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Computer Simulation of Earthing Systems under Variable Frequency and Transient Conditions

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Abstract

Earthing systems are essential for the secure dissipation of fault currents and those induced by lightning across a broad spectrum of frequencies, encompassing both power frequency and fast transient conditions. However, their behaviour at high frequencies is significantly influenced by inductive and capacitive effects, which are not adequately captured by conventional low-frequency design approaches. computer simulations were conducted to assess the high-frequency operational characteristics of earth electrode systems. The effect of electrode length has been simulated on the scaled 25mesh earth grid, with 5m x 5m dimensions. The results showed that the effective length is affected by soil resistivity and energisation characteristics such as frequency or impulse rise time. The effect of the downlead was also investigated, and it was found that length and path have a significant influence on impedance magnitude and transient potential rise values.

To improve the performance under high frequency energisation, an insulated conductor will be bonded at the point of injection at one end and to positions out on the earth grid at the other end. The insulated horizontal enhancement will facilitate a diminution in the magnitude of impedance by enabling the dispersion of current to occur at a greater distance from the injection locus and by mitigating the inductive influence attributable to the supplementary parallel current pathways. The results underscore essential design parameters for contemporary earthing systems aimed at ensuring dependable functionality in the presence of lightning strikes and high-frequency environments. This paper presents an extensive numerical analysis of the transient and high-frequency behavior of vertical earth electrodes and earthing grids employing the CDEGS HIFREQ module.

Keywords: Earthing systems, Grounding, Soil Resistivity, High Frequency, Transient, Downlead, Effective Length, Effective Area

1. Introduction

There is extensive and detailed guidance available, such as in modern standards [1 – 4], surrounding how to effectively and safely earth the critical parts of a power system when considering high voltages and fault currents at power frequency. It has been well documented that earthing systems do not have the same response when subjected to High Frequency (HF) or impulse currents. Although there are many publications and a substantial amount of references on the response of earthing system to HF currents, modern standards fall short of providing sufficient guidance. In addition to power frequency faults (such as a phase-to-earth overhead line faults), the earthing system of a substation is subject to high frequency faults, the source of which are lightning and switching surges.

The characteristics of an earthing systems under lightning conditions differ from those at power frequency, and the earthing system must be designed to operate satisfactorily under all conditions. At high frequencies, the performance of the earthing system will be influenced by inductive and capacitive effects. For example, the inductance of a small earthing system such a rod dominates the high frequency impedance characteristic, thereby lowering its effective length.

Numerous experimental and theoretical studies on the high frequency performance of earthing systems have been documented [5-13]. The experimental research involves both field and laboratory assessments. Numerous experiments have been conducted on basic arrangements of earth electrodes. These basic earth electrodes are widely employed today in grounding systems for electrical networks and lightning protection systems, serving either as primary earth electrodes or as supplementary electrodes to reduce earth impedance and enhance the performance of the grounding system during high frequency and transient conditions caused by power frequency faults and surge currents. Most theoretical research seeks to create appropriate models that explain the experimental behavior of these electrodes, and this work has been expanded to include earth grids and combinations of grid-electrodes [14-15]. Moreover, the rapid advancement in computing power has resulted in the enhancement of highly efficient numerical computational models to evaluate the behavior of intricate earthing system configurations. A soil resistivity test was conducted near the earth electrodes to obtain a soil resistivity model that can be used in the CDEGS models [16]. This soil resistivity test will be conducted again to assess the impact of seasonal changes on the soil resistivity at the test location

An extensive test programme on the scaled earth grid including the high frequency response and transient Earth Potential Rise (TEPR) of an impulse current on the earth grid with/without above insulated conductor was carried out analysed in this paper.

