

# Surge Generator according to IEC61000-4-5: Study and Experimental Implementation

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**Abstract** - The scope of this paper is the study and experimental implementation of a Surge Generator according to IEC 61000-4-5, the Electromagnetic Compatibility (EMC) Standard, which describes the test instruments, procedure of testing and verification of a device for immunity against surge voltages. This is very important, as surge voltages are a very common and usual phenomenon. Their causes are either natural (lightning) or man-made (switching transients). Considering the IEC 61000-4-5, theoretical study and experimental implementation of the combination wave generator (1,2/50 $\mu$ s – 8/20 $\mu$ s) circuit was made. The results of the experimental prototype were compared with the simulation results of the surge generator using MATLAB/Simulink and LTSpice software.

**Keywords** - Electromagnetic Compatibility, Surge Generator, IEC 61000-4-5, Matlab, LTSpice.

## I. INTRODUCTION

Electromagnetic compatibility (EMC) is defined as the capability of systems or equipment to be operated in the intended working environment at designed levels of efficiency without degradation due to electromagnetic interactions. EMC is an important factor for the test and certification of every device. Interconnected devices or devices connected to a public low voltage network or even devices operating next to each other must fulfil certain EMC conditions [1].

A very common cause for overvoltage on the power grid is lightning or the switching transients [2-4]. Thus, the IEC61000-4-5 was introduced to standard the overvoltage into the power grid [5]. This standard IEC61000-4-5 describes the test and measurements techniques for the immunity caused by overcurrent or overvoltage. Therefore, before connecting a device to the public power grid it must be certified that fulfils certain overvoltage tests.

Applying surges on electronic equipment may cause hardware damage and complete failure, or in some cases, operational upset [6]. Under some level and dependent on equipment design, no effect is observed. Above this level, a surge may cause the operation of the equipment to change state, without any long-term effect on the circuit components. But,

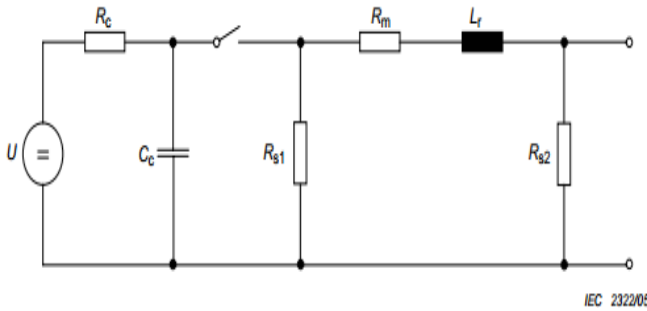
at a higher level, there may be enough energy to cause a breakdown in critical components. The maximum voltage that is likely to occur is limited by flashover considerations. For instance, in typical domestic mains supply no more than 6 kV can be withstood by the wiring components. The designer should know what surge voltage can be sustained by the product's interfaces without protection, and what voltage is expected in the protection zone in which the product will be used and decide whether any of these interfaces need additional protection.

In this paper one aspect of the IEC 61000-4-5 standard is explored. The circuit of combination wave generator (1.2/50  $\mu$ s – 8/20  $\mu$ s) is studied in order to obtain the mathematical equations and simulations are performed to meet the requirements in [5]. Also, the experimental implementation of the surge generator has been accomplished and the results are compared with the simulations.

## II. THE IEC61000-4-5 STANDARD

IEC 61000-4-5 standard relates to the immunity requirements, test methods, and range of recommended test levels for equipment to unidirectional surges caused by overvoltage from switching and lightning transients. Test levels for the electrical and electronic equipment are defined according with different environment and installation

