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HIGH-FREQUENCY PERFORMANCE OF GROUND RODS IN HIGHLY RESISTIVE SOIL

Leonid Grcev
Faculty of Electrical Engineering, St. Cyril and Methodius University, Skopje, Macedonia

Abstract - Some of the design requirements for power transmission line grounding in highly resistive soil to reduce lightning flashback rate are often contradictory, such as: low values of both low-frequency ground resistance and high-frequency (HF) ground impedance. Former requires larger dimensions of the grounding electrodes that lead to higher values of their HF impedance due to inductive effects. Paper investigates dominant parameters that govern HF behavior of long ground rods in highly resistive soil, and proposes arrangements of grounding electrodes for better HF performance. Comparison between field measurements and rigorous and simplified theoretical results is also presented.

1 - INTRODUCTION

One of the factors that strongly influence the power transmission lines lightning back flashover rate is the magnitude of the tower grounding surge impedance. To reduce the probability of the back flashover, the surge ground potential rise has to be minimized. Therefore, usually there is a requirement that the ground resistance of the tower grounding is limited to some low value, for example, to 10 Ω at the Electricité de France (EDF) [1]. However, high-frequency (HF) ground impedance also has to be kept at low values.

Ground rods are often used for transmission line grounding. They are usually not much longer than few meters and are considered as concentrated grounds. They are consequently modeled with frequency independent ground resistance. However, to achieve ground resistance of about 10 Ω in highly resistive soil (ρ > 300 Ω·m), very long ground rods are often used. For example, 30-meter long vertical rods are used by the EDF [1]. In such cases their HF ground impedance may be much greater than resistance due to the inductive effects and consequently their HF performance much worsen.

The primary motivation of the analysis in this paper was an investigation of effective means to improve HF performance of long ground rods. The purpose of the study in this paper was twofold:

- to identify dominant parameters that govern the HF performance of long ground rods, and
- to investigate arrangements of ground electrodes that enable better HF performance.

The paper first presents comparison of the experimental results by EDF with recently developed rigorous methods for analysis of HF behavior of grounding systems [3]–[6]. These methods are based on formulations derived from the full set of the Maxwell's equations, and reader is referred to [5] for full details on the model and its validation by comparison with field measurement and with other authors' models. This choice has been made since the simplified methods are based on quasi-static approximation and their validity may be limited to some lower frequency range that depends on the size of the grounding system and the electrical characteristics of the soil [2]. The paper also includes comparison between computations based on simple formulas and rigorous methods.

2 - ANALYSIS OF THE FREQUENCY RESPONSE

To compare the HF performance of different grounding systems and analyze the influence of different parameters the following frequency dependent ground impedance may be used [7]:

$$Z(j\omega) = V(j\omega)/1\text{A} \qquad (1)$$

Here $V(j\omega)$ is maximal GPR at feed point, obtained as response to time-harmonic steady-state 1 A current in a frequency range of interest for the transient study. Here also ω is the angular frequency and $j = \sqrt{-1}$. The main advantage of the ground impedance (1) is that it is dependent only on the geometry of the system and the electromagnetic characteristics of the soil and is independent of the excitation.

An inherent part of the above definition (1) is the neglect of the soil breakdown. For large enough currents the electric fields at the ground electrode surface may become greater than the ionization threshold of approximately 300 kV/m [8], and breakdown of the soil may occur. This will decrease the ground impedance of the electrode. The analysis in this paper considers more conservative upper bound of the ground impedance, when breakdown of the soil has not occurred.

3 - COMPARISON BETWEEN COMPUTATIONS AND MEASUREMENTS

Detailed description of recent measurements of frequency dependent and transient impedance of ground rods with different lengths by the EDF may be found in [1]. Here only brief description is included for completeness.

