1nF	P18 P19	800 2160	1.3 1.5	19.3 31	8.8 10.4	3-8, 16-18.4-20.9-23, 24.2, 45-50, 60.5 0-8, 16-18.4-19.7-23, 24.2, 43-50, 60.5
C m	RG 214 on floor/ SC & G at C_m (UNG locally)	Direct	K10	200	42.2	-	275	5.4-7.0-8.4-10
	RG 214 on floor/ SC & G at C_m (G locally)	Direct	K11	200	4.6	-	72	8.2, 15-15.6-17.2-18
K n	RG 223 on floor/ SC, UNG at Knight	Integrator only	L19	800	13.3	-	NM	3-4.5-8.2-10 (probe bandwidth 20 MHz)
	RG 223 on floor/ SC & G at Knight	Integrator only	L20	800	51	-	NM	3-6.6-9.2-10 (probe bandwidth 20 MHz)

Note: In the last column of the table single frequencies and bands are indicated; predominant frequencies are indicated in bold type.

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Knight, Kn) is positioned at the distance of about 2 m from the HV-divider. Its frame is connected to the base of the HV-divider. Both the measuring capacitor C_m and the Knight are used as differentiating sensors; the former is connected to the full HV (now limited to 800 kV), the latter looks at the HV-divider at about 40 percent of its height. In Fig. 2 we present some of the current paths for hf interference when the HV-divider is used as a signal source. There are many loops that form resonators at a number of different frequencies; each resonator can be excited by the fast breakdown of the spark switches in the Marx generator. A coupling occurs between all the loops, mainly around the single grounding point. One of the loops deserves special attention; it is formed by the braid of the signal cable and the conducting floor.
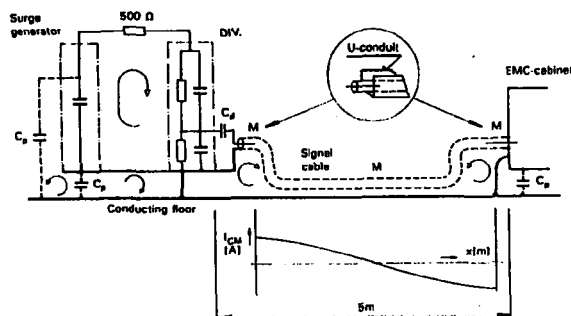

Fig. 2: Schematic picture of the experimental setup. Interference currents in the cable were measured at several locations M. The signal cable was connected in a number of different ways; in the picture a differentiating capacitor C_d is shown.

2.2 Measuring system

The digital storage oscilloscope NICOLET 4094C, maximum sampling rate 200 MHz, 8 bit resolution, was situated in an EMC-cabinet at the distance of only 5 m from the HV-divider. At this small distance from the main interference source a minimum interference was ensured by fully closing the EMC-cabinet. The cabinet was also grounded locally to the conducting floor.

Different signal cables between the signal source and the cabinet were lying either directly on the conducting floor or 35 cm above the floor. A simple U-shaped steel conduit [4], with dimensions 3 x 3 cm, 2 mm wall thickness, was used in some of the measurements. All cable braids and the conduit were insulated from the conducting floor over their full length. In the measurements done to determine the DM interference voltage, the cables were coaxially short circuited at the signal source; their braids were connected to the local ground, at about the same position as during normal measurements.

For each cable in the conduit the braid was connected circumferentially to the conduit at the signal source end; there the conduit was also grounded. The braid was always connected to the EMC-cabinet through the BNC-connector. The conduit was grounded to the EMC-cabinet via a bolted box that allows space for a current probe around the signal cable.

When the signal from the low voltage arm of the HV-divider was measured with the D/I-system, a differentiating capacitor C_d of 1 nF, placed in series with the signal cable at the HV-divider, was included in the measuring chain. This value for C_d was selected from the earlier experiments [7]. For the DM interference measurement the circuit was also shorted between the divider and C_d. A passive integrator was mounted on the inside wall of the EMC-cabinet; its input resistance was 50 Ω. Subsequent active integrators were used when the integrating transfer had to be extended to lower frequencies. The 0 dB gain of our integrators was at 13.9 or at 0.49 kHz. The merits of our D/I system have been discussed elsewhere [4,8].

