Electric Power Systems Research 113 (2014) 180–187

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Comparison of equivalent circuit models for the simulation of soil ionization

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ARTICLE INFO

Article history:
Received 31 August 2013
Received in revised form 10 February 2014
Accepted 27 February 2014
Available online 23 March 2014

Keywords:
Transient response
Soil ionization
Equivalent circuit
Simulation

ABSTRACT

The main characteristic of the transient behaviour of a grounding system is the decrease of the grounding impedance, due to soil ionization phenomena that take place, when the density of the injected current exceeds a critical value. In this paper three circuit models proposed by researchers have been implemented using the ATP/EMTP programme in order to simulate the transient response of a grounding system taking soil ionization into account. The simulation results are compared to measurements received by imposing impulse voltages on soil samples. The accuracy of each model is evaluated according to the level of proximity to the oscillograms and conclusions are drawn about the effectiveness of each modelling approach.

1. Ionization circuit models

The transient behaviour of a grounding system has been a subject of investigation for many decades since it differs from the steady state behaviour due to ionization phenomena that take place when the density of the injected current exceeds a critical value. As a result a decrease of the soil resistivity and consequently of the grounding impedance is observed. Various equivalent circuits have been proposed by researchers in an attempt to explain this phenomenon.

Measurements with high impulse voltages applied by Nor et al. [1] on soil samples yielded current waveforms with two peak values. This led to the formation of an equivalent circuit that consists of two parallel branches representing the pre-ionization and post-ionization stages, respectively, as shown in Fig. 1 [1]. The pre-ionization resistance R_1 expresses the conduction behaviour related to the thermal effects and their interaction with the properties and structure of the soil. The post-ionization resistance R_2 accounts for the final state of conduction after the ionization procedure has reached its full extent of expansion and is therefore always lower than the pre-ionization resistance R_1. The resistance values R_1 and R_2 are calculated using the two peak currents and their corresponding instantaneous voltages as in Eqs. (1) and (2). The inductance element L introduces the required time delay for the expansion of the ionization zone.

$$R_1 = \frac{V_{\mathrm{Ipeak1}}}{I_{\mathrm{peak1}}} \tag{1}$$

$$R_2 = \frac{V_{\mathrm{Ipeak2}}}{I_{\mathrm{peak2}}} \tag{2}$$

Based on experimental I–V curves Kalat, Loboda et al. proposed the dynamic sand surge conduction model depicted in Fig. 2 [2]. The soil conductance for small current values is taken into account by the linear elements g_{LDC} and g_{LAC}. The looped shape of the curve is interpreted by a non-linear conductance g_N which is described by the steady state characteristic (3) and the differential equation (4).

$$i_{No} = Au^a \tag{3}$$

$$\frac{di_N}{dt} = \frac{1}{T}[i_{No}(u) - i_N] \tag{4}$$

The model is completed by the following equations:

$$ug_{\mathrm{LDC}} + i_C + i_N = i(t) \tag{5}$$

$$Ri_C + \frac{1}{C}\int i_C\,dt = u \tag{6}$$

Liew and Darveniza [3] attributed the dynamic response of a grounding electrode to the time variation of soil resistivity in the ionization region. According to their model the area around the electrode can be divided into three regions with resistivity value

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http://dx.doi.org/10.1016/j.epsr.2014.02.024

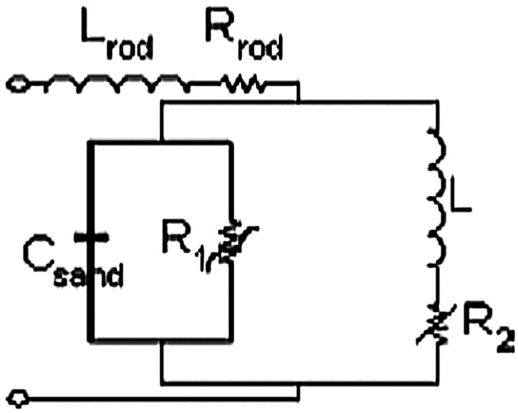

Fig. 1. The ionization circuit proposed by Nor et al. [1].