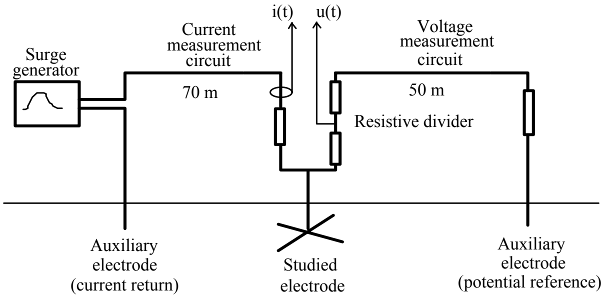

Figure 1. Measuring set-up [1].

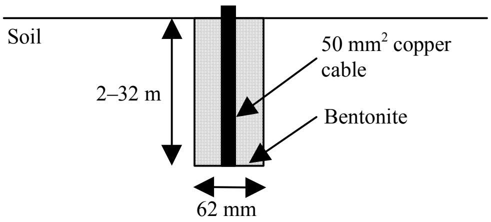

Figure 2. Installation of the measured earth electrode in the ground [1].

Figure 1 provides only a simple illustration of the measuring set-up. The impulse current is obtained by applying a biexponential impulse voltage of the lightning type supplied by an 800 kV impulse generator. A current measuring coil with a bandwidth of 100 MHz was used to measure the current. Resistors to limit the reflection phenomena were used to adapt the transmission lines created by both circuits. The voltage measuring circuit was installed perpendicular to the current injection circuit to avoid inductive coupling between the two circuits. The voltage measurement was performed using a resistive divider with a bandwidth up to 1 MHz and low voltage output of the divider was connected to a digitizer via optical fibers [1]. By this way transient GPR was directly measured, while the frequency dependent impedance $Z(j\omega)$ was deducted using signal processing.

The studied earth electrode was constructed of a 50 mm^2 copper cable inserted in holes 62 mm in diameter filled with a mixture of bentonite and water, Fig. 2. Different lengths of earth electrodes were measured in the range from 2 m to 32 m. The semi-liquid mixture coating of the earth electrodes had a resistivity about 1 Ω·m, while the resistivity of the surrounding soil was measured to 1300 Ω·m. However, the equivalent resistivity of homogeneous soil has been assumed to match the ground resistances of the rods measured at low frequency (120 Hz).

Figures 3 and 4 illustrate computed and measured frequency dependent impedance of ground rods with length 4 m and 16 m, respectively. In the computations the value of the average soil resistivity is assumed to 450 Ω·m and soil relative permittivity is varied for 10, 40 and 80. Computations were made with the rigorous electromagnetic field approach [5]. The results confirm the conclusions in [1] that in poorly conductive soil the impedance of ground rods is purely resistive up to a few tens kiloherz and then is capacitive for rods shorter that about 8 m and inductive for longer rods.

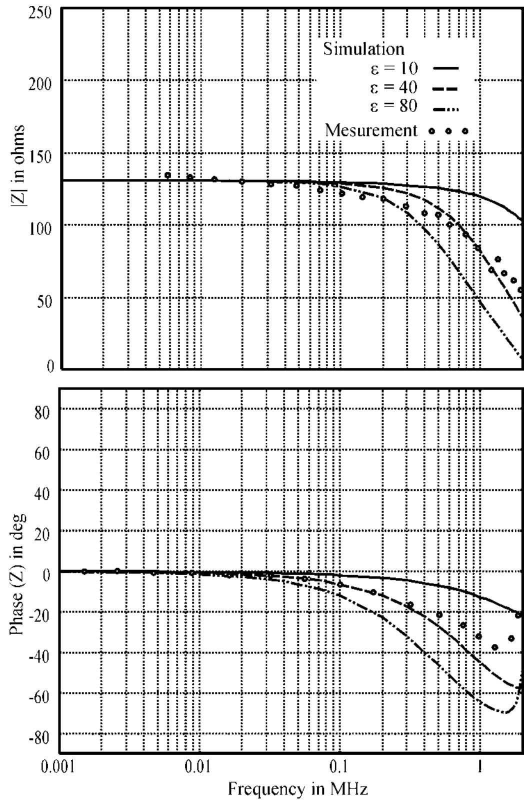

Figure 3. Measurement and simulation of frequency dependent impedance of 4-m rod in soil with ρ = 450 Ω·m.