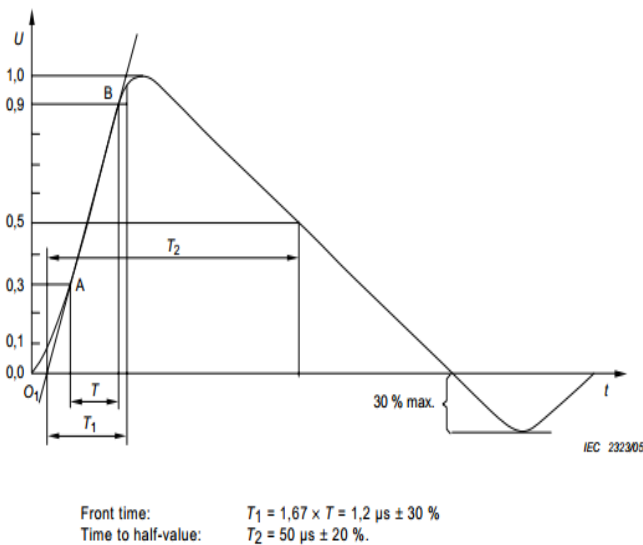
conditions. The main propose of this standard is to establish a common reference for evaluating the immunity of electrical and electronic equipment when subjected to surges. A simplified electrical schematic of the wave generator is shown in Fig. 1.



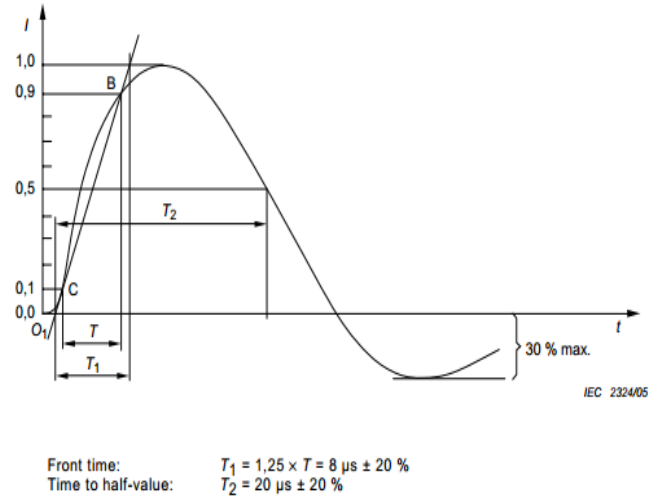
**Fig. 1.** Simplified circuit diagram of the combination wave generator [5]

The surge generator waveforms defined according to IEC 61000-4-5, are specified as open-circuit voltage and short-circuit current and therefore are measured without the Equipment Under Test (EUT) condition. These waveforms definition is according the reality, since protective devices in the EUT will inherently switch from high to low impedance as they operate.

Accordingly with IEC 61000-4-5, the surge generator (1,2/50 $\mu$ s – 8/20 $\mu$ s) is intended to generate waveforms as: an open-circuit voltage front time of 1,2  $\mu$ s; an open-circuit voltage time to half value of 50  $\mu$ s (as indicated in Fig. 2); an short-circuit current front time of 8  $\mu$ s; and a short circuit current time to half value of 20  $\mu$ s, as represented in Fig. 3.



**Fig. 2.** Waveform of open-circuit voltage (1,2/50  $\mu$ s) at the output of the generator



**Fig. 3.** Waveform of short-circuit current (8/20  $\mu$ s) at the output of the generator

The selection of Fig. 1 circuit components is the key aspect to produce these waveforms. One of the conventions established for convenience is the effective output impedance of the generator. This definition corresponds to the ratio between peak open-circuit output voltage and peak short-circuit current of the generator. For this generator, the ratio defines an effective output impedance of 2  $\Omega$ , where the relation between short-circuit current and open-circuit voltage peaks is shown in Table I.