2. Frequency Response of a Vertical Electrode

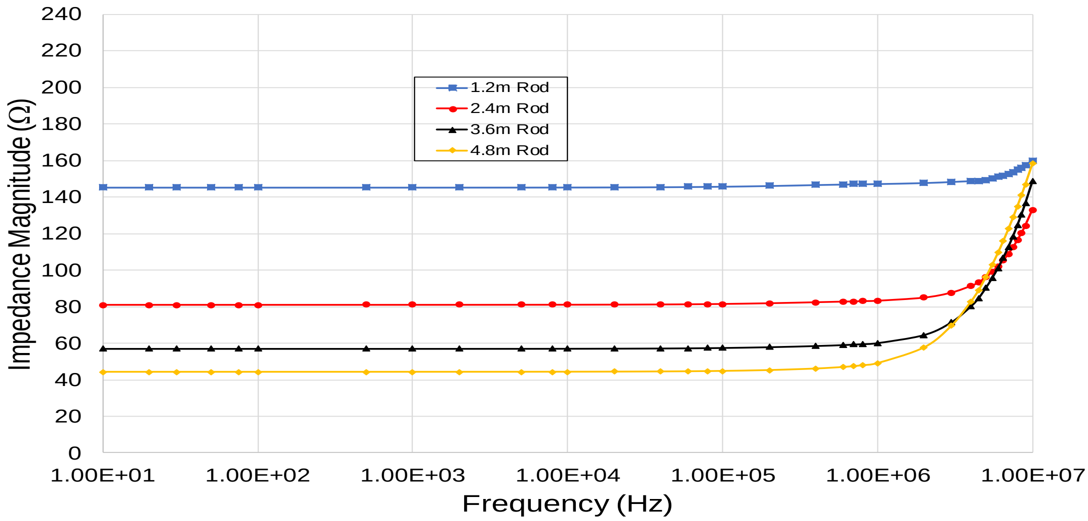
Numerous soil resistivity measurements have been conducted at the field-testing location to anticipate the effectiveness of a specific grounding system when designing a new system, and to perform comparison between the CDEGS simulations and future practical test results. Table 1 shows the most recently derived model, of which the two Layer Model will be used throughout the first part of this paper.

In the numerical model, a 1A current is applied at different frequencies from DC to 10MHz employing CDEGS software 'HIFREQ module' [16] as shown in Figure 1. The copper vertical electrode reference is assumed to possess a radius of 7mm. The figure shows that in the low frequency range, increasing the earth rod length from 1.2m to 4.8m results in a substantial decrease in earth impedance, where earth impedance (Z) closely resembles DC resistance.

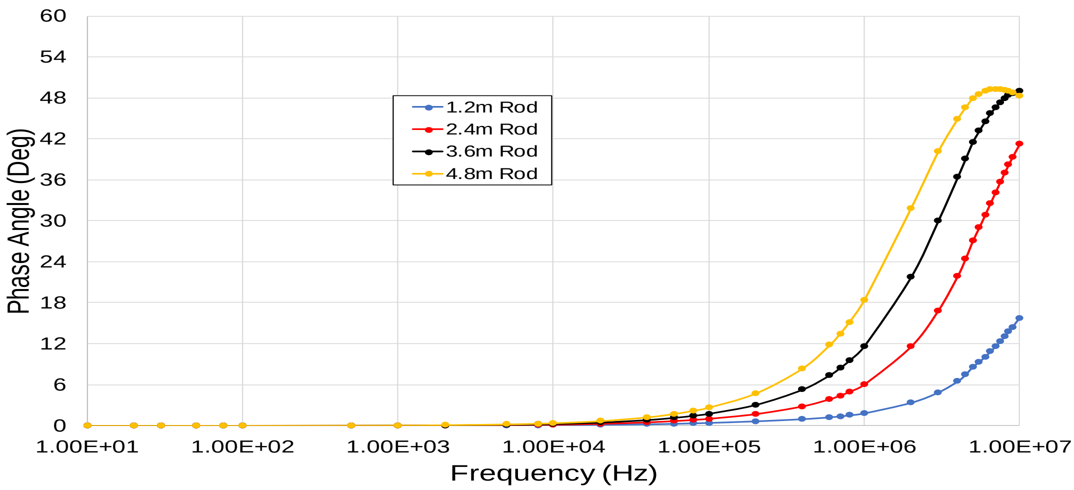
At higher frequencies, the inductive effect dominates, causing an increase in impedance magnitudes for all electrode lengths. The increase in impedance frequency response is observed for all rods embedded in the same soil resistivity environment,but the characteristic frequency, marking the transition from low frequency to high frequency modes, is reduced with increasing rod length [15].

Table 1: Soil Resistivity Model Using CDEGS Software

3 Layer of soil Model	Top		Middle		Bottom	
	Soil Resistivity (Ωm)	Depth (m)	Soil Resistivity (Ωm)	Depth (m)	Soil Resistivity (Ωm)	Depth (m)
	220	11	50	14	75	∞
Uniform soil Model	Soil Resistivity (Ωm)					
	220					



(a) Impedance magnitude of simulated earth rod.



(b) Phase angle of impedance magnitude of simulated earth rod.

Fig. 1: Impedance magnitude of different length of earth rod

3. Effective of Soil Permittivity (ε)

The influence of soil permittivity on the impedance magnitude of a 5m earth electrode was examined across various soil resistivities (10Ωm, 100Ωm, 1kΩm, and 10kΩm) and frequencies up to 10MHz, and the results are presented in Figure 2. The figure demonstrates that the impedance magnitude of the HF rod remains unaffected by variations in soil permittivity at low soil resistivity. However, for higher soil resistivities, the effect of soil permittivity becomes increasingly significant, and the reduction seen in impedance magnitude may be attributable to capacitive effect enhancement. At the highest frequencies, a damped resonant behaviour is observed.