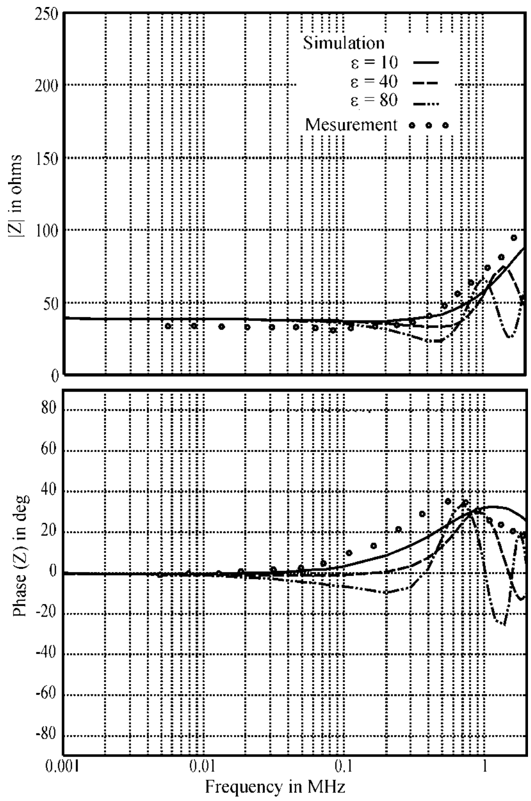

Figure 4. Measurement and simulation of frequency dependent impedance of 16-m rod in soil with ρ = 450 Ω·m.

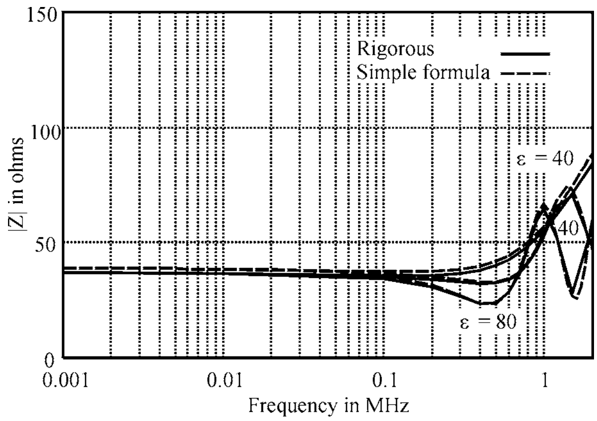

Figure 5. Comparison between rigorous method and simple formulas. Impedance of 16-m rod in soil with ρ = 450 Ω·m.

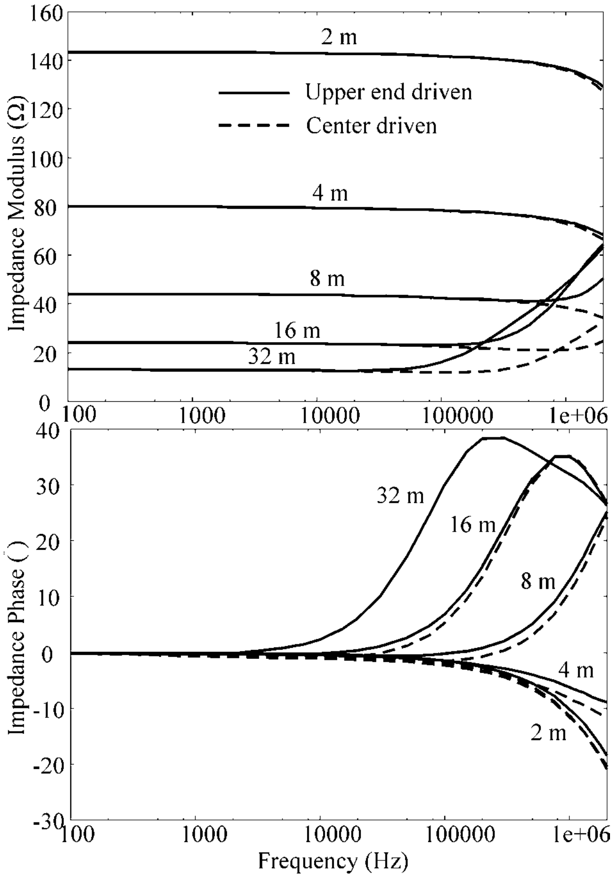

Figure 6. Impedance of ground rods in in soil with ρ = 300 Ω·m.