Table I - Short-circuit current and open-circuit voltage peaks

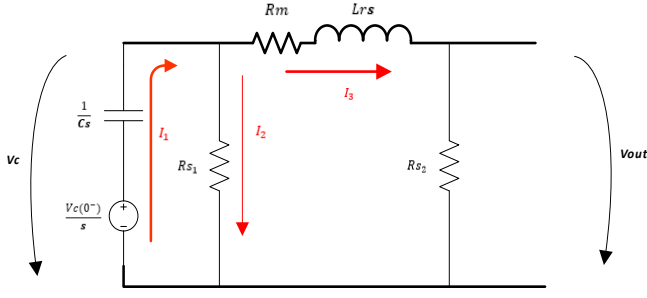
Open-circuit peak voltage $\pm 10 \%$	Short-circuit peak current $\pm 10 \%$	Effective output impedance
0.5 kV	0.25 kA	2 $\Omega$
1.0 kV	0.5 kA	
2.0 kV	1.0 kA	
4.0 kV	2.0 kA	

### III. CIRCUIT ANALYSIS

Considering the circuit of Fig. 1, there are two basic operating conditions which are: the open-circuit and the short-circuit, which are described in the following points. For the analysis of the surge generator circuit of Fig. 1 it was considered linear operating modes and Laplace Transform was used.

#### A) Open-Circuit Analysis

Considering the equivalent circuit of Fig. 1 in Laplace domain, shown in Fig. 4 for open-circuit regime, the equations that describe the behavior of the system were obtained through Current Kirchhoff's law and represented in (1).



**Fig. 4.** Surge generator annotated schematic (open-circuit regime)

$$\begin{cases} I_1 = I_2 + I_3 \\ -R_{s1}I_2 + R_m I_3 + L_r \frac{dI_3}{dt} + R_{s2}I_3 = 0 \\ V_{out} = R_{s2}I_3 \end{cases} \quad (1)$$

Considering (1) and solving it in order of the output voltage  $V_{out}$ , and by applying the Inverse Laplace Transform, obtains,

$$V_{out} = V_c \tau_1 \frac{R_{s2}}{L_r} \left( 1 - e^{-\frac{t}{\tau_1}} \right) e^{-\frac{t}{\tau_2}} \quad (2)$$

being,

$$\tau_1 = \frac{CR_{s1}L_r}{\sqrt{R_{s1}^2(R_{s2} + R_m)^2 C^2 - [2R_{s1}(R_{s2} + R_m) + 4R_{s1}^2]L_r C + L_r^2}} \quad (3)$$

$$\tau_2 = \frac{2CR_{s1}L_r}{CR_{s1}(R_{s2} + R_m) + L_r - \sqrt{R_{s1}^2(R_{s2} + R_m)^2 C^2 - [2R_{s1}(R_{s2} + R_m) + 4R_{s1}^2]L_r C + L_r^2}} \quad (4)$$

To determine the occurrence of the peak of the output voltage,  $V_{out}$ , the zero-crossing of (2) derivative was solved in order of time  $t$ , obtaining

$$t_{peak} = \tau_1 \ln \left( \frac{\tau_1 + \tau_2}{\tau_1} \right) \quad (5)$$

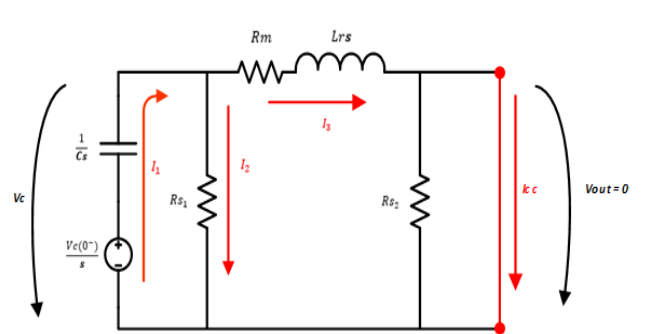
The peak value for the output voltage is henceforward described by (6).

$$V_{out}(t_{peak}) = V_c \tau_1 \frac{R_{s2}}{L_r} \left( 1 - e^{-\frac{t_{peak}}{\tau_1}} \right) e^{-\frac{t_{peak}}{\tau_2}} \quad (6)$$

### B) Short-Circuit Analysis

Considering the equivalent circuit of Fig. 1 in Laplace domain, shown in Fig. 5 for short-circuit regime, the equations that describe the behavior of the system were obtained through Current Kirchhoff's law and represented in (7).

