A portable LEMP simulator as testing device in the building phase of LEMP RF-sensors

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***Abstract*--This paper presents a portable LEMP simulator, used as testing device in the building phase of LEMP RF-sensors. The construction details such as the antenna design, the electric circuit, and the tips for the chassis montage as well as the theoretical support are reported.**

***Index Terms*-- LEMP, RF- Sensors, Lightning Detectors.**

I. Introduction

FOR several years ago, three research groups at the Universidad Nacional de Colombia (E3P – Engineering, Energy and Education Policy, GREDyP - Grupo de Redes de Distribución y Electrónica de Potencia and GTT - Grupo de investigación en Telemática y Telecomunicaciones), are working together on a detailed characterization study of LEMP (Lightning Electromagnetic Pulse). As part of the goals set, was designed and implemented the LEMPSA-I (Lightning Electro-Magnetic Pulse Spectrum Analyzer version I), whose project was originally presented at SICEL-2009 [1]. A patent of this device is currently undergoing examination. The LEMPSA-I consists of two main modules: (A) An RF-based Detector for sensing LEMP and (B) a Magnetic Field Sensor (see figure 1). The signals sensed by these modules are recorded and are subsequently processed digitally (DSP) in order to obtain spectral characterization.

The LEMPSA-I is an SDR (Software-Defined Radio) technology device. This involves an RF Front End stage (Antenna System, Radio-receivers and the M-Field sensor), a PC equipped with a high-speed sampling ADC (rates > 200 MSPS) and a DSP software application. To obtain reliable results in the construction process of this system, the modules should be tested preferably with antennas installed in its final location site (roofs, high places, etc.). Now, to test the equipments it is only required a lightning strike nearby. However, the atmospheric discharges are not always available when are needed, becoming this situation in the first important problem to solve. The solution: a device that induces in the antenna an EM-pulse with similar characteristics to that generated by lightning (LEMP).

In that way, initially as a first solution, our research group developed and implemented a simulated LEMP Generator [2] based on the circuits proposed by Erwin Marx [3]. This generator, which we have called GLEMP01, was presented to the scientific community at the SICEL-2011 held in Asuncion, Paraguay. But although it was very effective to test the software module of the system, it was not so with the Front Stage modules, and because of this, it became necessary the development of one new portable generator of simulated LEMP with wireless functionality. The new generator which will be called hereafter: GLEMP02, was assembled in October 2012, has been well tested and has become an excellent helping tool in the construction process of LEMP-Sensors based in radio-techniques (RF). The GLEMP02 is presented in this paper with all details of design and implementation.

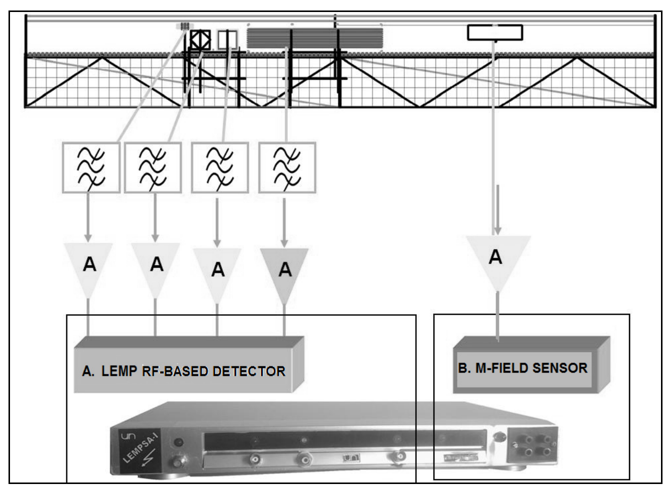

Fig. 1. Functional modules of Front-End stage of the LEMPSA-I system.

II. Technical Requirements

In order to test the front End modules at different stages of the building phase, it was necessary that the new simulated LEMP generator could satisfy the following specifications:

- Antenna: The simulator must be equipped with an EM field emission antenna.
- Waveform: The waveform of the emitted EM field should be a lightning-type pulse, according to IEC 60060-1 Standard [4] and ANSI / IEEE Standard 4-USA [5].
- Pulse duration: The output pulse must be of very short duration, so that in relation to the times of the systems under test, can be interpreted as a unit impulse. Furthermore, the pulse should not present oscillatory characteristics.
- Power: The emitted pulse must have sufficient radiation energy.