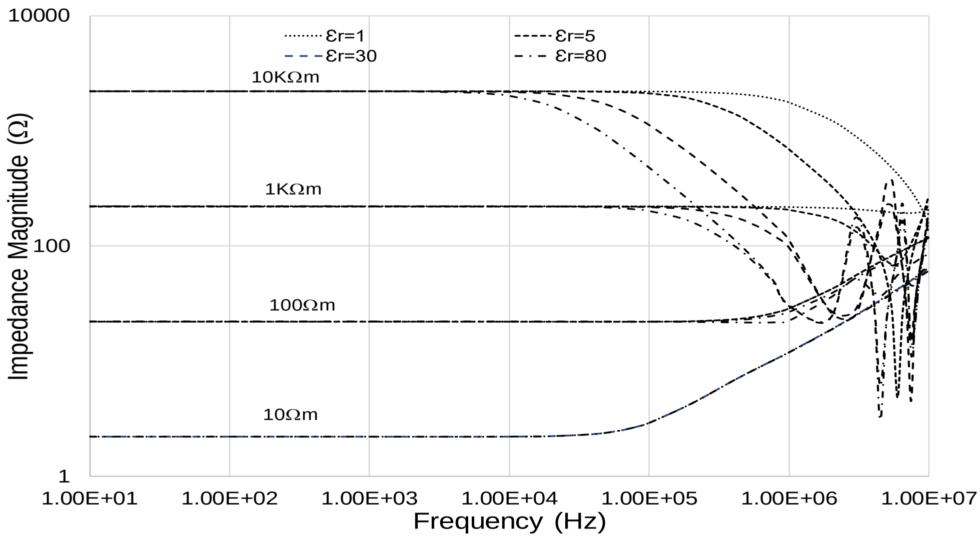


Fig. 2: Impact of frequency response on 5m vertical rod with different values of relative permittivity and soil resistivity

4. Effective Length of Earth Electrode

To analyze the impact of the earth rod on the frequency response, the length of the vertical earth electrode was adjusted between 5m and 25m during the simulation experiments.The investigation was conducted for a wide range of soil resistivity (10Ωm, 100Ωm, 1kΩm and 10kΩm) for three selected frequencies of 50Hz, 100KHz and 1MHz, and the earth impedance was calculated using CDEGS software (HIFREQ Module), as shown in Figure 3. As expected, the impedance magnitude at 50Hz declines as the electrode length increases for all soil resistivities. For the lower soil resistivities (10Ωm), the impedance of the vertical rod flattens, indicating an effective length of approximately 10m. At high frequencies, the earth impedance magnitude also decreases with increasing depth and soil resistivity.

