VOLTAGE IMPULSE GENERATOR USING BOOST CONVERTER ARRAY APPLIED IN ELECTRICAL GROUNDING SYSTEMS

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***Abstract* –This paper describes a voltage impulse generator, which is utilized in the commissioning of an electrical grounding system. Unlike the Marx generator with spark gap switches, this converter uses semiconductor devices, which have a long life, better efficiency, and it can operate at high frequencies. The generator's topology uses a boost converter array operating in Discontinuous Conduction Mode (DCM). Therefore, it is responsible to inject an impulse voltage signal similar to a lightning stroke into the installed grounding system. Furthermore, one acquisition subsystem is responsible to acquire the response signals (voltage and current) at a high sample rate, and a developed software extracts the features from the transient signals. In this work, four grounding system configurations which are widely used by electricity companies are exploited, and the results are discussed.**

***Keywords* –Boost converter array, Grounding system, Voltage impulse generator.**

I. INTRODUCTION

The Grounding System (GS) is a common term for the connection of one equipment and electrical facilities to earth. The lightning stroke is the most common causes of transients in power systems. Due to its large territory, Brazil has been one of the hardest hit in the world with about 60 million lightning per year. Therefore, the correct design of a GS are of vital importance for the safety and protection of personnel, equipments and facilities, as well to the correct operation of the electricity supply network, etc. The selection of correct configuration, i.e. number and disposition of rods, for the GS is dependent upon several factors, which includes the soil resistivity, the available area to install the GS, the season, weather characteristics of the region, the demands of the project, etc [1].

In some Brazilian utilities a single rod (2.4m long and with 0.0150m diameter) is frequently applied throughout medium-voltage lines at the service entrances of low-voltage consumers, and to provide periodical grounding points. In other cases, as in pole-mounted distribution transformers protected by surge arresters, the typical grounding configurations applied are three parallel rods in straight line (2.4m long with 0.0150m diameter), spaced in intervals of 3m. In most cases, the installation of such medium voltage lines and the corresponding GS is made by third party companies and the verification of GS is done visually, which in most cases is inefficient due to the fact that the GS is covered or cemented. Once the configuration of the GS to be installed is defined, its installation should be properly implemented. However, in some cases, this does not happen, mainly because of errors during the project execution, such as installing an incorrect number of rods (usually less than specified) and/or by forgetting to properly connecting the rods. This situation has a small probability to happen, but for a large amount of installations its effect can be very significant, since in some situations it can be the cause of interruptions in electrical distribution, damage electrical equipments, etc. The problem of incorrectly installing the GS can be minimized by visually inspecting the GS after its installation. However, there is the possibility that the GS have already been covered or cemented, thereby hindering a visual inspection of the installed system. Under this kind of situation, it would be beneficial to have a method, independent of visual inspection and easy to mount, to check whether the configuration of GS is arranged properly or not. To tackle this problem, a new method for inspecting GS was developed, such method requires a portable voltage impulse generator device, which can inject an impulse voltage signal similar to a lightning stroke, enabling the acquisition of the transitory of the GS responses (current and voltage)[2]. The transitory contains the RLC characteristic of the ground-rod set [3]. The widely used and researched way to obtain an impulsive wave form is the Marx generator with spark switches [4]-[6]. However the development of power electronics, the voltage impulse generator can be built with semiconductor devices. This manuscript presents a boost converter array operation in DCM, which uses the GS as load. Furthermore, the GS is tested with four GS configurations (one, two, three, four parallel rods).

II. SYSTEM DESCRIPTION AND PRINCIPLE OF OPERATION

In this work, the high voltage impulse is obtained without high voltage transformer and a high voltage dc source, as shown in Figure 1.