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- Portability: Optionally, the simulator must be lightweight and powered with rechargeable batteries in order to facilitate their travel to the sites of location of antennas (usually high places such as roofs, decks, etc.).

III. Design Analysis and Theoretical Support

To obtain a lightning-type impulse, of short duration without oscillatory behavior, it must be necessary the design of a passive circuit of first order. Condition that meet RC or RL circuits. However, in order to generate the appropriate magnetic field (magnetic induction emission), the antenna must be coil type. From which it follows that the circuit must be just of the RL type (see figure 2), because if it is chosen an RC-type circuit and is connecting to a coil antenna, the circuit would change to a 2nd-order type (RLC tuned circuit). Let us analyze then how works a 1st-order RL circuit:

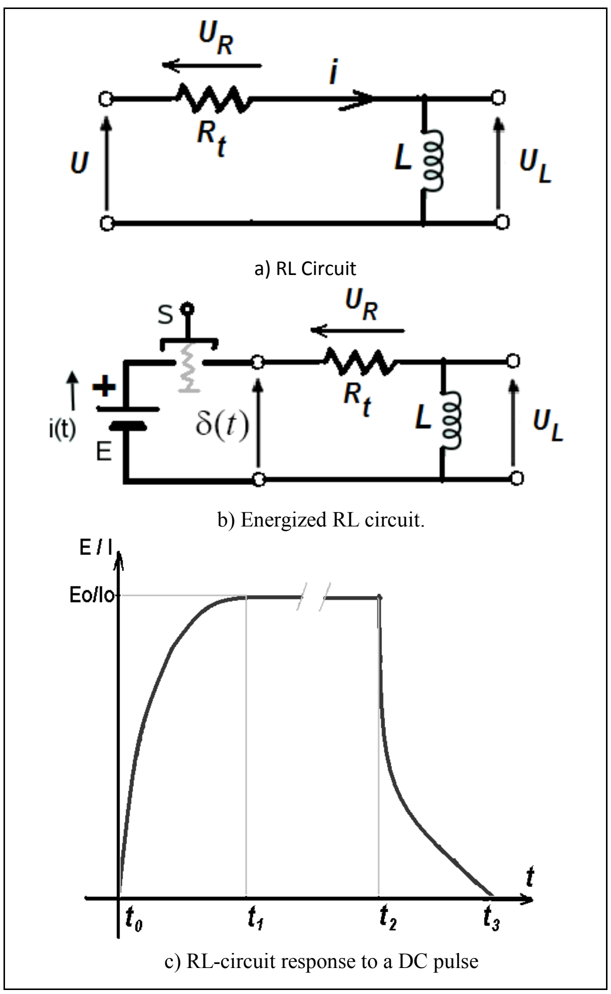

Fig. 2. First-order RL Circuit.

1st-order circuits are circuits that contain only a component **C** or **L** that stores energy, and also can be described using only a first-order differential equation. RC and RL are the two possible types of first-order circuits. In the Figure 2a we can see an RL circuit and the differential equation which governs the circuit is:

$$U(t) = L\frac{di}{dt} + R_t.i \qquad (1)$$

Now for energize the circuit, is connecting a DC source and a switch (see Figure 2b).

Let us see how it works:

Closing switch **S** in the RL series circuit (Figure 2b), coil creates an electromotive force (emf) that opposes the current flowing through the circuit. As a result, at the instant of switch closure (t_0 in Figure 2c), the intensity will be null and will increase exponentially until it reaches its maximum value, thus $I_0 = E/R_t$ (from t_0 to t_1). If then on the same circuit we open S (forming an open circuit on the RL network), the value of I_0 does not disappear instantly, but exponentially decreases until it becomes zero (from t_2 to t_3). Therefore are given two types of operating conditions:

- Transient: from t_0 to t_1 (load) and from t_2 to t_3 (download).
- Permanent: from t_1 to t_2.

Transient duration depends on the values of the resistor R_t and the self-inductance L of the coil. Initially at zero time $I_L(t=0)= 0$, then in the charging process takes the following value:

$$I_L(t_0 < t \le t_1) = I_0\left(1 - e^{-\frac{t}{\tau}}\right) \qquad (2)$$

Where τ is called the ***time constant*** (in seconds), and its value in a RL circuit:

$$\tau = \frac{L}{R_T} \qquad (3)$$

The ***time constant*** τ characterizes the "duration" of the transitional regime. Thus, the permanent current of the circuit is set to 1% after a 5τ duration. When the current becomes permanent, (1) is simplified to:

$$U(t_1 < t \le t_2) = R_t.i \qquad (4)$$

Because at that moment, $L\frac{di}{dt} = 0$.