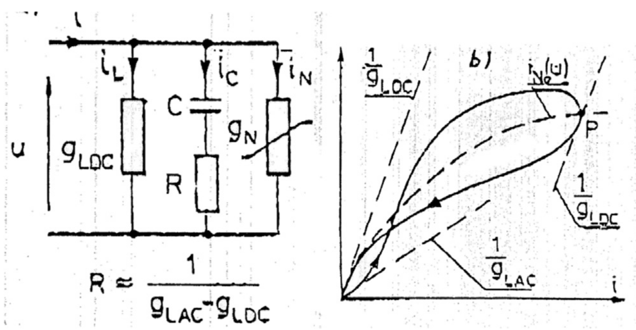

Fig. 2. The surge conduction model proposed by Kalat, Loboda et al. for sand soil sample [2].

controlled by the current density: the region where the ionization has started to evolve (Region 1), the resistivity decreases, the region where the soil de-ionizes and the resistivity recovers (Region 2) and the region where soil ionization does not occur and the resistivity remains steady (Region 3). Each region comprises shells that have different current density; therefore, calculations for each shell should be performed in order to calculate the overall resistance. Nixon proposed a simplification of this model [4] by treating the ionization and the de-ionization regions as a complete unit with resistivity value defined using the current density at the outer border of these regions as shown in Fig. 3:

$$\text{Region 1}: \quad \rho_i = \rho_{\text{soil}} \exp \frac{-t_i}{\tau_i} \quad \text{for} \quad J \geq J_c \text{ and } r \leq r_i \tag{7}$$

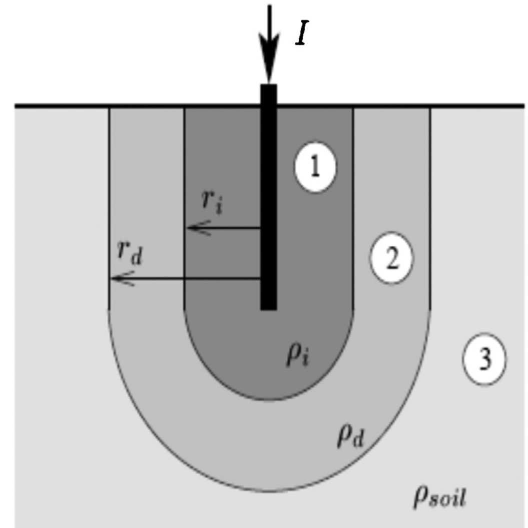

Fig. 3. The ionization circuit proposed by Nixon [4].

$$\text{Region 2}: \quad \rho_{dn} = \rho_m + (\rho_{\text{soil}} - \rho_m)\left(1 - \exp \frac{-t_d}{\tau_d}\right)\left(1 - \frac{J}{J_c}\right)^2$$
$$\text{for} \quad J < J_c \quad \text{and} \quad r_i < r \leq r_d \tag{8}$$

$$\text{Region 3}: \quad \rho = \rho_{\text{soil}} \quad \text{for} \quad J < J_c \text{ and } r > r_d \tag{9}$$

where ρ_{soil} soil resistivity (Ω m), J current density (A/m) at a radial distance r (m).

$$J_c = \frac{E_0}{\rho_{\text{soil}}} \quad \text{the critical ionization current density} \tag{10}$$

E_0 (V/m) the ionization gradient, τ_i ionization time constant (s), t_i time since the onset of ionization (s), τ_d de-ionization time constant (s), t_d time since the onset of de-ionization (s), r_i ionization radius (m), r_d de-ionization radius (m).

2. Experimental setup

Along with the simulations, series of measurements were carried out by applying on soil samples 1.2/50 μs positive impulse voltages produced by the impulse voltage generator presented in Fig. 4 [5,6]. The impulse voltage generator is supplied by a variac and a transformer with ratio 220 V/200 kV. The fluctuation of the

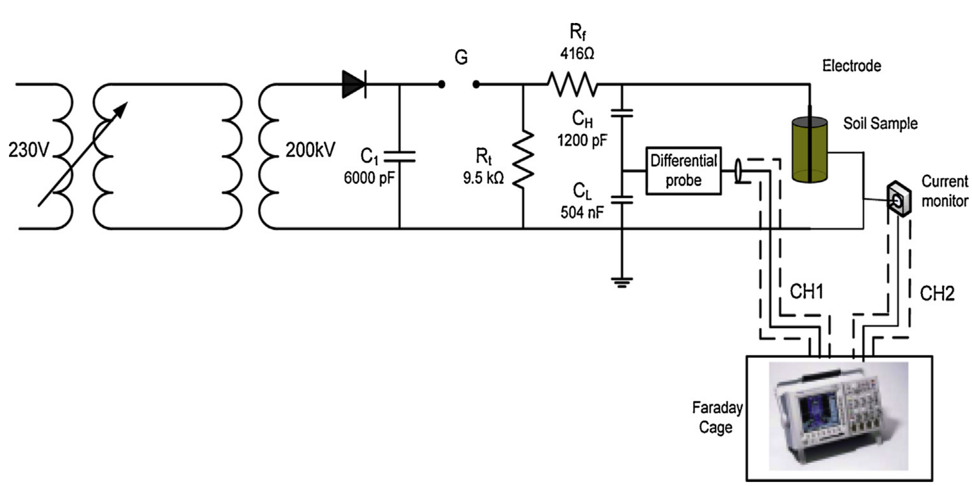

Fig. 4. Experimental setup [5,6].