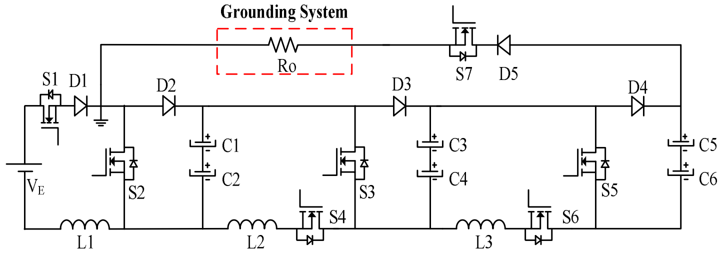

Fig.1. Voltage impulse generator using boost converter array.

The depicted circuit operates at high frequency with high reliability and has a longer life in comparison with the Marx generator. This topology allows the voltage control through three stages to obtain the required voltage output [5]-[7]. In others applications, it might be necessary to use a much larger number of semiconductor switches.

A. Circuit Configuration

It is important to highlight that the high-output voltage value applied to the load is only possible due to the sum of the voltages across each capacitor C_n, i.e. each capacitor is subjected to its rated voltage without compromising its life time. Since the duty cycle of the converter is very small, the converter works in discontinuous conduction mode (DCM). The voltage across each capacitor is given by

$$V_{C_{n,n+1}} = V_E.\left(1+\frac{t_c}{t_o}\right)^n. \tag{1}$$

Where:

$V_{Cn,n+1}$ - Capacitor voltage ($n \geq 1$)
V_E - Input voltage
t_c - Pulse width
t_o - Inductor discharge time

Since the parameters t_c e t_o(1) are not normally specified during the design. It can be replaced by [5]-[6]:

$$V_{C_{n,n+1}} = V_{C_{n-2,n-1}}.\left(1+\frac{\mathrm{D}^2.V_{C_{n-2,n-1}}}{2.f.L_n.I_{T\_av}}\right). \tag{2}$$

Where:

$V_{Cn-2,n-1}$- Capacitor Voltage between(n-2)th and (n-1)th
L_n - Inductance
I_{T_av} - Load average current
f - Switching frequency
D - Duty cycle

B. Operation Stages and Waveforms

The converter operates in four operation stages. The four operation stages are described below and shown in Figure 2:

- Stage 1: The switches S_1 – S_6 are closed and the inductors L_1, L_2 and $L_3$are magnetized. The current in the L_1, L_2 and L_3 increases linearly during this step. At this mode, the diodes D_2, D_3 and D_4 are in reverse biased condition.

- Stage 2: The switches S_2, S_3 and S_5 are open and the inductors L_1, L_2 and L_3 start to transfer energy to the capacitors C_1-C_6, respectively. At this mode, the diodes D_1–D_4 are in forward biased condition.

- Stage 3: the all switches S_1– S_7 stay opened and the diodes D_1– D_5 are turn off. In this step, the capacitors C_1– C_6 are loaded.

- Stage 4: the switches S_2, S_3, S_5 and S_7 stay closed while the switches S_1, S_4 and S_6 stay opened. This arrangement turns the fully charged capacitors C_1-C_6 in series with the load. Therefore, the capacitors voltage are added applying a voltage impulse to a load. This converter is a suitable and reliable way to generate a voltage impulse.