Then in the download process (t_2 to t_3), I_L takes the following value:

$$I_L(t_2 < t \le t_3) = I_0.e^{-\frac{t}{\tau}} \qquad (5)$$

Now, the equations (3), (4) and (5) are sufficient to calculate the current I_L of the coil, however, considering that the first requirement established for our RL circuit, is the generation of a pulse of very short duration (lightning type), then an interpretation of Figure 2 from the point of view of the signal theory [6], gives us a more appropriate approach to our goal. Let us see:

The **RL** circuit (not energized) in Figure 2.a. can be interpreted as an **LTI** system [7], whose transfer function **H(s)** is given by:

$$H(s) = \frac{Y(s)}{X(s)} \tag{6}$$

Now if in (1) we divide the terms by $\boldsymbol{R_t}$, and do $\boldsymbol{i = y}$, we can express it as:

$$\tau y(t)' + y(t) = x(t) \tag{7}$$

Applying the Laplace transform,

$$\tau s Y(s) + Y(s) = X(s) \tag{8}$$

And clearing in (6), the transfer function is:

$$H(s) = \frac{1}{\tau s + 1} \tag{9}$$

Now, if the transfer function of a system is given by **H(s)**, then the impulse response of a system is given by ***h(t)***, where ***h(t)*** is the inverse Laplace Transform of **H(s)**.

$$h(t) = \mathcal{L}^{-1}\{H(s)\} \tag{10}$$

Usually, to obtain the impulse response, must be applied at the system input an unit impulse **δ(t)**. Such that if in Figure 2.b. is replaced the switch **S** by one fast push-button and we assume that the pulse applied to the system has a duration close to zero **(t→0)**, then, in practice we get an unit impulse **δ(t)**, and Figure 2.b. can be reinterpreted as Figure 3.

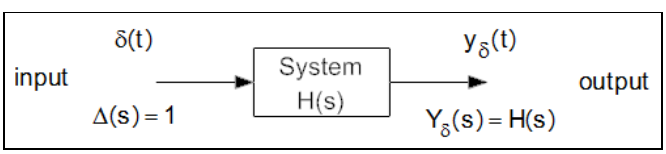

Fig. 3. LTI system excited at its input by δ(t).

Now, if x (t) = δ (t), X (s) = 1, and hence

$$Y(s) = H(s) \tag{11}$$

Thus by applying the inverse Laplace transform in (9) yields the impulse response

$$h(t) = y_\delta(t) = \frac{1}{\tau} e^{\frac{-t}{\tau}} \tag{12}$$

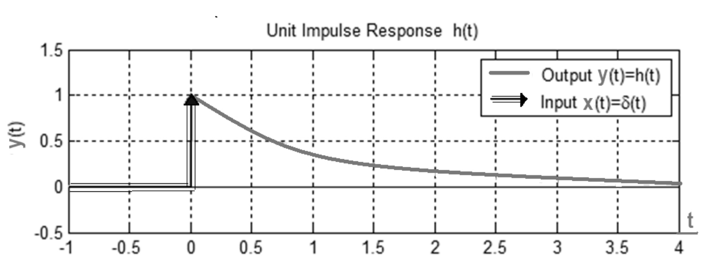

Fig. 4. Impulse Response of First-Order Systems

In Figure 4 we plot the function expressed in (12) and as you can see, was obtained theoretically the desired pulse, now just remains move from theory to practice.

IV. The GLEMP02 Electrical Circuit

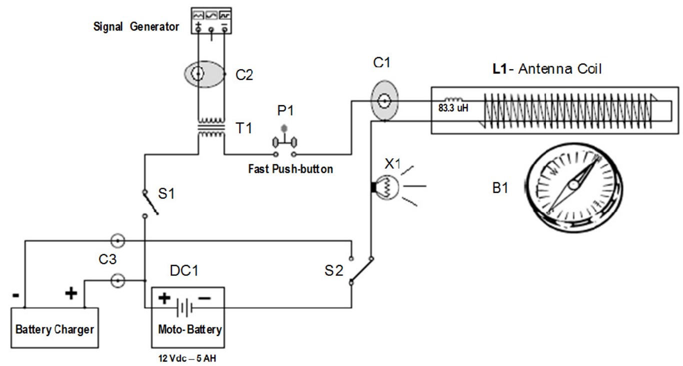

Fig. 5. The GLEMP02 Electrical circuit

Figure 5 shows the implemented circuit design, which is composed of the following elements:

