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# Practical model for tower earthing systems in lightning simulations

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ABSTRACT

In assessing the lightning performance of a transmission line with an Electromagnetic Transient (EMT) approach, the representation of the earthing system or tower footing can have a major impact on the simulation results. In this paper, a practical circuit for a direct implementation into an EMT software is presented, which uses a minimum of input parameters to represent a common four rod tower footing arrangement. Based on an available description of the frequency-dependency of a single rod in soil and a description of the ionization in soil for a single rod, a combined circuit model is developed for a tower earthing arrangement with four rods in a square arrangement. This approach takes into account the merging of the ionization zones from each rod.



## 1. Introduction

In the majority of performed studies to determine the lightning performance of a transmission line, a simple resistance model or variable resistance model is used [1–4]. This originates from the fact that in practice transmission codes state tower footing requirements (combined soil and electrode) as a resistance at power frequencies. Using formulas, such as from Ref. [5], the combined resistance of a tower earthing system and soil resistivity taken from measurements can be calculated. In the assessment of the lightning performance of a transmission line with an EMT approach this type of modelling leads to conservative results due to the underestimation of the real performance of the earthing system [6].

However, several studies show that the frequency-dependency of soil has a major influence on the back-flashover rate of insulators and therefore should be included in lightning simulations [7,8]. Furthermore, several studies show that the lightning performance of a tower is also very sensitive to the soil ionization process [9,10]. Therefore these effects should also be included in simulations of lightning strikes to transmission lines. To simulate the behaviour of an earthing system subject to lightning impulses, models available in the literature are either based on electromagnetic field theory (EMF) [11–15], such as finite element methods (FEM) and Method of Moments (MoM), transmission line (TL) [16] or circuit theory [17]. Although EMF-based methods are the most accurate, computation time and complexity hinders the fast and simple simulation of a whole transmission line [18], but they are often used to verify circuit approaches or derive parameters for circuit elements, such as the pi-circuit based on EMF simulation results fitting in Ref. [19]. All these modelling approaches, lack the ease of a direct utilization in EMT simulations with a few input parameters.

In this paper, a practical model for tower foundations using so-called mini-piles is investigated, which are commonly employed in dense or rocky soil. This arrangement can be modelled with a four-rod in a square arrangement which features a high resistivity of the surrounding soil. Due to the general complexity of models, the soil ionization and frequency-dependent soil phenomena are separated in most simulation models and represented as a variable resistance or voltage/current source [20,21]. In this paper both a frequency-dependent soil model and a single rod model available in the literature are combined, adapted and extended to model the four rod in a square arrangement. Since more than one rod is considered, a mathematical description of both the dynamic mutual coupling as well as the dynamic merging of the ionization zones of the rods is proposed which uses only geometry parameters and low-frequency soil resistivity. Furthermore the model is verified with measurement results available in the literature.

## 2. Ionization models

Although sole ionization models based on R-L-C circuits, such as in Ref. [22] feature a closer fit to some measurements, the overall performance differs only slightly from variable resistance models [23]. Therefore only variable resistance models for rods compatible to be included into circuits for frequency-dependency are considered. For a later comparison of the developed model in this paper, the similarity approach and CIGRE ionization model are taken as references.

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### 2.1. Similarity approach ionization model

A basic variable resistance model for a single rod, mentioned in Ref. [24], is based on Korsuncev similarity method with the dimensionless factors $\Pi$ in Eqs. (1) and (2). There, $s$ is the distance between the center and the outermost point of the metallic structure in m, $R_0$ is the footing resistance in $\Omega$, $\rho$ is the soil resistivity in $\Omega$m, $I$ is the instantaneous current in kA and $E_c$ is the breakdown electric field strength in kV/m. It is shown that a rod shaped electrode can be modelled as a hemispherical electrode shape with reasonable accuracy in (3), where $A$ is the electrode surface area in $m^2$.

$$\Pi_1 = \frac{sR_0}{\rho} \tag{1}$$

$$\Pi_2 = \frac{\rho I}{E_c s^2} \tag{2}$$

$$\Pi_1^0 = 0.4517 + \frac{1}{2\pi} ln\left(\frac{s^2}{A}\right) \tag{3}$$

Furthermore, above a critical distance, the ionized zone can be simplified with a sphere electrode shape, where the correlation between $\Pi_1$ and $\Pi_2$ in the range of 0.3–10 for $\Pi_2$ in Eq. (4) can be applied.

$$\Pi_1 = 0.2631 \cdot \Pi_2^{-0.3082} \tag{4}$$

The resistive behaviour is now established with Eqs. (1) and (3) until $\Pi_1$ in Eq. (4) is greater than $\Pi_1^0$ in Eq. (3), which is the criterion for the start of the ionization process. For a four rod arrangement, the total resistance is calculated with equations provided in the Appendix of Ref. [25] and apply Eqs. (1) and (3). The resulting variable footing resistance $R_F$ as well as the derived critical current $I_C$ where ionization starts, depend on a previously calculated total footing resistance $R_0$, in Eqs. (5) and (6).