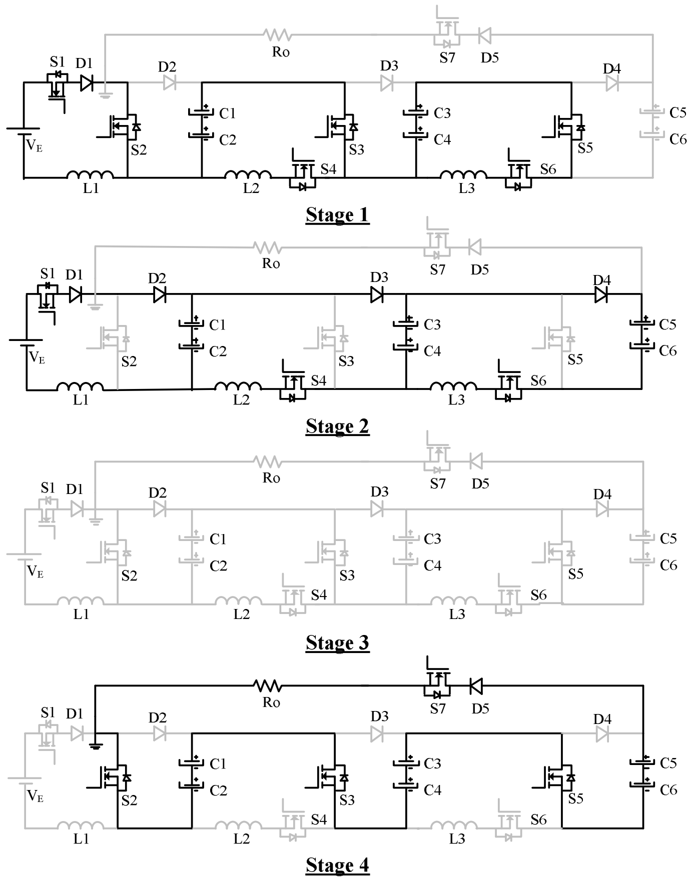

Fig.2. Voltage impulse generator operation stages.

The main theoretical waveforms of the converter are shown in Figure 3. In order, to verify the proposed circuit, the GS was considered as a pure resistance in all simulations, as shown in Figure1.

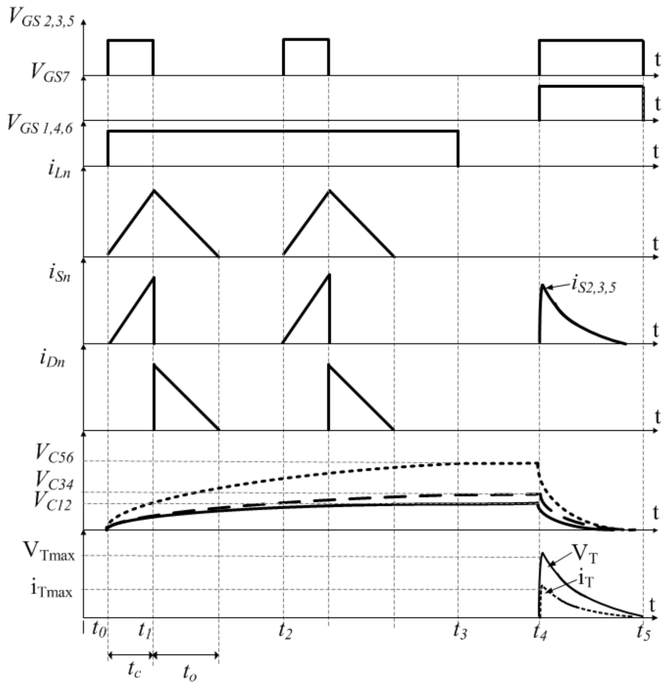

Fig.3. Main theoretical converter waveform.

C. Design of the Proposed Circuit

As the converter operates in DCM, the duty cycle is very small, thus the voltage drop across the capacitor should be considered [5]-[7]. The determined duty cycle has a value of 0.08.

$$\Delta V_n = \frac{V_T.t_c}{C_n.R_o} \quad (3)$$

Where:

ΔV_n - Voltage variation at the n^{th} capacitor
V_T - Voltage across the Load (GS)
C_n - Capacitance of the n^{th} capacitor
R_o - Ground resistance

The inductance can be found through expression given by [5]-[6]

$$L_n < \frac{V_{c_{n,n+1}}.D^2}{2.f.I_{Ln\_av}.(1+D)} \quad (4)$$

The determined inductance for the prototype has 200µH. The proposed converter has as input DC voltage value of V_E = 155V and its voltage peak output is around 800 to 1000V, depending upon the GS resistance value. The peak voltage pulse applied to the GS is determined as follows:

$$V_T = \sum_{i=1}^{n} V_{ci} \quad (5)$$

Where:

V_{ci} - Voltage at the i^{th} capacitor.