1) <u>L1- Coil Antenna</u>: This antenna was built with enameled copper wire 14 AWG, as core was used a PVC pipe of 21 mm diameter and has the following data: L= 83.3 µH, winding length: 55 cm, Turns: 337.
2) <u>B1- Compass</u>: Used to confirm if the antenna emits EM field.
3) <u>T1- Signal transformer</u>: This element is optional and plays the role of spectral injector. Tip: By the RL circuit side, must be connected the secondary coil (lowest ohmic resistance).
4) <u>DC1- Motorcycle battery</u>: To provide portability to the system, is used a small lightweight motorcycle battery with the following data: V=12 VDC, AH = 5.0 Amp.H. Advantage = Rechargeable.
5) <u>X1- Car Lamp</u>: As main resistor is used a car lamp with the following data: V = 12 V DC, P = 6 W, R = 24Ω, Advantage = serves as indicator lamp. Tip: Keep in mind that since the RL circuit resistance should be very small if we want to get a pulse of very short duration, then if the circuit of Figure 2.b. is replicated, we get a shorted and possibly the battery can explode, aspect that is solved by using a car lamp in place.
6) <u>P1- Push-button switch</u>: Must be fast to ensure a very short pulse.
7) <u>C1- BNC female connector</u>: To attach the antenna coil.
8) <u>C2- BNC female connector</u>: To attach the signal generator (for spectral injection). C2 is connected to the primary coil of T1.
9) <u>C3a/b- Bananas female</u>: To engage the battery charger.
10) <u>S1/2- Switches of one and two-ways</u>: They connect the battery to the system.

If the circuits of Figures 5 and 2b) are compared carefully, it is clear that the design of the GLEMP02 is based entirely on the RL circuit shown in the Figure 2b) and therefore its operation is the same as described above for that circuit, maintaining of course the following correspondence: **U** = the voltage supplied by the battery (DC1); **S**= Push Bottom (P1); $\mathbf{R_T}$ = The car lamp (X1) and **L** = The Coil Antenna.

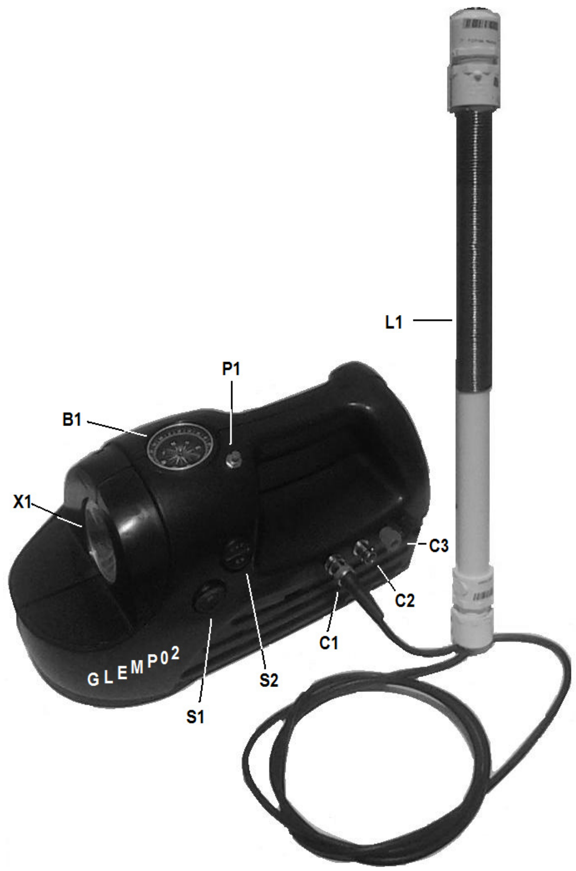

Fig. 6. A photo of the GLEMP02 - Portable Device made by UNal.

For final assembly it was used the chassis of one Small Portable-Air Compressor. Figure 6 shows the obtained prototype.