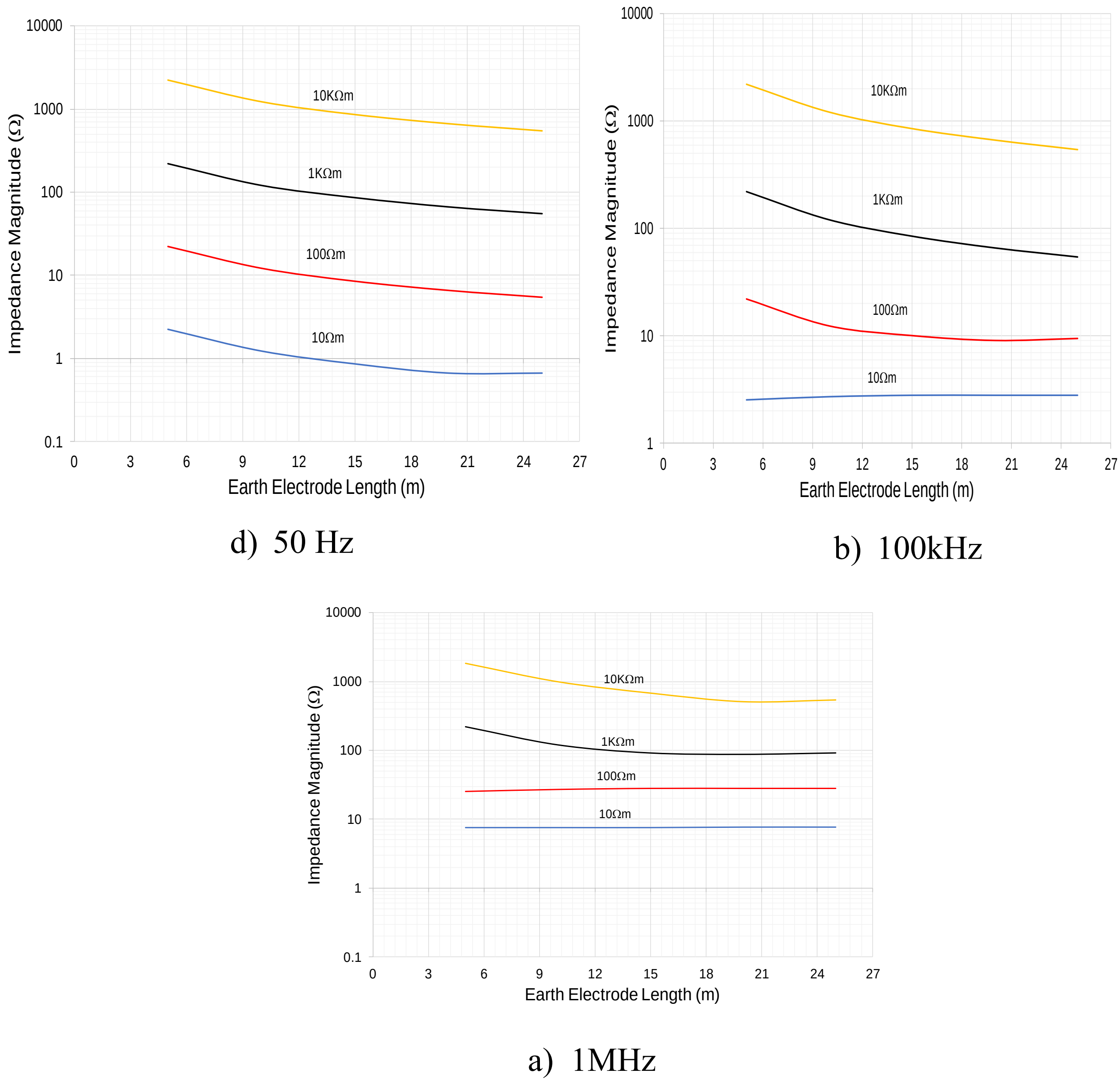


Fig.3: Impact the length of rod on impedance magnitude of a vertical ground electrode at selected frequencies

The analysed findings are reported in Figure 4, showing the peak the transient earth potential rise for two selected impulse shapes of 8/20 and 1.2/50 impulses having 1A peak value as a function of length for a soil resistivity of 100Ωm.The length of the vertical earth electrode is varied from 5m to 25m. As can see from figure, for both impulses, the value of the TEPR decreases as the vertical rod length decreases. The effective length for 1.2/50µs impulse is approximately 10m but, for the 8/20µs impulse the plateau region, hence the effective length, is not reached yet. This would suggest the effective length of the rod is dependent on frequency or impulse rise time of the energisation current. It is, therefore, important that both capacitive and inductive impacts are carefully considered in a fast-transient impulse current study.