The semiconductor switch used in this prototype is the MOSFET model SPT4N150 from ST Microelectronics that supports a drain – source breakdown voltage up to 1500V. Furthermore, optocouplers HCPL3120 are used to protect the switch.

Ultra-fast recovery diodes were used. The chosen diode has a reverse recovery time of 75 *ns* and a maximum repetitive peak reverse voltage of 1000 V.

One PIC microcontroller model 16F877A from Microchip is used to generate the duty cycle and set the switches in each mode.

According to the requirements of operating voltage, frequency, six capacitors of 330µF/450V were used. Each boost capacitor has two capacitors in series with a total capacitance of 165µF, which allows a voltage up to 900V. In the fourth stage where C_1-C_6 are connected in series, the total capacitance will be 55µF.

III. EXPERIMENTAL METHODOLOGY

The soils measurements were carried out at the test field during the dry period/season with ground rods with 2,4m length. In this paper, two signals are acquired as responses. The first one is the voltage signal, $v_r(t)$, and second one is the current signal, $i_r(t)$, responses. These signals are collected by two auxiliary electrodes, in straight line, placed from distances d_v and d_i from the GS under test. The Figure 4 shows the structure of the proposed system.

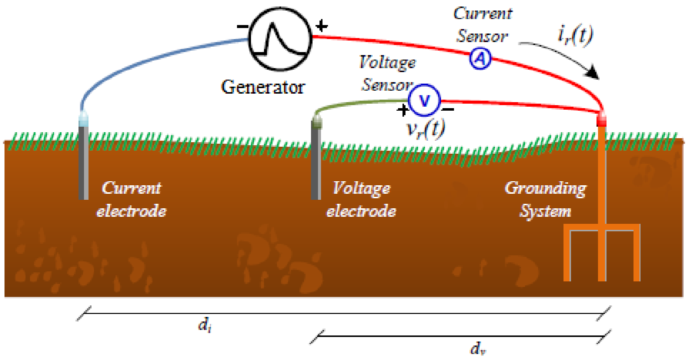

Fig.4. Architecture of the proposed excitation system.

The structure of the proposed system is based on the 3-point method fall of potential test for measuring the resistivity of the soil, but differently of this methodology the value of d_v is kept fixed in all experiments. The 3-point method fall of potential method is used to measure the ability of an earth ground system or an individual electrode to dissipate energy from a site. In this method the generator outputs are connected to the two separate electrodes driven in earth. These two electrodes are kept in same line generally at distance of 25 meters and 50 meters due to which there will not be mutual interference in the field of individual spikes [9].

In this paper, the distances d_v and d_i were defined as d_v = 12.5m and d_i = 20m. The current and voltage electrodes were disposed in straight line in all experiments. These distances were defined empirically. However, others can use different values for these distances, under the constraint that it should keep it fixed for all experiments.

The transient response, which is assumed to contain the information necessary to discriminate different grounding configurations, is in the order of micro seconds (µs). To allow the acquisition of the transient signal, this work acquires the data with a sample rate of 2MSa/s, by using the data acquisition system U2531A from Agilent. This sample rate is enough to capture data samples in the order of micro seconds. The voltage and current values were acquired using two Hall Effect transducers from LEM.

IV. EXPERIMENTAL RESULTS

In order to evaluate the designed impulse generator, a set of four experiments were conducted. In all tests, the configuration with one, two, three and four ground rods in straight line were mounted. All the ground rods have 2.4m length with 0.0150m diameter, and for the configurations with two, three and four ground rods, the rods were spaced in intervals of 3m. For each test the voltage between the voltage electrode and the GS was measured.