The CM currents were measured by three current probes with flat transfer bandwidths ranging from 100 kHz to over 100 MHz. Outside the EMC-cabinet we employed good quality RG223 signal cables (up to 7 m length) in order to reduce interference on the current signals. Inside the EMC-cabinet we used 2 m long RG58 cables. Passive attenuators were used when needed, mounted on the inside wall of the cabinet at the BNC entrance of the signals. The cables were terminated at the oscilloscope.

3. Experimental results

High frequency (above 1 MHz) interference currents in the grounding structures have been determined for three setups with the HV-divider, the measuring capacitor C_m or the Knight as a signal source. For some selected experimental conditions we present in Table 1:
- peak values of the CM current, measured at the EMC-cabinet;
- peak values of the DM interference;
- main frequency components of the current and voltage waveforms.

Several cables have been used with different quality of their braids. The CM current and DM interference voltage waveform for the shot Q16 (charging voltage of the generator 2.16 MV) are given in Fig. 3 and 4, together with their spectra. Most of the high frequency interference occurs in the first 3 μs of the surge duration. The CM currents do not scale with the charging voltage for a certain configuration. This reflects a non-linear behavior of the spark gaps in the generator; at higher voltage the longer sparks probably develop slower, generating less hf interference than expected from a simple linear scaling with the charging voltage.

Additional protection provided by the conduit is apparent from Table 1. The CM current through the cable braid, and the DM voltage are reduced about one order of magnitude for the two cables investigated.

At high frequencies one expects drastic amplitude variations of the CM currents when measured at different positions, depending on the resonator mode excited. Such a behavior is depicted in the lower part of Fig. 2 for a half wavelength standing wave in the resonator formed by the cable between the HV-divider and the EMC-cabinet, and by the conducting floor. With one current probe at various positions along the cable, and one fixed at the EMC-cabinet, the phase reversals and the zero crossing of the current have indeed been observed at 10.3 MHz. One naively would expect a half wavelength (14.6 m) to correspond to the length of the cable (5.3 m actual length). However, the additional impedance formed by the increased height of both ends of the cable, substantially lowers the resonance frequency. This is confirmed by a simple model calculation for the cable, with a low impedance middle part (75 Ω) and two high impedance (300 Ω) sections with lengths taken from the real cable.

In a separate experiment we determined the transfer impedance of the RG58 and RG214 signal cables as a function of frequency in the same situation as indicated in Table 1 [Q08, Q09, Q15, Q16]. A sinusoidal current was injected at the signal source end of the cable; current and voltage were measured as above. For high frequencies (above 10 MHz) the transfer impedance of the RG214 is about a factor 40 lower than the one of the RG58. These results were in agreement with the measurements in Table 1 at the frequencies present in the interference waveform, within the error of the measurements (20 percent).

The low frequency part of the current waveform (up to about 600 kHz) was obtained by an analogue integration of the signal from the current probe. A CM current maximum of 9.7 A was found with the HV-divider as the signal source; this corresponds to a DM voltage of 0.23 V for the RG214 cable. Compared to the real signals involved (1 kV) this presents a small error, for both the direct and the D/I measuring system.

In Fig. 5 an actual record of the lightning surge voltage is shown, for a charging voltage of the generator of 2.16 MV. The surge maximum was 1.58 MV at the top of the HV-divider; the efficiency of our generator is 73 percent. This value for the efficiency was confirmed separately by a calibration with a spherical spark gap.

A more accurate look at the registration than Fig. 5 allows, reveals a minor hf interference at the beginning of the surge waveform. It has been shown that this interference originates in the LV-arm of the HV divider. As such it is a legal DM signal that cannot be reduced by improvements in the registration. The LV-arm itself could be improved from the EMC point of view. Minor modifications resulted in some decrease of this interference. The final limit will probably depend on the quality of the capacitors used for the LV-arm.