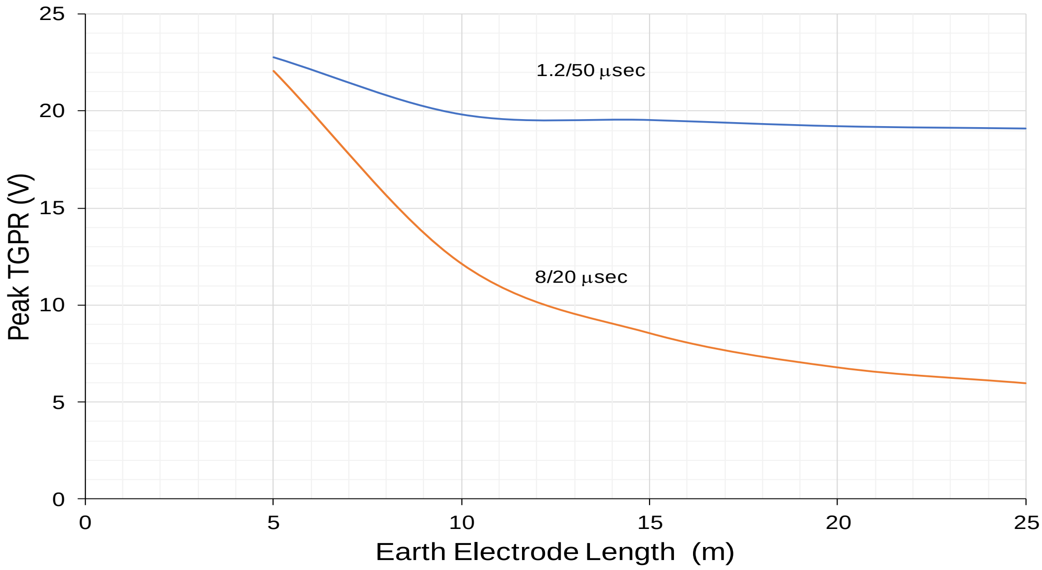
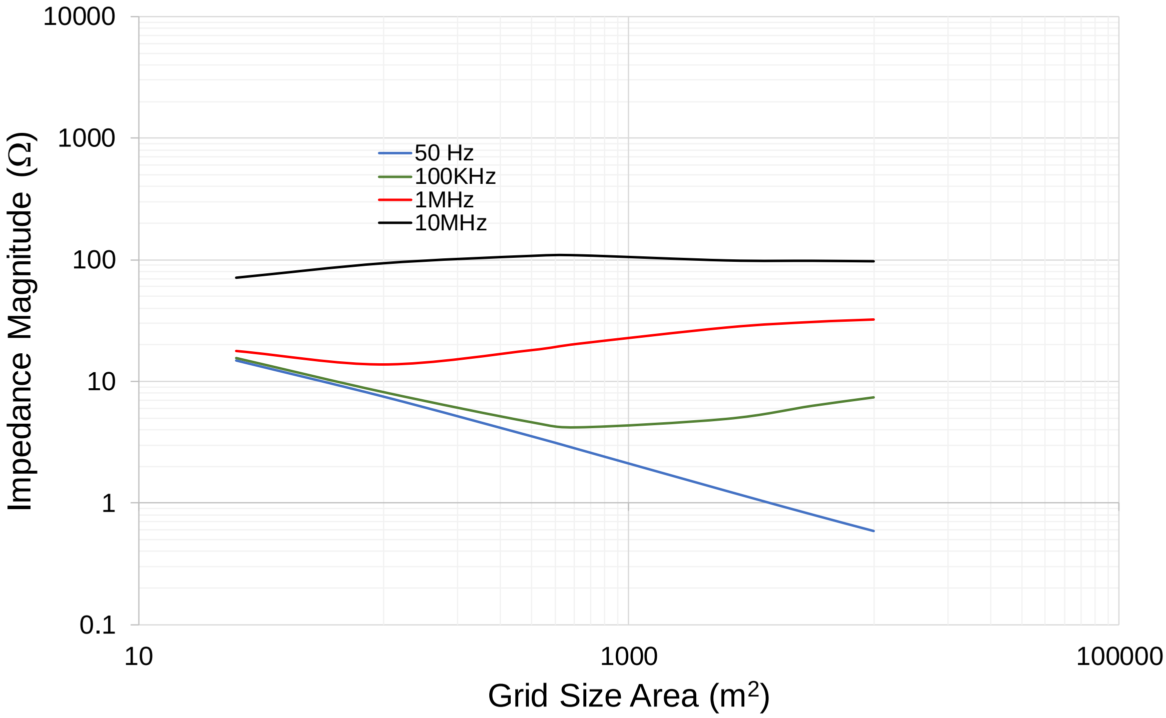
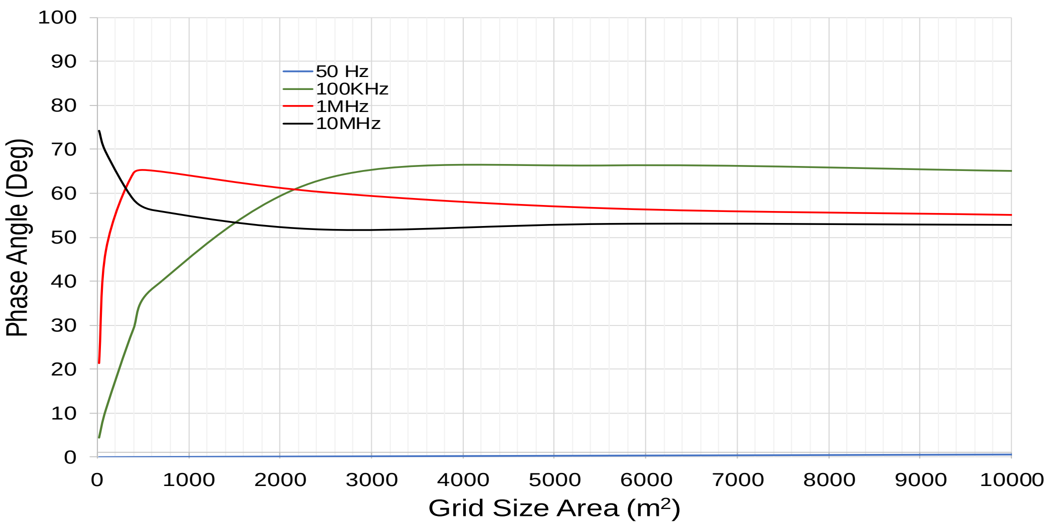