$$\begin{cases} I_1 = I_2 + I_3 \\ -R_{s1}I_2 + R_m I_3 + L_r \frac{dI_3}{dt} = 0 \\ V_c = R_{s1}I_2 \end{cases} \quad (7)$$



**Fig. 5.** Surge generator annotated schematic (short-circuit regime)

Since the main goal of this analysis is to describe the maximum output current,  $I_{sc}$ , once again the system was solved in Laplace's domain and afterwards converted to its time domain. The resulting equation is represented in (8).

$$I_{sc}(t) = \frac{V_c}{L_r \omega_{sc}} e^{-\frac{t}{\tau_{sc}}} \sin(\omega_{sc} t) \quad (8)$$

being,

$$\tau_{sc} = \frac{2CR_{s1}L_r}{CR_{s1}R_m + L_r} \quad (9)$$

$$\omega_{sc} = \frac{\sqrt{(4R_{s1} + R_m)CR_{s1}L_r - C^2R_m^2R_{s1}^2 - L_r^2}}{2CR_{s1}L_r} \quad (10)$$

Similarly, with the peak output voltage, by zero-crossing the derivative of short-circuit current (8), and solving in order to time  $t$  domain, obtains the time,  $t_{peakSC}$  (11), that describes the time when the short-circuit current has its peak value,

$$t_{peakSC} = \frac{\tan^{-1}(\tau_{sc}\omega_{sc})}{\omega_{sc}} + n\pi, n \in \mathbb{N}_0 \quad (11)$$

Should be noted that (11) has more than one solution, for both positive and negative current output. If  $n$  is an even number it represents the peak value of positive current values, and negative current values for odd numbers.

By substituting (11) in (8), obtains the peak value of the short-circuit current as described in (12),

$$I_{sc}(t_{peakSC}) = \frac{V_c \tau_{sc} e^{-\frac{\tan^{-1}(\tau_{sc}\omega_{sc})}{\omega_{sc}}}}{L_r \sqrt{\tau_{sc}^2 \omega_{sc}^2 + 1}} \quad (12)$$

Finally, from (11), the mathematical expression describing the peak value of the first short-circuit current (undershoot) will then be described by (13).

$$I_{SC}(t_{-peak_{SC}}) = -\frac{V\tau_{SC}e^{-\frac{\tan^{-1}(\tau_{SC}\omega_{SC})+\pi}{\omega_{SC}}}}{L_r\sqrt{\tau_{SC}^2\omega_{SC}^2+1}} \quad (13)$$

### C) Sizing

After obtaining the equations that describe the operations of the shock wave generator circuit in the previous sections, the sizing was performed to comply with the requirements mentioned in [5], which are, with results shown in Table II,

Open-Circuit Requirements:

- Front Time: 1.2  $\mu$ s;
- Time to half-value: 50  $\mu$ s;
- Voltage peak: 1 kV;

Short-Circuit Requirements

- Front Time: 8  $\mu$ s;
- Time to half-value: 20  $\mu$ s;
- Current peak: 500 A;
- Undershoot Max. Current peak: 30% of current peak

peak

Table II - Obtained results

	Solution
$V$	1082 V
$C_s$	6.04 $\mu$ F
$R_{s1}$	25.1 $\Omega$
$R_m$	0.94 $\Omega$
$L_{rs}$	10.4 $\mu$ H
$R_{s2}$	19.8 $\Omega$

## IV. SIMULATION RESULTS

To validate, the process used to obtain the equations and the respective sizing presented in the previous chapters, the circuit simulation was performed using MATLAB/Simulink and LTSpice software.

### A) MATLAB/Simulink Simulation

MATLAB was used to perform the simulation of the developed mathematical model. By constructing a vector of time values, it is possible to feed the mathematical functions corresponding to the equations describing the open circuit voltage waveform (Fig. 6) and the short circuit current waveform (Fig. 7).

The open-circuit voltage and short-circuit waveforms simulated in Matlab are shown in Fig. 6 and Fig. 7, respectively.

