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One-port nonlinear electric circuit for simulating grounding systems under impulse current

Ruy Alberto Corrêa Altafim [a], Luiz Gonçalves Jr. [b], Ruy Alberto Pisani Altafim [c,*], Renato Crivellari Creppe [b], Alexandre Piantini [d]

[a] Electrical Engineering Department, Engineering School of São Carlos, University of São Paulo, São Carlos, SP, Brazil
[b] Electrical Engineering Department, State University of São Paulo Júlio de Mesquita Filho, Bauru, SP, Brazil
[c] Computer Systems Department, Informatics Center, Federal University of Paraíba, João Pessoa, PB, Brazil
[d] Institute of Energy and Environment, University of São Paulo, São Paulo, SP, Brazil

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ABSTRACT

A one-port nonlinear electric circuit to simulate grounding systems behaviors under high impulse currents is presented. The circuit is based on Loboda's and Pochanke's equations, which describe nonlinear behaviors of soil ionization phenomena. One of the major features of this nonlinear circuit is the possibility to simulate both ionization regions (linear and nonlinear) as a complete grounding system, in commercial simulation software such as Pspice, WorkBench®, ATP or EMTP. In order to determine the linear and nonlinear circuit parameters, two known impulse current curves $i(t)$ were applied on scale models and the corresponding impulse voltages $U(t)$ were measured. From these circuit parameters, the $U(t) \times i(t)$ experimental curves were compared with one-port simulated results and the similarities, evaluated using the Area Under Curve (AUC) method, varied in the range 92–99%. In order to compare simulations with experimental data, a field circuit was elaborated to test three experimental scale models using single rods of different lengths.

1. Introduction

The protection of electrical power equipment is strongly related to grounding systems, therefore understanding their behavior under different electrical stimulations is fundamental for the proper design and evaluation of these systems.

The resistance of grounding systems submitted to industrial power frequency currents are linear, well-known and can be predicted by equations and mathematical models obtained from measurements of the soil resistivity. However, when these systems are subjected to impulse currents they can also present transient nonlinear behaviors, which are more complex.

The study of the transient behavior of grounding systems dates back to 1929, when Towne described it for the first time subjecting a grounding system to lightning strikes [1]. Since then researchers have proposed different methods to simulate the nonlinear behavior of grounding systems subject to impulse currents. In 1934, a systematic experimental and theoretical investigation into this transient phenomenon was conducted by Bewley as part of his research on lightning protection in power systems [2]. After Bewley's experiments, many other models were proposed to simulate nonlinear grounding phenomena, mainly based on the assumption that the nonlinear behavior of the impedance of an electrode is due to an ionization zone that appears surrounding the electrode when the soil critical breakdown electric field strength is exceeded [3–6].

In 1981, Kosztaluk and others developed a model to simulate ionization-grounding zones by studying the transient behavior of ground impedances with surge arrester varistor blocks [7]. Later in 1984, Velazquez and Mukhedkar investigated the same behavior under high impulse currents by means of an equivalent circuit model for long ground electrode, considering the non-linear and linear behavior of soil. This equivalent circuit based on the concept of telegraphy line was solved with a specific computational algorithm [8].

Later in 1985, Loboda and Pochanke [9,10] investigated the transient analysis of grounding systems by determining surge characteristics of grounding under non-uniform electric fields. From this, a set of equations to evaluate the transient impulse impedance, the voltage and the current distributions in any part of a single or complex grounding electrode was developed. Afterwards, they performed a numerical approximation on the experimental data and calculated some electrical parameters [11], which were in 1992,

* Corresponding author. Tel.: +55 83999272909.
E-mail address: altafim@gmail.com (R.A. Pisani Altafim).

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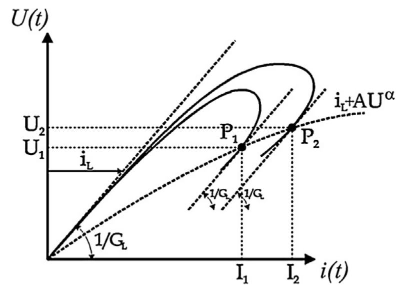

Fig. 1. Illustration of the voltage nonlinear behavior of a grounding system for two different impulse currents obtained from experimental results.

used to simulate the Electromagnetic Transient Problem (EMTP) for different soil conditions in a simulation software such as Alternative Transient Program (ATP) [12]. Other methodologies employed on determination of soil ionization can be found in the review presented in [13].

In 1990, Altafim et al. developed a one-port electric circuit for investigating earthing electrodes associations under impulse currents [14]. This circuit implemented only considering simulations of the nonlinear behavior of grounding systems could be implemented in electric circuit simulation software such as, Pspice and WorkBench®, which are easy and reliable tool for solving complex electric circuits.

In the present work the circuit developed by Altafim et al. was extended to simulate both linear and nonlinear behaviors as in a complete grounding system. A detailed mathematical description of the circuit demonstrating its similarity with Loboda and Pochanke equations is presented followed by experimental tests in scale models and simulations with the one-port nonlinear circuit.