Fig.4: Impact of impulse wave form on peak transient earth potential rise

5. Influence of Earth Grid Area on Earthing Systems

To determine the effect of the high frequency rod on the earthing impedance of large substation earthing systems, the size of the grid was varied up to squares of 100m x 100m in all cases, the earth grid is a square having 25 mesh, with side length increasing from 5 to 100m, equivalent to the grid area ranging from $25m^2$ to $10000m^2$. 1A current was applied at the center of each earth grid at frequencies of 50Hz, 100kHz, 1MHz, and 10MHz. Figure 5 illustrates the impedance magnitude calculated with HIFREQ for earth grids from various regions. As anticipated at 50Hz, enlarging the grid area demonstrates a considerable decrease in impedance magnitude from 15Ω to 0.6Ω within the examined range. At 100kHz, there is a notable decrease in impedance magnitude from $25m^2$ to $625m^2$, and approaches a constant value of 7Ω.



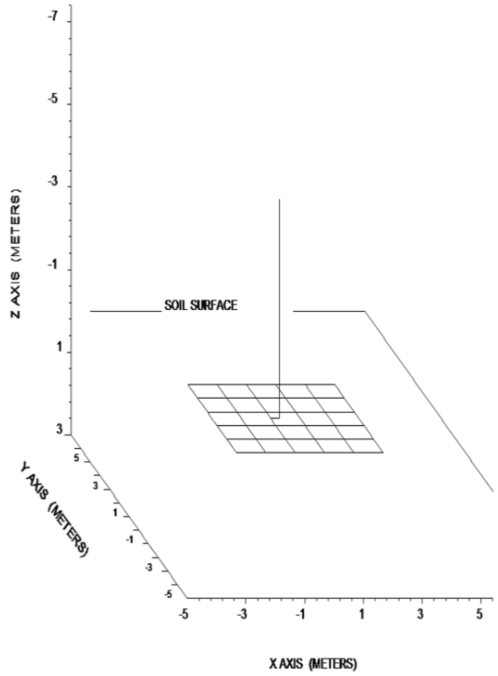


(a) Impedance Phase Angle

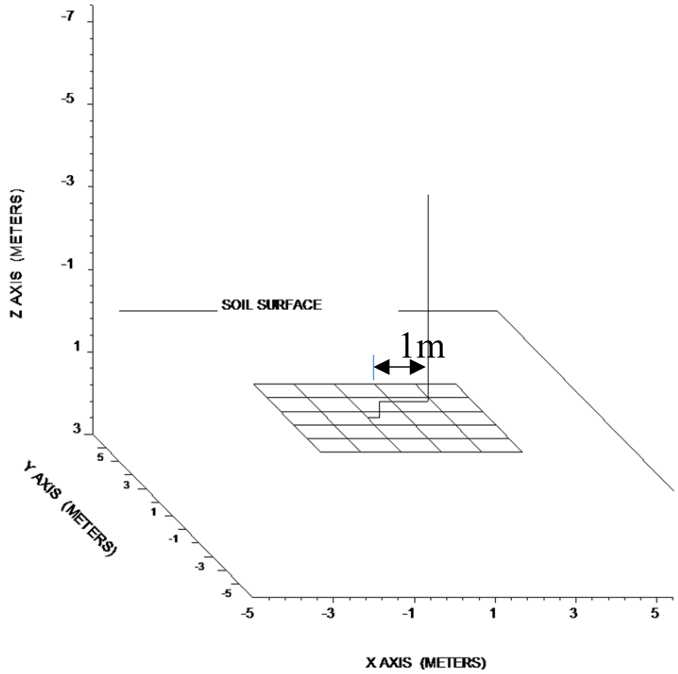
Fig.5: impedance magnitude for earth grids of different area (Centre Injection)

6. Effect of Downlead

Figure 6 shows the downlead arrangements (lengths of from 0.3m to 30m were used). The constant current of 1A current is applied at the top of the downlead conductor connected at the central lead of the earth grid (5m×5m, 25mesh). Simulation was conducted for three frequencies of the injected current: 50Hz, 100KHz, and 1MHz. Figure 7 shows the results of these simulations. At the higher frequencies, it can be expected that this system has higher impedance than was seen for low frequency (50Hz). Connecting very long and bent downlead to the grid results in a significant increase in impedance magnitude at higher frequencies where the inductive effect becomes dominant. Such configurations are not recommended by the standards [17].