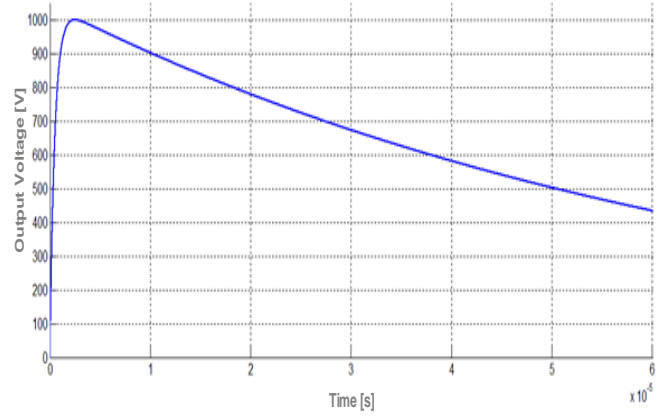


Fig. 6. Mathematical Simulation: waveform of open-circuit voltage (1.2/50  $\mu$ s) at the output of the generator

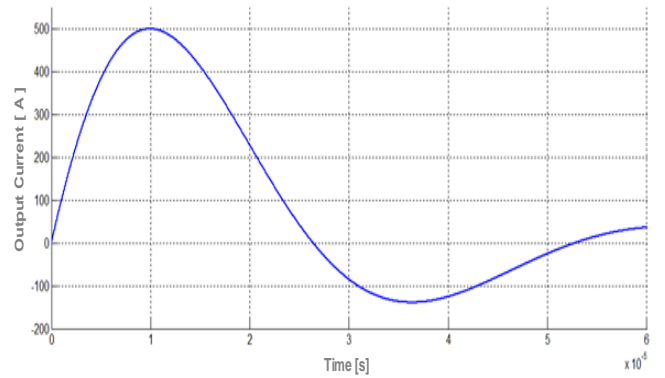


Fig. 7. Mathematical Simulation: waveform of short-circuit current (8/20  $\mu$ s) at the output of the generator

Table III compares the obtained simulation results with the requirements defined in [5].

Table III – Simulation vs standard

	IEC 61000-4-5	Simulation Results	Comply ?
Open Circuit			
Voltage peak [kV]	1 ± 10 %	1	YES
Front Time [μs]	1.2 ± 30 %	1.47	
Time to half- value [μs]	50 ± 20 %	50.35	
Short-Circuit			
Current peak [A]	500 ± 10 %	499.76	YES
Front Time [μs]	8 ± 20 %	7.68	
Time to half- value [μs]	20 ± 20 %	19.46	
Undershoot Máx. Current peak [%]	máx. 30 % Ipeak	-138.95	

The simulation results from the described model with MATLAB software shows that the requirements defined in [5], are fulfilled.

### B) LTSpice Simulation

The tool used to carry out the simulation was the LTSpice, a software made available free by the semiconductor manufacturer Linear Technology.

Likewise, simulation in MATLAB, it was considered an ideal controlled switching device. For the SPICE simulation it is necessary to define the basic characteristics differing from zero. Meaning, a short-circuited must be different than zero and an open circuit one must be different that infinity. Therefore, short-circuits have a resistance of 1 m $\Omega$ , and an open circuit 1 M $\Omega$ .

The open-circuit voltage and short-circuit current waveforms simulated in LTSpice are shown in Fig. 8 and Fig. 9, respectively.

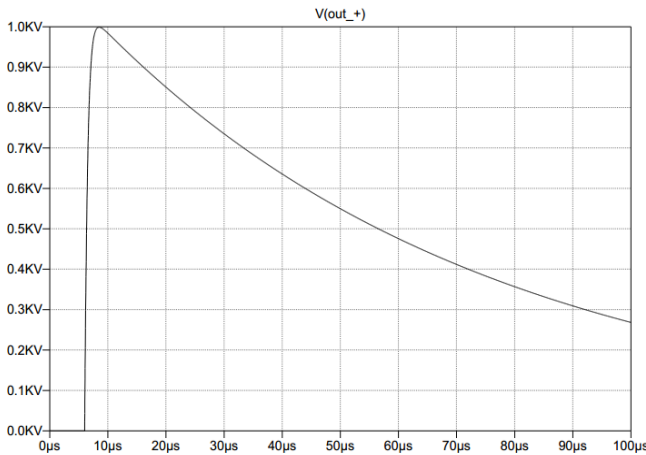


Fig. 8. Spice simulation: waveform of open-circuit voltage (1.2/50  $\mu$ s) at the output of the generator