It can be seen that soil permittivity has significant influence on the ground impedance. Unfortunately, soil permittivity has not been measured. In spite of the differences, it can be concluded that simulations are consistent with measurements.

4 - COMPARISON BETWEEN RIGOROUS AND SIMPLIFIED THEORETICAL METHODS

Simple formulas for the characteristic impedance $\underline{Z}_C$ and the propagation coefficient $\underline{\gamma}$ are [9]:

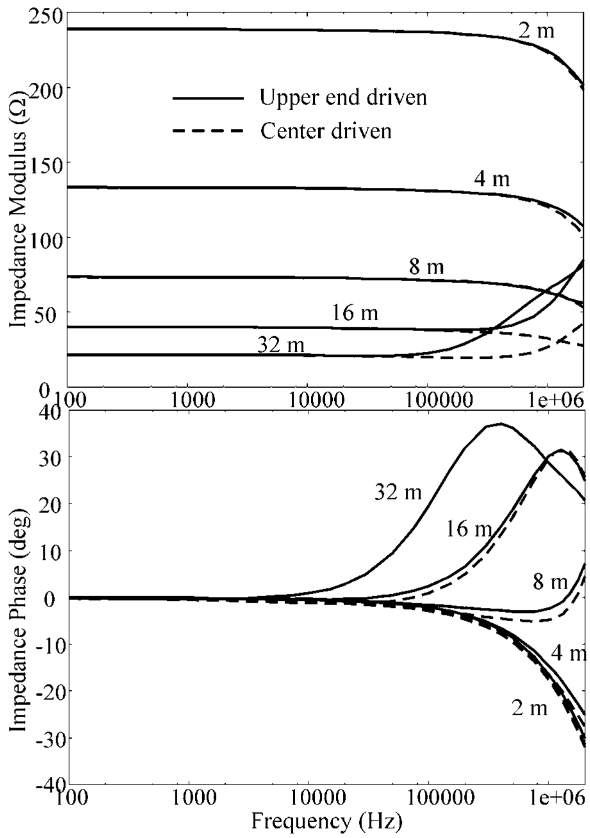

Figure 7. Impedance of ground rods in soil with ρ = 500 Ω·m.

$$\underline{Z}_C = \frac{\rho}{2\pi}\left(\ln\frac{4\ell}{a}-1\right)\sqrt{\frac{j\omega\mu_0}{\rho(1+j\omega\varepsilon\rho)}}$$

$$\underline{\gamma} = \sqrt{j\omega\mu_0(1/\rho + j\omega\varepsilon)} \quad (2)$$

The grounding impedance of the electrode $\underline{Z}$ with length ℓ is obtained by:

$$\underline{Z} = \underline{Z}_C \coth(\underline{\gamma}\ell) \quad (3)$$

Figure 5 illustrates comparison between the simple formulas (3) and (4) and the rigorous approach for the same case as in Fig. 4. The agreement between results is excellent in the observed frequency range. This indicates that simple formulas may be used for computation of HF ground impedance of ground rods in highly resistive soil.

5 - FREQUENCY DEPENDENT IMPEDANCE OF GROUND RODS

Figures 6, 7 and 8 present computations of the frequency dependent impedance of ground rods with length from 2 to 32 meters in soil with resistivity 300, 500 and 1000 Ω·m, and relative permittivity 10. For the current injected in the upper end of the electrodes impedance is denoted with full line in figures.