In Table 1 the lower limit of the DM interference voltage is about 8 mV. We short circuited the 2 m RG58 signal cable in the EMC-cabinet and connected it internally to a BNC feedthrough close to the signal entrance point. The same interference voltage was observed. This apparently is the lower limit of our setup; it was observed both when the integrator was included or not. Such an interference voltage cannot be expected behind our honest integrator.

The source of this interference was found inside the EMC-cabinet
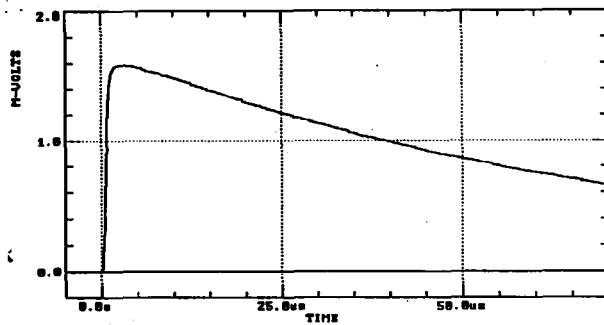
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Fig. 5: The full lightning impulse voltage waveform 1.2/50 μs, measured by the HV divider, HAEFELY and our D/I system with C_d = 1 nF. The voltage amplitude is 1.58 MV [M19].

itself. The DM voltage was measured together with the CM currents. The signals from the current probes were of the order of 40 V, even after attenuation. The corresponding high frequency DM current in the 2m long RG58 cable inside the cabinet is about 1 A. This current can produce a signal in the digital oscilloscope, via the transfer impedance of this cable, followed by penetration into other channels. When the current measurement was omitted, the interference went down to the level of resolution of the digital oscilloscope (1 mV).

4. Discussion

Low values for the interference (about 0.1 V for the direct system) can be obtained for the RG214 cable, but also for the RG58 when placed in the conduit. Our simple conduit strongly reduces the current in the braid and thereby the DM interference voltage. Steel has two advantages over e.g. copper as a conduit material [1,4]:

- at not too high frequencies it results in a lower transfer impedance due to the skin effect;
- the skin effect increases the impedance for the CM current in the loop formed by the conduit and the conducting floor.

This conduit was specially constructed for the setup. However, one may also use other steel elements, like H-shaped beams, that may be present e.g. for construction purposes, provided that they are properly connected to allow the CM-current to flow. A signal cable in the corner of such a beam is quite well protected.

What we want to emphasize is the minor importance of the overall "EM-environment". A careful design of the measuring system, of the lay-out and routing of cables, gives excellent results.

The braids of the cables and the conduit were insulated from the floor between the signal source and the EMC-cabinet. However, when several extra grounding connections are made along their lengths, one offers the CM-current earlier return paths; this "peeling off" effect reduces the CM-current and thereby the interference.

Even sensitive digital oscilloscopes are adequately protected by the EMC-cabinet. However, some high frequency interference is occasionally found in the recording. Two points are important:

- improve the quality and lay-out of the cables and the leads inside the cabinet;
- avoid simultaneous measurement of large and small signals.

A good quality screenroom door is necessary when the cabinet is close to the generator (5 m in our case). If the EMC-cabinet is at a larger distance or in an adjacent room its door can usually be left open.

5. Conclusion

Proper EMC-measures result in a correct registration of the surge waveform. Our EMC-cabinet brings a reliable separation between the HV-world outside and the digital micro-electronics world inside. General purpose digital equipment can be used. This allows HV- or High Power labs to follow the fast development in this field.

6. List of Symbols

C_d	differentiating capacitor
C_m	measuring capacitor
CM	Common Mode
C_p	parasitic capacitance
D/I	Differentiating/Integrating
DM	Differential Mode
G	Grounded
I_{CM}	Common Mode current
I_{CMp}	Common Mode current, peak value
M	Measuring point
NM	Not Measured
SC	Short-Circuited
U_{DM}	Differential Mode voltage
U_{DMp}	Differential Mode voltage, peak value
UNG	UNGrounded
U_c	charging voltage of the surge generator
x	distance

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