Journal of Electrostatics 72 (2014) 372–380

Contents lists available at ScienceDirect

Journal of Electrostatics

journal homepage: www.elsevier.com/locate/elstat

Impulse coefficient for square grounding grids in low resistivity soils: Influence of injection electrode

Rodrigo M.S. de Oliveira [a,*], Jonathas F.M. Modesto [a], Marcos Rodrigo V. Maia [a], Daiyuki Maia Fujiyoshi [a], Adroaldo Raizer [b]

[a] *Electrical and Computer Engineering Post-Graduation Course (PPGEE), Institute of Technology (ITEC), Federal University of Para (UFPA), Belem 66075-110, Para, Brazil*
[b] *Federal University of Santa Catarina (UFSC), Brazil*

ARTICLE INFO

Article history:
Received 31 December 2013
Received in revised form
29 May 2014
Accepted 27 June 2014
Available online 11 July 2014

Keywords:
Electromagnetic analysis
Grounding grids
Impulse coefficient
Injection electrode
Lightning
Low resistivity ground

ABSTRACT

Impulse coefficient is calculated, for the first time, by considering the response of the current injection electrode connected to ground grids for lightning subsequent return strokes. It is observed that the impulse coefficient can be substantially amplified specially for low resistivity soils (e.g. forest grounds) and the enlargement is a function of the length of the injection electrode. Several rigorous finite-difference time-domain (FDTD)-based simulations have been performed and a new semi-empirical formula for impulse coefficient, which takes into account the injection electrode's length, is provided. The proposed expression is verified experimentally.

1. Introduction

Evaluation of grounding systems must take into account their transient performance when lightning surges are considered [1–10]. When discharge pulses with small zero-to-peak time are injected into grounding systems, transient current flows, during the initial fractions of the first microsecond, over a small region around the injection point of the structure due to the finite propagation velocity of the electromagnetic field, as illustrated by Fig. 1 (notice the progressive spatial expansion of the wavefront over time).

A way to quantify difficulty imposed to transient currents to flow into ground through a grounding system, in relation to the resistance R imposed to DC currents, is the evaluation of the impulse coefficient A, given by Ref. [1]

$$A = \frac{Z}{R}, \tag{1}$$

in which

$$Z = \frac{V_m}{I_m}, \tag{2}$$

where Z is the impulse impedance, V_m is the maximum voltage measured at the injection point (in volts) in relation to remote ground and I_m is the peak of the injected current [1], given in amperes. For classical square grounding grids, R can be calculated in ohms by Ref. [11]

$$R = \frac{\rho\sqrt{\pi}}{4a}, \tag{3}$$

where a is the square grid-side length in meters and ρ is the ground resistivity (Ω m).

In applications such as grounding of substation equipment or lightning arresters, as illustrated by Fig. 2(a) and (b), respectively, it

* Corresponding author.
E-mail addresses: rdglinux@yahoo.com.br, rdglinux@gmail.com, rmso@ufpa.br (R.M.S. de Oliveira), jonathas.modesto@itec.ufpa.br (J.F.M. Modesto), marcos.maia@itec.ufpa.br (M.R.V. Maia), d.maiafujiyoshi@gmail.com (D.M. Fujiyoshi), adroaldo.raizer@gmail.com (A. Raizer).