As it is well known, the impedance is equal to the low-frequency (LF) resistance up to some characteristic frequency. Such characteristic frequencies are in the 10 kHz or 100 kHz range and are smaller for smaller dimensions and better conductive soil. For frequencies larger than such characteristic frequency, impedance is smaller (capacitive behavior) or larger (inductive behavior) than LF resistance, depending on the length of the electrode and soil characteristics. Results in Figs. 6, 7 and 8, enable estimate of a critical length of the ground electrodes, such that larger electrodes exhibit inductive and smaller capacitive behavior, nearly for any value of soil's resistivity of practical interest. Soil's permittivity also may has significant influence on the value of critical lengths, however its value is rarely measured and it is not taken into account in the analysis in this paper.

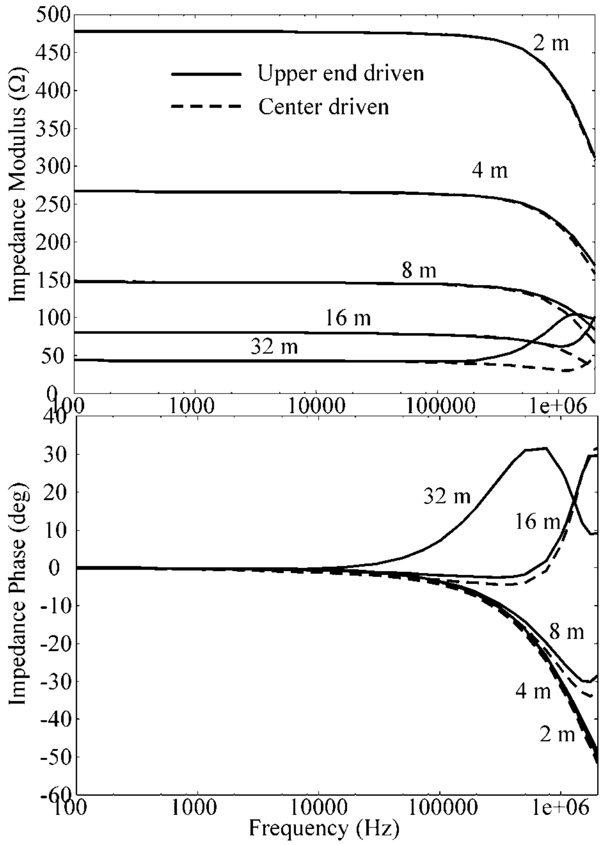

Figure 8. Impedance of ground rods in soil with ρ = 1000 Ω·m.

6 - IMPROVED HF PERFORMANCE OF GROUND RODS

To improve the HF performance, an alternative way of energization of the ground rods to the one in [1] is considered. In [1] only the current injected in the upper end of the electrodes is considered. If insulated down conductor [10] connected to the middle point of the ground electrode, Fig. 9, is used much better HF performance is achieved. Broken lines in Figures 6, 7 and 8, denote the corresponding results. It can be seen that critical lengths are considerably larger (about 2 times larger) than the ones determined for upper end driven rods. Computed critical lengths, which are significantly larger than in [1], are given in Table I.

TABLE I. COMPUTED CRITICAL LENGTHS OF DRIVEN RODS.

Energi-zation	Critical length (m)		
	ρ = 300 Ω·m	ρ = 500 Ω·m	ρ = 1000 Ω·m
Top	5	10	14
Center	10	20	26

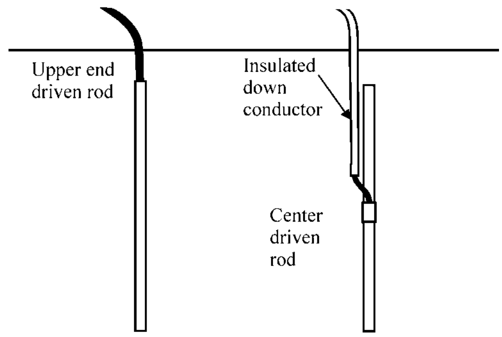

Figure 9. Upper end and center driven rods.