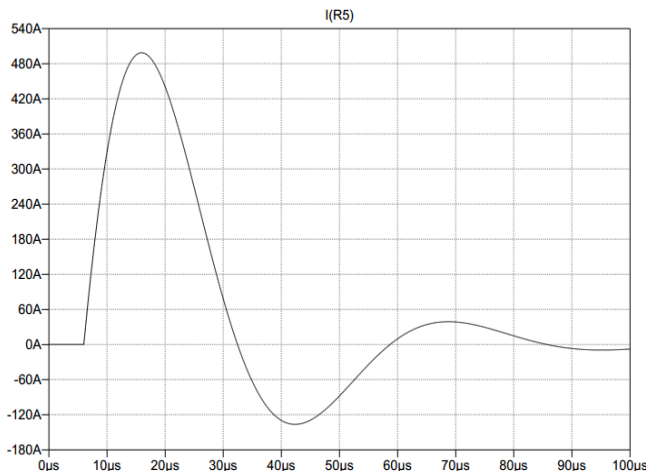


Fig. 9. Spice simulation: waveform of short-circuit current (8/20  $\mu$ s) at the output of the generator

Table IV illustrates the comparison between the requirements from [5] and the simulation results obtained through LTSpice software.

Table IV – Matlab vs LTSpice simulations

	IEC 61000-4-5	Matlab Sim. Results	LTSpice Sim. Results	Difference between Simulations
<b>Open Circuit</b>				
<b>Voltage peak [V]</b>	1000 $\pm$ 10 %	1000	998.9	-0.11 %
<b>Front Time [<math>\mu</math>s]</b>	1.2 $\pm$ 30 %	1.47	1.48	0.68 %
<b>Time to half-value [<math>\mu</math>s]</b>	50 $\pm$ 20 %	50.35	50.58	0.46 %
<b>Short-Circuit</b>				
<b>Current peak [A]</b>	500 $\pm$ 10 %	499.76	498.70	-0.21 %
<b>Front Time [<math>\mu</math>s]</b>	8 $\pm$ 20 %	7.68	7.71	0.39 %
<b>Time to half-value [<math>\mu</math>s]</b>	20 $\pm$ 20 %	19.46	19.47	0.05 %
<b>Undershoot Máx.Current peak [%]</b>	máx. 30 % Ipeak	-138.95	-136.46	1.82 %

The simulation results obtained from LTSpice confirms the veracity of simulations results obtained from the mathematical model for the output voltage of the generator in an open circuit domain output and current of the generator in a short circuit domain. The difference between them was below 1%, except for the value of the undershoot current where the difference reaches 1.82%. However, it is considered acceptable since the difference remains well below the tolerances allowed by the standard [5].

## V. EXPERIMENTAL RESULTS

Here it is detailed the experimental procedures of implementing the surge generator defined by [5] and presented in Fig. 1.

### A) Directives Selection of Components for Generator

To assembly the circuit of the Fig. 1 it was necessary to establish guidelines to choose components to minimize differences between the simulation models and the experiment itself. In doing so, the waveform of the current and voltage will resemble the one defined in [5] and the components used will withstand the power, voltage and current of the experiment.

Power Semiconductor :

- Has to withstand the charging voltage of the power supply capacitors.
- The rise time of semiconductor should be in ns order.
- Should withstand the peak current and respective power dissipation while under short-circuit operating mode.
- The voltage loss of the component should be as low as possible for every operating mode.

Capacity:

- The capacitor or battery should withstand the charging voltage, taking into consideration a safety margin.
- The Equivalent Series Resistance (ESR) should be as low as possible, to minimize power leakage.