V. Testing the GLEMP02

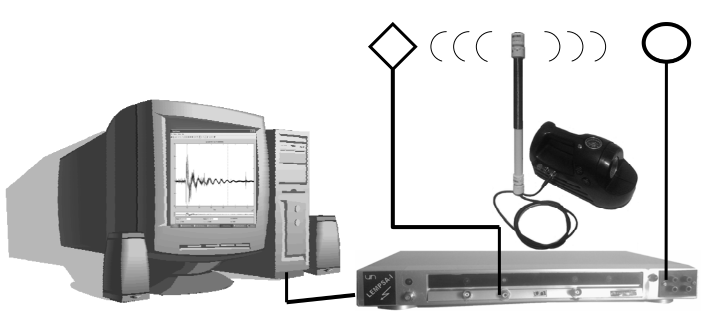

Fig. 7. GLEMP02 testing layout.

Once assembled the device, the GLEMP02 pass to the testing phase. Initially, and in order to test the waveform generated by the device, will used the Magnetic Field Sensor Module (see Figures 1 and 7).

A. Testing the GLEMP02 with a Lightning´s M-Field Sensor (LEMPSA-I module B).

1. Calculating the expected signal

The magnetic field sensor device is an adaptation of the circuit proposed by Krider & Noggle [8], and must deliver at its output a voltage signal ***v(t)*** proportional to the magnetic flux density ***B*** of the pulse generated by the GLEMP device and defined as:

$$v(t) = \frac{kA\cos\phi}{R_I C_I} B \qquad (13)$$

Where K, A, R_I, C_I are the specific values directly related to the design of the sensor and $\boldsymbol{\phi}$- the angle between the plane of the loop antenna and the signal sensor induced by the GLEMP02.

In general terms we can express (13) as:

$$v(t) = ЖB \qquad (14)$$

Where, ***Ж***- is a proportionality factor determined by specifications of the circuit, of the antenna effective area, and of the incidence angle of the LEMP signal.

On the other hand the relation between the induced current by GLEMP02 and the registered magnetic field would be given by:

$$B_{GLEMP} = \frac{\mu_0 I_{GLEMP}}{2\pi r} \qquad (15)$$

Were $\boldsymbol{\mu_0}$ is a constant and $\boldsymbol{r}$ is the distance from the GLEMP antenna to the sensor loop antenna.

2. Testing the device with the module B of LEMPSA-I.

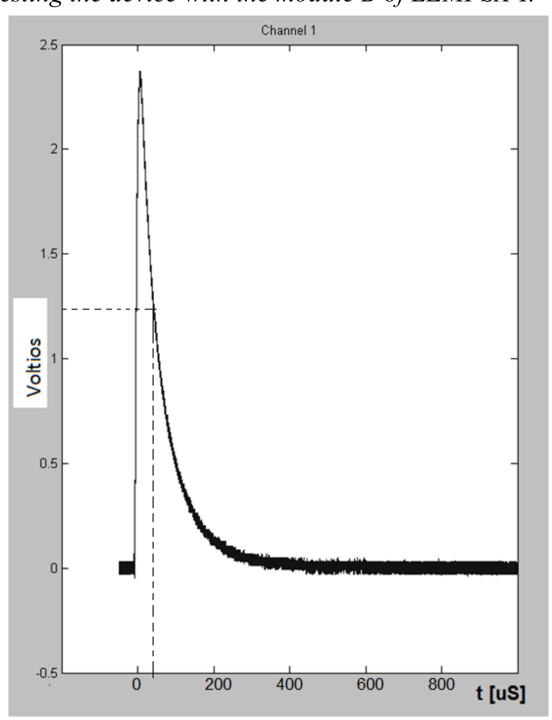

Fig. 8. A GLEMP02 pulse recorded with a Lightning M-Field Sensor.

So, from (13), (14) and (15) follows that the waveform at the output of the M-field sensor should be analog and proportional to the issued by the GLEMP02 and therefore should show a similarity with the signal in Figure 4, as effectively can be verified by checking Figure 8, recorded by the LEMPSA-I and obtained with a pulse induced by the GLEMP02 in a loop antenna connected to the lightning M-field sensor module.

Doing an analysis of the pulse obtained and shown in Figure 8, we can see that the pulse in the middle of their amplitude (50%) has a temporal length of around 50 µS and that also the wavefront (T1) is less than 5 µS, so therefore it can be stated that the waveform meets the requirements established in the IEC 60060-1 Standard [4] (see Figure 9).