As shown in Figure 5, the peak voltage is 282V and the peak current is 1.54A. As shown in Figure 6, for two ground rods, the voltage waveform has a peak voltage of 182V and peak current of 1.8A. As shown in Figure 7, using three ground rods the voltage waveform has a peak of 130V peak current of 1.9A. Finally, the last configuration of four rods had a voltage peak of 98V and current peak of 2A, as shown in Figure 8. According to the Figures 5 – 8, the peak voltage decreases proportionally with the number of ground rods. Since, a larger number of parallel rods installed in the ground reduce the ground resistance. Therefore, the peak voltage is reduced in so far, the number of ground rods is increased [9]. Figure 9 show the GS and the driven electrodes during one experimental test.

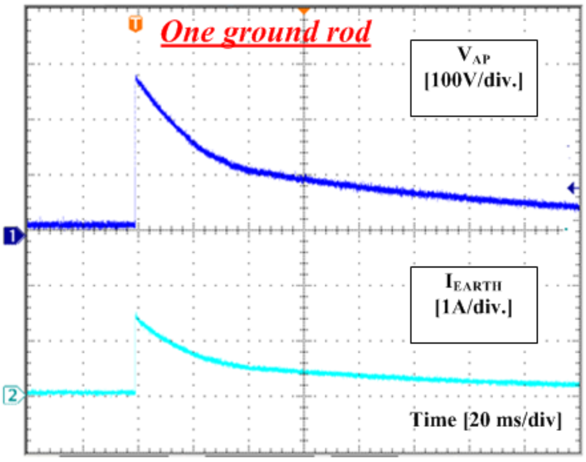

Fig.5. Voltage and current measurements for one straight line ground rod configuration.

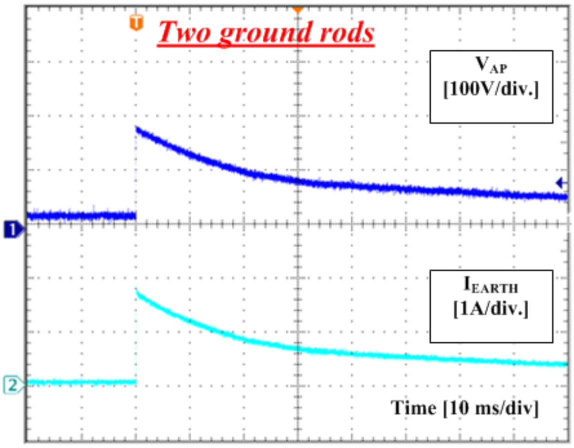

Fig.6. Voltage and current measurements for two straight line ground rod configuration.

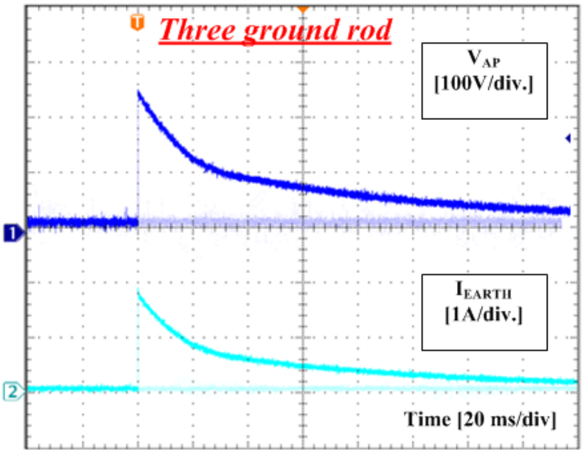

Fig.7. Voltage and current measurements for three straight line ground rod configuration.