Resistors:

- Resistors should not be coiled to avoid undesirable induction values and able to withstand the changes in current from the commutation circuit.
- The resistors should be power resistors to withstand the Joule losses.

Inductors:

- Should withstand the maximum current applied to it and should not alter the waveform.

### B) Experimental Implementation

Fig. 10 shows the simplified block diagram of a surge generator system. In it, it's possible to observe the blocks that need galvanic insulation to separate the control domain from the high-voltage domain.

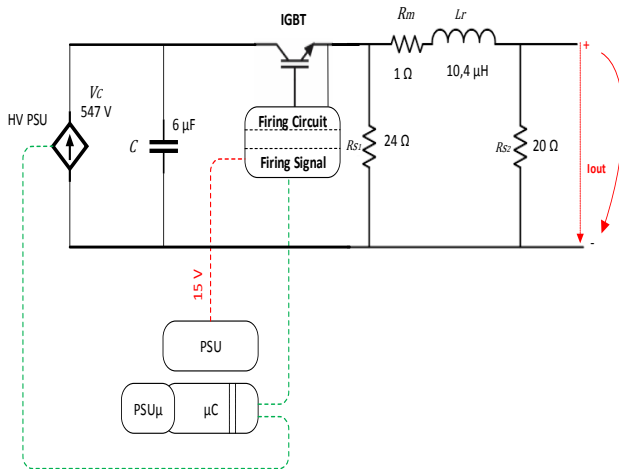


Fig. 10. Simplified circuit block diagram of experimental implementation

The waveform generating circuit is composed of four additional blocks. The first block is a current controlled power supply with the goal of charging the capacitors of the circuits. The second block is the power semiconductor device, which requires its own power supply block with is the third block. Lastly, the control block represented as  $\mu C$ , which has galvanic isolation to prevent from transient current.

### C) Experimental Results

Due to physical limitations of the components, it was only possible to test the surge generator at 500 V, defined as level 1 in [5]. Therefore, the input voltage VC was configured to reach the peak voltage of 500 V, corresponding to a level 1 test in [5]. The experimental results of open-circuit voltage and short-circuit current waveforms were obtained and are shown in Fig. 11 and Fig. 12, respectively.

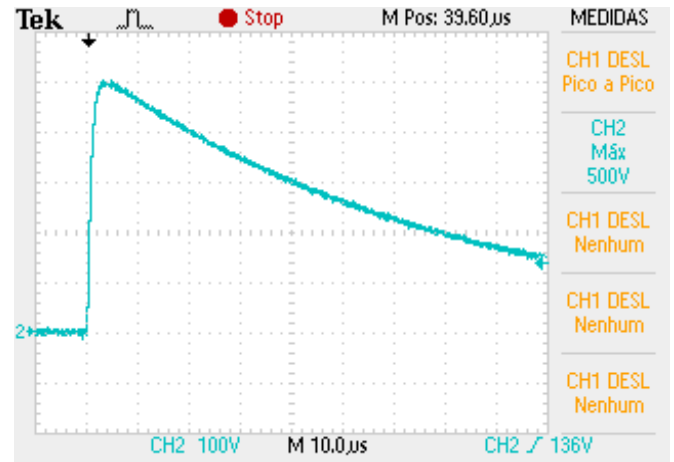


Fig. 11. Experimental result in open-circuit: waveform of open-circuit voltage (1.2/50  $\mu s$ ) at the output of the generator

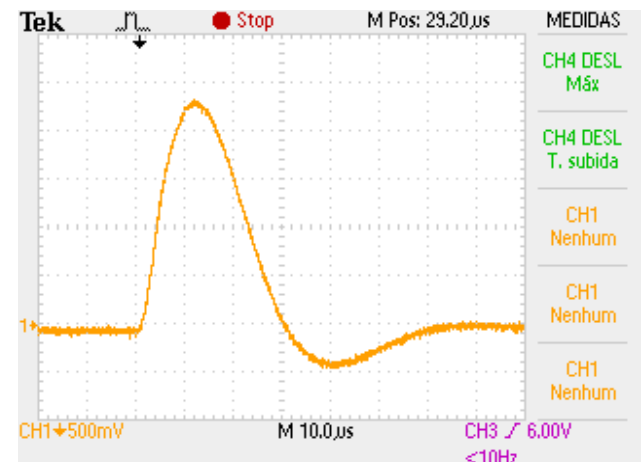


Fig. 12. Experimental result in short-circuit: waveform of short-circuit current (8/20  $\mu s$ ) at the output of the generator