http://dx.doi.org/10.1016/j.elstat.2014.06.010
0304-3886/

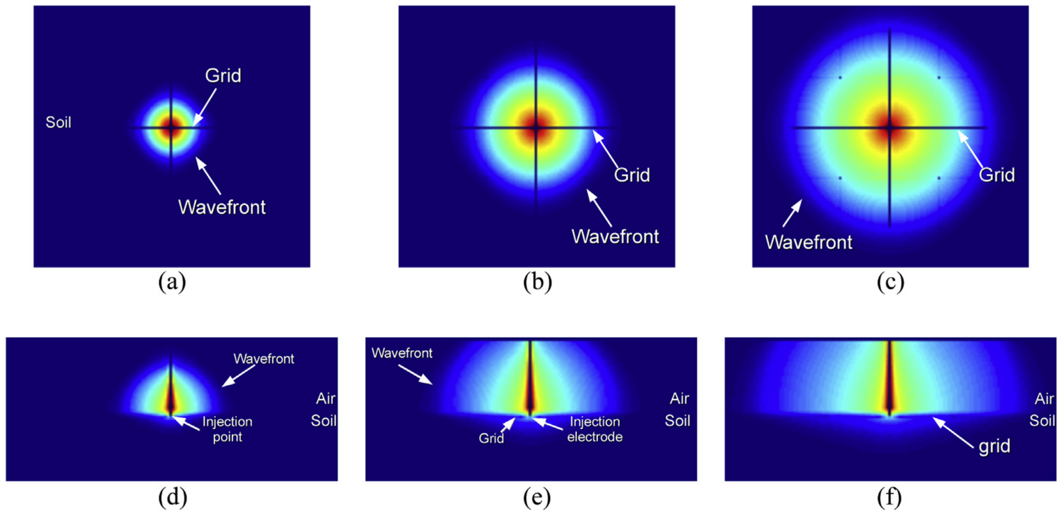

Fig. 1. Temporal evolution of wave propagation due lightning current on the grids' plane, obtained via FDTD simulation, at (a) $t = 0.0126$ µs, (b) $t = 0.0252$ µs and (c) $t = 0.0381$ µs and on vertical plane at (d) $t = 0.0126$ µs, (e) $t = 0.0252$ µs and (f) $t = 0.0126$ µs.

is usual to employ connecting wires and injection electrodes (the buried part of the injection wire) between the hardware to be grounded and the grounding grid itself. The injected current I_g (Fig. 2) is conducted by the injection electrode to the grounding grid, as illustrated by Fig. 1(d) to (f). This means that, at the injection point P (Fig. 2), it is "seen" the impedance of the association of injection electrode, grounding grid and soil. Furthermore, during the initial fractions of a microsecond, in which current flows only over the injection electrode, the instantaneous relation voltage/current is dependent only on soil parameters and on the electrode, affecting, this way, A. Notice that high values of ground conductivity produce high reflection coefficients on air-soil interface. This effect, of central importance, increments the impulse coefficient A.

In previous works [1,12], grounding grids were analyzed in such way that the current injection cable has not been considered for determining A (the current source was placed on the grid itself). In this case, A can be calculated by the empirical equation

$$A = \frac{a}{a_{\text{eff}}} = \frac{a}{\exp\left[0.84(\rho T_1)^{0.22}\right]}, \quad \left(a \geq a_{\text{eff}}\right) \tag{4}$$

which was obtained from simulation results produced via the Method of Moments (MoM) by Ref. [12]. In (4), T_1 is the lightning current zero-to-peak time, given in microseconds and a_{eff} is the grid's effective area [1]. However, if $a < a_{\text{eff}}$, then $A = 1$. For subsequent return strokes, $T_1 = 0.8$ µs as defined by CIGRÉ in Ref. [13].

In this context, the influence of the current injection electrode is taken into account in this work and substantial percentage increases of impulse coefficient A are observed specially for low resistivity soils (in the range 10–1000 Ω m). In particular, the importance of investigating the behavior of A in such high conductivity soils lays on the fact that there are large cities surrounded by forest environments (such as authors'). In addition, forest soils, rarely studied from electrical point of view, present typically resistivities in the range 40–1000 Ω m, as demonstrated by the experiments conducted in Refs. [14,15].

For performing simulations, the finite-difference time-domain method (FDTD) [16,17], is used. Results solidly agree with (4) for grids with no injection electrode. Several FDTD simulations have been performed with the injection structure and a new semi-empirical formula (including length of the injection electrode h) is provided for calculating A.

2. Methodology and the numerical solver

Maxwell's equations

$$\nabla \times \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t} \tag{5}$$

and

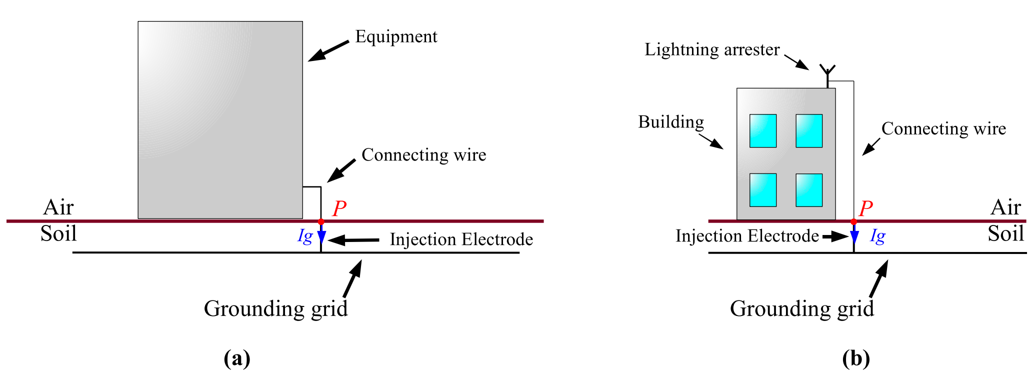

Fig. 2. Injection Electrode: (a) equipment grounding and (b) grounded lightning arrester.