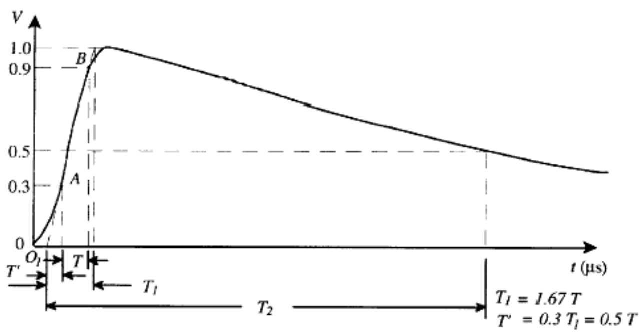

Fig. 9. Standard LI 1.2/50 μs (IEC 60060-1) with time parameters T1-T2

B. Testing the GLEMP02 with a LEMP RF-Detector (LEMPSA-I module A).

1. Calculating the expected signal.

The transfer function and impulse response contains the same information about the system dynamics, making it possible to obtain the dynamic characteristics of a system by exciting with a unit impulse and measuring its response [7].

We can describe mathematically the LEMP RF-Detector as a LTI System of 2nd order (RLC tuned circuit), and the LEMP signal can be characterized as the unit impulse ***u(t)*= *δ(t)*** - taking into account that is a pulse of very short duration (t→0) compared with the significant times of the System (RF-Detector), so when this signal excites the system input (antenna), the RF-detector will give at its output a signal ***y(t)*** associated with the impulse response ***h(t)*** of the system, through the convolution integral which would be defined as:

$$y(t)=\int_{-\infty}^{\infty}u(\tau)h(t-\tau)d\tau \qquad (16)$$

Moreover, the RLC systems of 2nd-order, are described by the differential equation:

$$y''+2\xi\omega_n y'+\omega_n^2 y=\omega_n^2 u \qquad (17)$$

So applying the Laplace transform:

$$s^2Y(s)+2\xi\omega_n sY(s)+\omega_n^2Y(s)=\omega_n^2U(s) \qquad (18)$$

We can obtain the Transfer Function:

$$H(s)=\frac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2} \qquad (19)$$

Where ω_n is the un-damped natural frequency and ζ is the damping factor.

Thus, by applying the inverse transform, we obtain the following solutions of ***h(t)*** [9]:

For ($0\le\zeta<1$) and ($t\ge 0$)

$$h(t)=\frac{\omega_n}{\sqrt{1-\zeta^2}}e^{-\sigma t}sen\left(\omega_n\sqrt{1-\zeta^2}\right)t \qquad (20)$$

Being σ= $\zeta\omega_n$ the damping constant.

For ($\zeta=1$) and ($t\ge 0$)

$$h(t)=\omega_n^2 te^{-\omega_n t} \qquad (21)$$

For ($\zeta>1$) and ($t\ge 0$)

$$h(t)=\frac{\omega_n}{2\sqrt{\zeta^2-1}}\left[e^{-\left(\sigma-\omega_n\sqrt{\zeta^2-1}\right)t}-e^{-\left(\sigma+\omega_n\sqrt{\zeta^2-1}\right)t}\right] \qquad (22)$$

Figure 10 shows the ***h(t)***-impulse response of different systems of second order obtained with equations (20), (21) and (22) with different values of **ζ.**

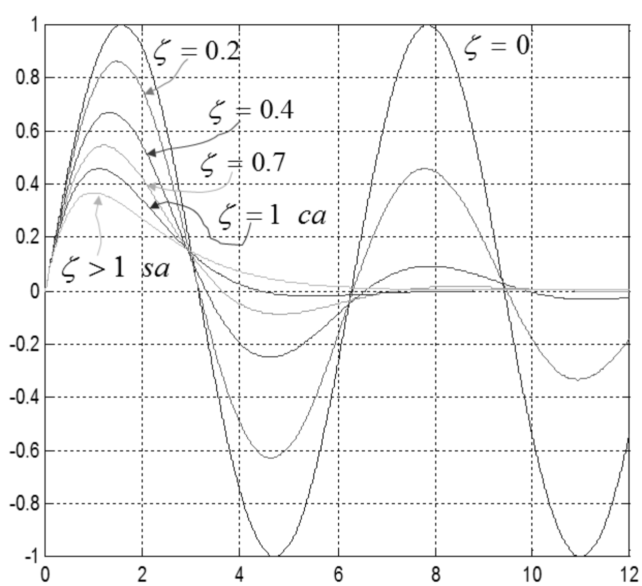

Fig. 10. Impulse response ***h(t)*** of different systems of second order

2. Testing the device with the module A of LEMPSA-I.

For the determination of ***h(t)*** is applied in practice one approximate impulse signal, that is why in our case we use as unit impulse **δ(t)** = the pulse generated by the GLEMP02 (see Figure 8).