2. One-port nonlinear equivalent circuit model

The present one-port nonlinear circuit was developed based on experimental data obtained from field tests elaborated with single rod scale models. From these tests, the corresponding $U(t) \times i(t)$ curves, where *U(t)* is the measured impulse voltage and *i(t)* is the applied impulse current, were obtained. These curves, presented in Fig. 1 are well described by the Loboda and Pochanke equations (1) and (2) [9], and provide the necessary parameters to represent the nonlinear behavior of a grounding system subjected to an impulse current.

$$i(t) = G_L \cdot U(t) + i_N(t) \tag{1}$$

$$\frac{di_N(t)}{dt} = \frac{1}{T}[A \cdot U(t)^\alpha - i_N(t)] \tag{2}$$

In Eqs. (1) and (2), *i(t)* is the total current over time, G_L, the conductance, $i_N(t)$, the current in the nonlinear region and the parameters *A*, *T*, and *α* depend on the analyzed grounding system and soil conditions.

These equations can be expressed by two dependent current sources, one dependent of *U(t)* and the other of $i_N(t)$, one inductor, and three resistances, as illustrated in Fig. 2, which shows the proposed one-port equivalent circuit model.

In order to demonstrate the one-port circuit equivalence to (1) and (2), Kirchhoff's laws were applied leading to (3)–(7) as follows:

$$i(t) = i_L(t) + i_N(t) \tag{3}$$

$$i_L(t) = G_L \cdot U(t) \tag{4}$$

or

$$L_N \frac{di_N(t)}{dt} = R_{N0} \cdot i_0(t) - R_N \cdot i_N(t) \tag{5}$$

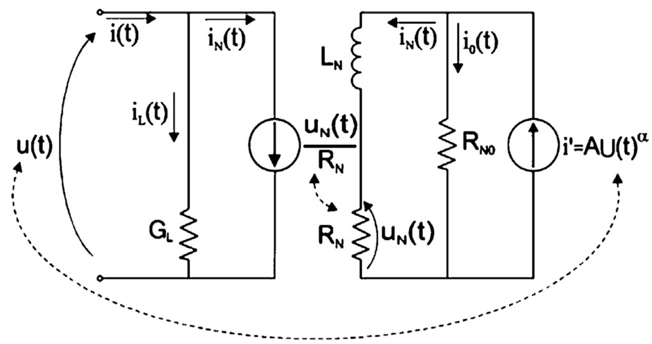

Fig. 2. Schematic representation of the one-port equivalent electric circuit model developed to simulate Loboda and Pochanke equations.

$$i_0(t) = A \cdot U(t)^\alpha - i_N(t) \tag{6}$$

where $i_L(t)$ is the current in the linear region and R_{N0} and R_N are resistances, and L_N is an inductance.

From a direct comparison between (5) and (6) and (1) and (2), only a close similarity is observed. However, if R_{N0} is much larger than R_N and $i_0(t)$ from (6) is replaced in (5), then:

$$\frac{di_N(t)}{dt} = \frac{R_{N0}}{L_N}[A \cdot U(t)^\alpha - i_N(t)] \tag{7}$$

And if one considers $1/T$ equal to R_{N0}/L_N and replace (4) into (3), the Eqs. (3) and (7) become identical to Lododa and Pochanke equations Eqs. (1) and (2), respectively.

2.1. Circuit parameters

The one-port equivalent circuit parameters and constants were obtained as described:

2.1.1. Conductance G_L

The conductance G_L, which corresponds to the linear region of the grounding system represented in (8), was determined by replacing (4) in (3) and differentiating (3) in relation to the current *i(t)* at $t = 0$.

$$G_L = \frac{1}{\left.\frac{dU(t)}{di}\right|_{t=0}} \tag{8}$$

To obtain the conductance G_L from the experimental curves $U(t) \times i(t)$, the mean value of derivatives for three points closed to $t = 0$ was determined for each of the two curves, avoiding unstable value.

2.1.2. Constants α and A

The nonlinear voltage behavior of a grounding system is presented in Fig. 1 for two different impulse currents. At the points P_1 and P_2 the derivative of *U(t)* with respect to *i(t)* is equal to $1/G_L$ *i.e.* $(dU(t)/di(t)) = 1/G_L$, and the currents *i(t)* at these points are equal to $AU(t)^\alpha + G_L U(t)$. Thus, from P_1 and P_2 coordinates, *i.e.* (I_1, U_1) and (I_2, U_2), expressed in (9), the constants *α* and *A* can be determined from (10) and (11), respectively.

$$\left(\frac{U_1}{U_2}\right)^\alpha = \frac{I_1 - G_L \cdot U_1}{I_2 - G_L \cdot U_2} \tag{9}$$

$$\alpha = \frac{\ln\left(I_1 - G_L \cdot U_1)/(I_2 - G_L \cdot U_2)\right)}{\ln\left((U_1)/(U_2)\right)} \tag{10}$$

$$A = \frac{I_1 - G_L \cdot U_1}{U_1^\alpha} \tag{11}$$