The experimental results show that the waveforms obtained experimentally correspond to the waveforms defined in the standard IEC 61000-4-5.

Table V compares the results of the experiment with the requirements defined in [5].

Table V – Standard vs experimental results

	IEC 61000-4-5	Experimental Results	Comply ?
Open Circuit			
Voltage peak [V]	500 ± 10 %	500	YES
Front Time [μs]	1.2 ± 30 %	1.54	
Time to half- value [μs]	50 ± 20 %	52	
Short-Circuit			
Current peak [A]	250 ± 10 %	242	YES
Front Time [μs]	8 ± 20 %	9.22	
Time to half- value [μs]	20 ± 20 %	22	
Undershoot Máx. Current peak [%]	máx. 30 % Ipeak	-41	

From Table V analyses, the requirements defined for the waveforms are met by the implemented generator.

## VI. CONCLUSIONS

A surge generator that meets the desirable requirements for the waveforms was implemented.

A theoretical model of the Surge generator of the Fig. 1 was developed and simulated in MATLAB/Simulink and LTSpice software respectively. The simulations results obtained from both software's are in accordance with the requirements defined in [5], revealing the veracity of the developed model. Also, the circuit of Fig. 1 was assembled, and experimental results was obtained to a voltage level 1, as defined in [5]. The experimental results show that all the requirements defined in [5] were met, thus validating the methodologies adopted for developing a surge generator represented in Fig. 1.

## VII. REFERENCES

- [1] T. Williams, Chapter 45 - EMC, Editor(s): Walt Boyes, Instrumentation Reference Book (Fourth Edition), Butterworth-Heinemann, 2010, Pages 797-871, ISBN 9780750683081, <https://doi.org/10.1016/B978-0-7506-8308-1.00045-0>.
- [2] S. Keitoue, I. Murat, B. Filipović-Grčić, A. Župan, I. Damjanović i I. Pavić, "Lightning caused overvoltages on power transformers recorded by on-line transient overvoltage monitoring system", Journal of Energy, vol.67, br. 2, str. 0-0, 2018. [Online]. Dostupno na: <https://hrcak.srce.hr/213483>. [Citirano: 27.12.2020.]
- [3] Othman, N. S., et al, "An Overview on Overvoltage Phenomena in Power Systems", in Materials Science and Engineering Conference Series, 2019, vol. 557, no. 1, p. 12013. doi:10.1088/1757-899X/557/1/012013.
- [4] S.R. Murty, Chapter 11 - Overvoltages, Editor(s): P.S.R. Murty, Electrical Power Systems, Butterworth-Heinemann, 2017, Pages 229-257, ISBN 9780081011249, <https://doi.org/10.1016/B978-0-08-101124-9.00011-5>.
- [5] IEC 61000-4-5:2005, Electromagnetic compatibility (EMC) – Part 4-5: Testing and measurement techniques – Surge immunity test.
- [6] S. B. Smith and R. B. Standler, "The effects of surges on electronic appliances," in IEEE Transactions on Power Delivery, vol. 7, no. 3, pp. 1275-1282, July 1992, doi: 10.1109/61.141841.
- [7] IEC 61000-4-5:2005, Electromagnetic compatibility (EMC) – Part 4-5: Testing and measurement techniques – Surge immunity test.
- [8] S. B. Smith and R. B. Standler, "The effects of surges on electronic appliances," in IEEE Transactions on Power Delivery, vol. 7, no. 3, pp. 1275-1282, July 1992, doi: 10.1109/61.141841.