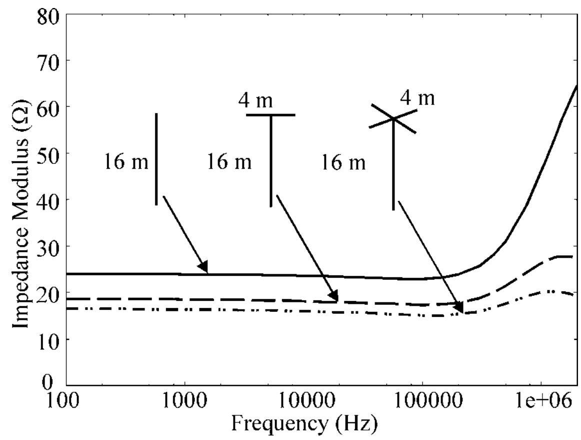

Figure 10. Improved HF impedance of ground rods in soil with ρ = 300 Ω·m.

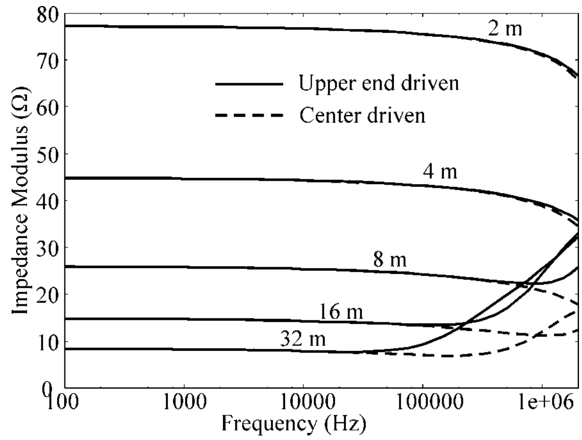

Figure 11. Impedance of two 16-m ground rods at 4-m distance in soil with ρ = 300 Ω·m.

Another possibility to improve HF performance of ground rods is illustrated in Fig. 10. Impedance of upper end driven 16-meter long rod in soil with resistivity 300 Ω·m is shown. It has dominant inductive behavior in HF range. But if short electrodes (4-meter long), that have dominant capacitive behavior, are connected, the overall behavior becomes less inductive, and HF performance is improved.

Another usual procedure is to drive two or more rods in parallel. This leads to lower LF ground resistance, but HF ground impedance is not affected. This is illustrated in Fig. 11, where the ground impedance of two 16-meter rods at 4-meter distance driven at their upper ends and at the middle points in soil with resistivity 300 Ω·m are shown for rods' lengths from 2- to 32-meters. The best overall performance may be achieved using as many parallel rods as necessary for low ground resistance, with lengths less than the critical length. If longer rods are necessary, insulated down conductors at their middle points may be used.

7 - CONCLUSIONS

1. Comparisons between measurements and computations based on rigorous theoretical methods and on simple formulas show that simulations are consistent with measurements and that simple formulas may be used for computation of HF impedance of ground rods in highly resistive soil in observed frequency ranges.
2. Presented results enable estimate of a critical length of the ground electrodes, such that larger electrodes exhibit inductive and smaller capacitive behavior, nearly for any value of soil's resistivity of practical interest.
3. In case of inductive behavior of long ground rods in highly resistive soil, their HF performance may be significantly improved by:
   - using insulated down conductors connected at the middle point of the rods, and
   - connection of smaller electrodes that have capacitive behavior for themselves.
4. Parallel connection of driven rods improves LF resistance, but has no influence on HF behavior. The best overall performance may be achieved using as many parallel rods as necessary for low ground LF resistance, with lengths less than the critical length. If longer rods are necessary, insulated down conductors connected at their middle points may be used.
5. Permittivity of the soil has large influence on the HF performance of ground electrodes in highly resistive soil, and has to be taken into account during measurements.

ACKNOWLEDGMENT

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Author
Leonid Grcev
Elektrotehnicki fakultet
Karpos II bb, P.O. Box 574
91000 Skopje, R. Macedonia
Fax: ++389 91 364 262; Phone: ++389 91 399 128
E-mail: leonid.grcev@ieee.org