$$R_F = 0.2631 \frac{\rho}{s}\left(\frac{\rho I}{E_c l^2}\right)^{-0.3082} \tag{5}$$

$$I_C = \frac{E_c s^2}{\rho}\left(\frac{\Pi_1}{0.2631}\right)^{\frac{1}{-0.3082}} \tag{6}$$

### 2.2. CIGRE ionization model

Another variable resistance model, such as proposed by Weck and adopted by CIGRE [26], takes into account the soil ionization effect in Eqs. (7) and (8).

$$R_F = \frac{R_0}{\sqrt{1 + \frac{I}{I_c}}} \tag{7}$$

$$I_c = \frac{E_c \rho}{2\pi {R_0}^2} \tag{8}$$

The model is developed for earthing rods and not meant to be for extensive earthing networks of more than 30 m [27], such as counterpoise. The footing resistance can be calculated with formulas, such as in Ref. [28].

The determination of a generalized approach for the breakdown electric field strength remains difficult. In Ref. [29], various measurements are summarized and re-evaluated, which leads to a resistivity-dependent breakdown electric field strength ranging from 400 kV/m for 10 $\Omega$m to 1750 kV/m for 10,000 $\Omega$m. For Eq. (2) an average of 1000 kV/m or the resistivity-dependent breakdown electric field strength from Ref. [29] is proposed. In Ref. [30] an investigation into previous experiments reported breakdown electric field strength is performed, which concludes to apply a value in the range of 300 kV/m–400 kV/m. Other researchers [31,32] confirm a value in the range of 300 kV/m–400 kV/m, which is also the recommendation by CIGRE [27].

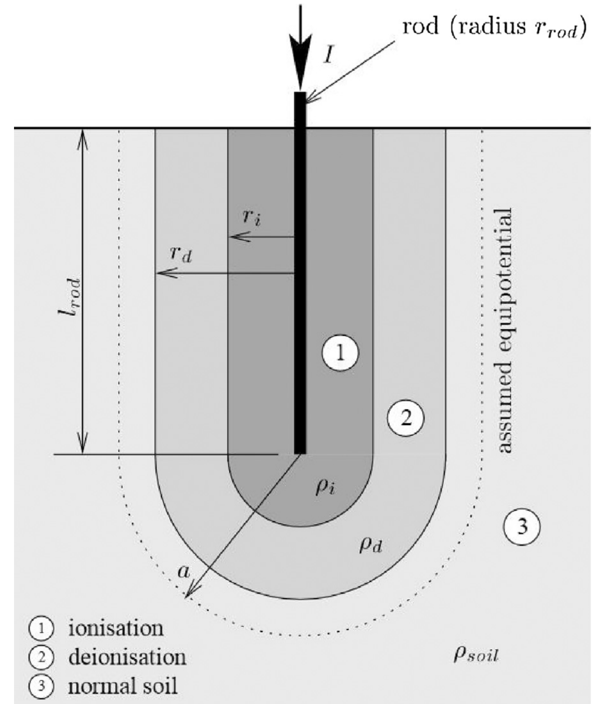


**Fig. 1.** Illustration of ionization and de-ionization zones of a rod electrode [37].

### 2.3. Shell single rod ionization model

A more elaborate soil ionization model for rods is based on the simplified physical description of the formation of the ionization zone in the form of conductive shells around the rod, as illustrated in Fig. 1, originally published by Liew and Darveniza [25] and later adapted and simplified by Nixon et al. [33] or changed to purely be based on physical constants by Cooray et al. [34].

As illustrated in Fig. 1, the ionization process starts at the rods surface, where the current density is the highest and streamers propagate in the direction away from the electrode until the electric field strength drops below the breakdown value [30]. The ionized zones in soil around the electrode increase the electrodes radius [27] and decrease the grounding system's resistance [28,35]. For high soil resistivity the ionization process is more pronounced than for low soil resistivity [36]. In contrast to the sole current-dependent ionization models in Sections 2.1 and 2.2, this model features an additional time- or waveshape-dependency.

The mathematical description of a shell around the rod with radius $a$ in m in Eq. (9) together with the various soil resistivities of each region, ionized, de-ionized and normal soil, enables the calculation of the total variable resistance.

$$dR = \frac{\rho}{2\pi l_{rod}}\left(\frac{1}{r_{rod}} - \frac{1}{a + l_{rod}}\right) da \tag{9}$$

As summarized in Refs. [25,33] the following assumptions are made for the model:

- The soil surrounding the driven rod is homogeneous and isotropic with resistivity $\rho_{soil}$.
- An injected impulse current $I$ in kA, results in equipotential surfaces that can be approximated by a cylindrical and hemispherical portion, as shown in Fig. 1.