Now, following the testing layout (see Figure 7) and in order to establish the impulse response ***h(t)*** of a VLF/LF receiver which is one of the components of the LEMP RF-Detector module, we use the GLEMP02, inducing a pulse to a loop antenna connected to said receiver. The sensed signal at the output of Detector, recorded and processed by the system LEMPSA-I, is shown in Figure 11, where we can appreciate that according to our calculations, the obtained ***h(t)*** physically corresponds to a damped sinusoidal signal ($0 \leq \zeta < 1$).

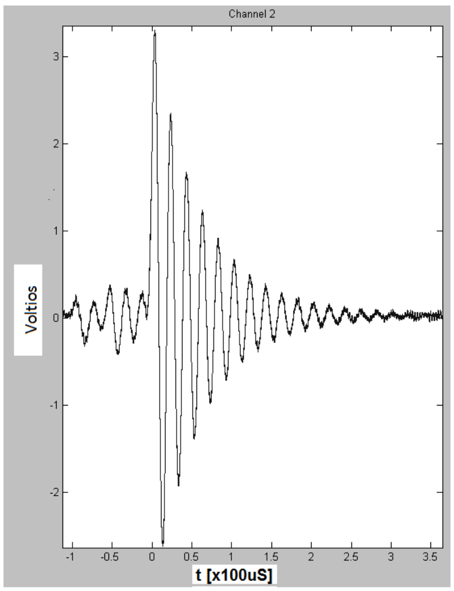

Fig. 11. A GLEMP02 pulse recorded with a LEMP RF-Detector.

The last step is to register and process real signals of the LEMP and compare them with those obtained in Figures 8 and 11. Figure 12 shows two real signals of the same atmospheric discharge (LEMP), detected and recorded by the RF-detector module and the M-Field Sensor module.

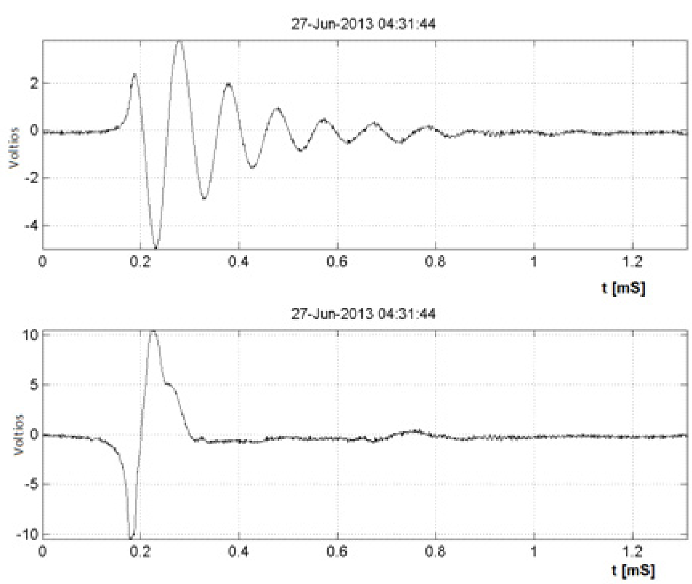

Fig. 12. Real LEMP signals detected by LEMPSA-I

VI. Conclusions

- Considering the similarity between signals of Figure 12 and signals of Figures 8 and 11, it can be concluded that the GLEMP02 is properly tested.
- Considering the waveform and the duration time of the pulse obtained in Figure 8, it can be concluded that the device "GLEMP02" emits a pulse according to the IEC 60060-1 [4].
- Was demonstrated that the GLEMP02 becomes a very effective tool, when it comes to physically determine the impulse response (system dynamics) of a LEMP RF-based Detector (RLC circuit).
- Finally, a new circuit for generating "*simulated LEMP*" has been presented to the scientific community as a small contribution towards research into lightning's spectral characteristics.

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