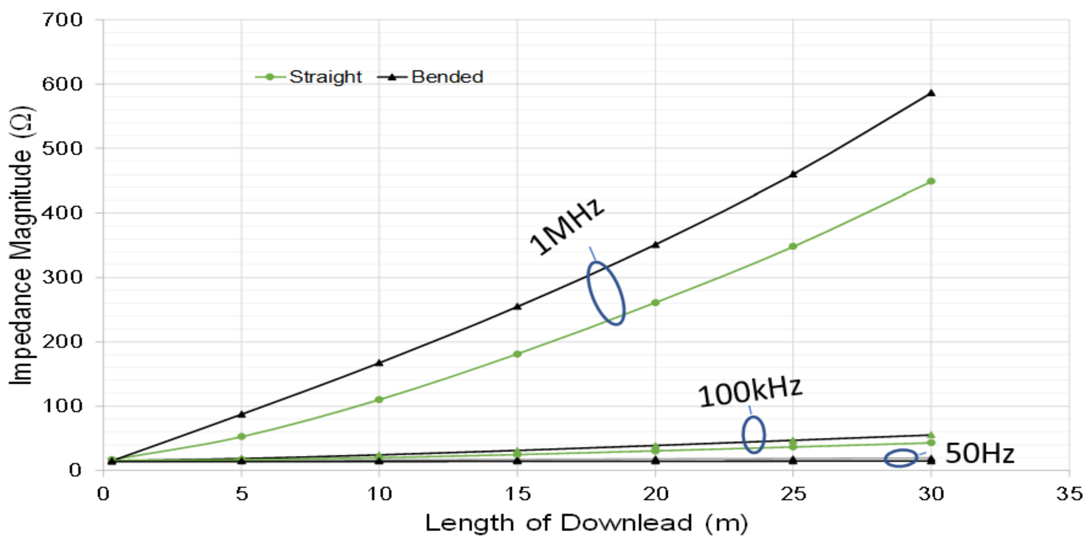


a) Straight Download

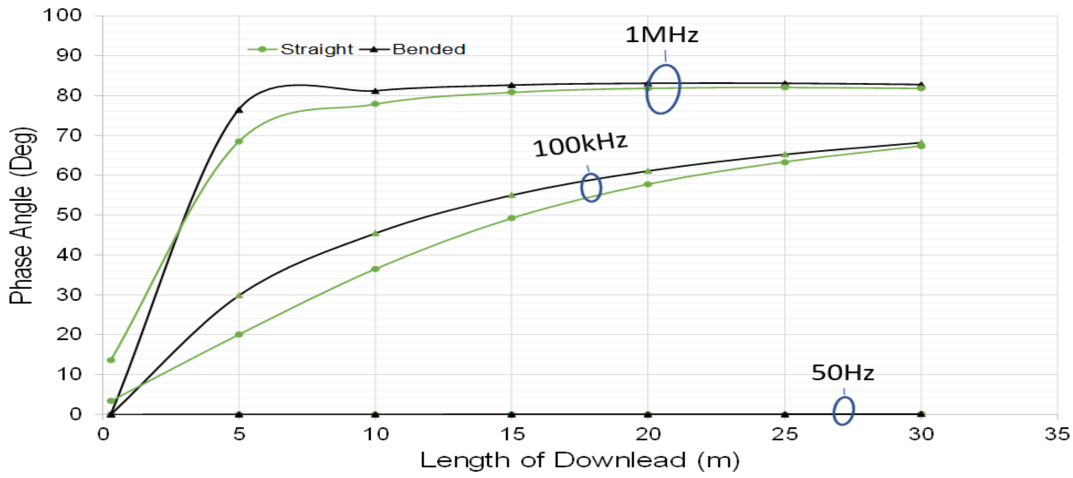


b) Download with bend

Figure 6: CDEGS simulations for the 5m x 5m,25mesh earth grid, with straight and bending downleads



(a) Impedance Magnitude



(b) Impedance Magnitude Phase Angle

Fig.7: Effect of length of downlead on impedance magnitude at selected frequencies

The test 5m x 5m earth grid was used in further computer simulations to investigate the effect of a transient current, as shown in Figure 8. Two wave shapes 1.2/50 µs and 8/20µs with a 1A peak current was used throughout the investigation to quantify the impact of downlead length for the two arrangements ((i)straight and (ii) bent) on the peak Transient Earth Potential Rise (TEPR). The position of the current injection point is at the nearest conductor close to the centre of the grid earth electrode. As can be seen on the figure, the peak voltage of the transient earth potential rise (TEPR) increases significantly with increasing length and bending of the downlead when the earth grid is subjected to faster rise time currents. For example, with a 30m downlead, the peak TEPR is increased by approx. 670% for 1.2/50 impulse compared with that obtained with 8/20.