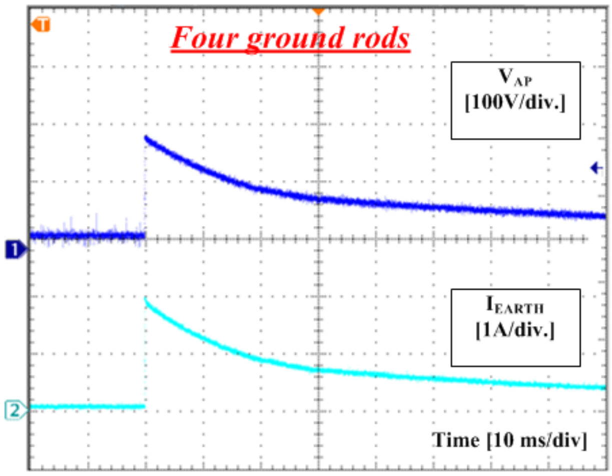

Fig.8. Voltage and current measurements for four straight line ground rod configuration.

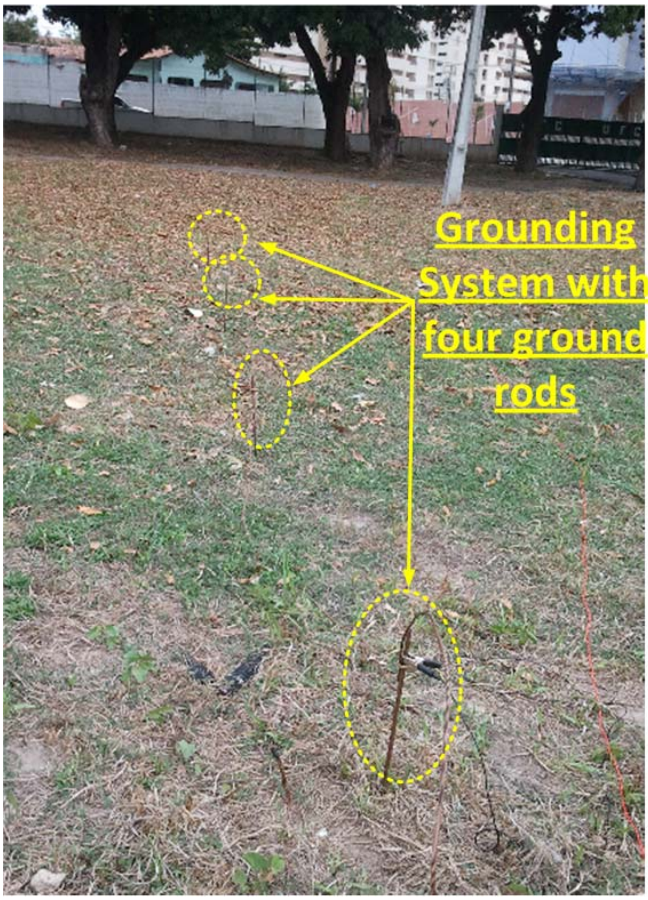

Fig.9. Experimental test for the four straight line ground rod configuration.

V. CONCLUSIONS

The impulse generator can be used to several applications in the industry, medicine, environment and agriculture according to reference [5]. In this work, it was presented the characteristics of a voltage impulse generator applied in GS. The impulse generator is a boost converter array operating in DCM. Such generator has some advantages in comparison with the Marx generator with spark gap switches, i.e. as the use of semiconductor devices which have: low voltage drop when conducting, long life, high efficiency, high operating frequency and low voltage drive control. The voltage impulse generator is responsible for the excitation of the GS, so that it can be properly evaluated. The data acquisition system captures the waveforms through the current and voltage sensors and sends it to the developed software, which saves the data during the tests. The peak value, rising and falling time are related with changes in GS parameters i.e. size of the rods, spacing, diameter. Thus, applying Fast Fourier Transform (FFT) in the transient response of the GS, the intelligent algorithm, which uses a machine learning based model is able to provide the characteristics of the GS with a great margin of reliability. Moreover, the developed impulse generator can be controlled to apply different values and standard of voltage and frequency for GS and also for others patterns of waveforms voltage, in order to investigate other types of parameters identification methods.

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