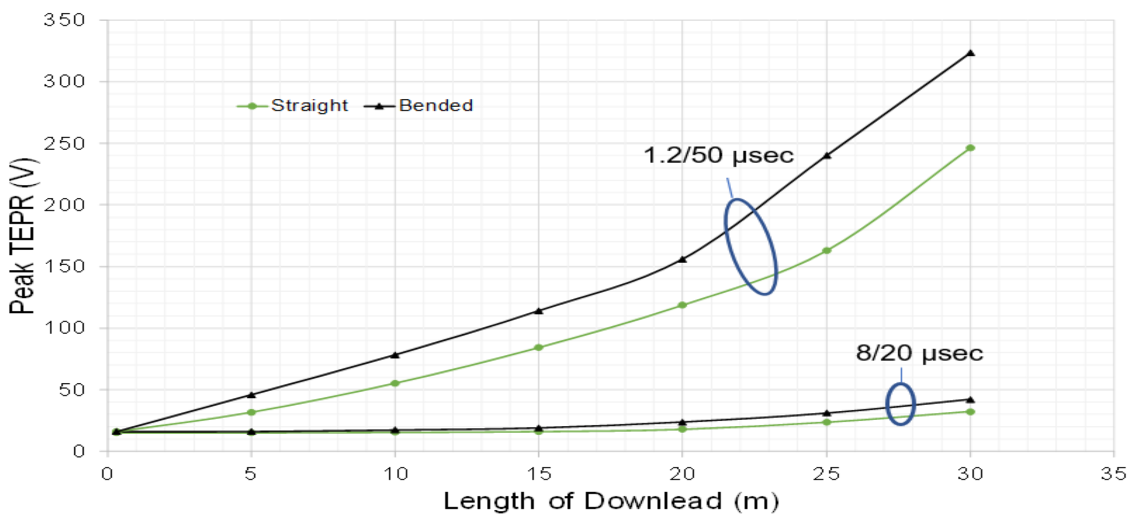


Fig.8: Impact of length of downlead on Transient Earth Potential Rise (TEPR)

7. Grid Mesh Density of with Horizontal Enhancements

The current was injected at a central grid cross-member, as shown in Figure 9. The impedance magnitude for the earth grid is calculated using HIFREQ module for each configuration with a 1A applied current of. To quantify any reduction in impedance magnitude by reducing the number of meshes in the grid, the scaled earth grid only 5m×5m, 25mesh, with HF rod and with 4HE were used. Full details for these models have been described at the previous deliverable. The computed impedance magnitude is shown in Figure 10. It can be seen that the horizontal enhancements have an unimportant effect on decreasing the impedance magnitude between 10Hz and 800kHz. However, at the higher frequencies of 1MHz and above, the reductions in impedance magnitude are achieved for the grid with 16 mesh and 25 mesh compared with other arrangements. For example, at 10MHz, for the grid with 16 mesh and 25 mesh the impedance magnitude decreases by 46.12% and 43.4%, respectively.

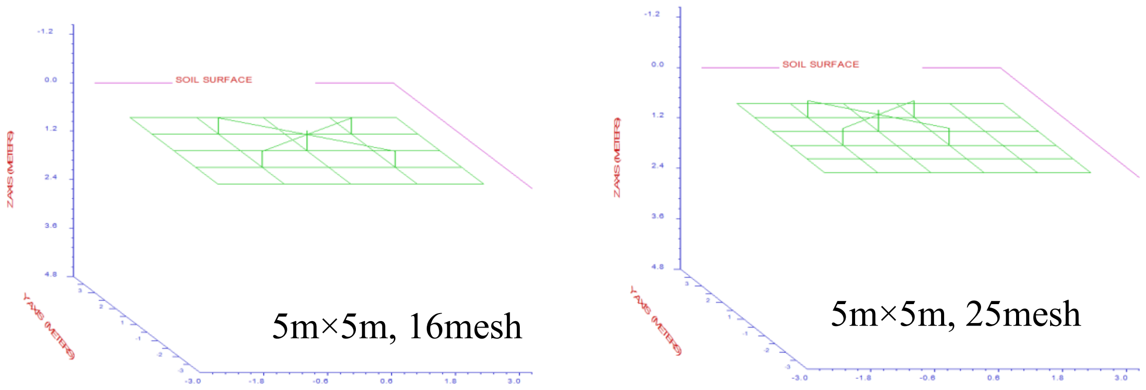


Fig. 9: 5m x 5m, 16mesh and 25mesh grid with four horizontal enhancements and centre cross member current injection

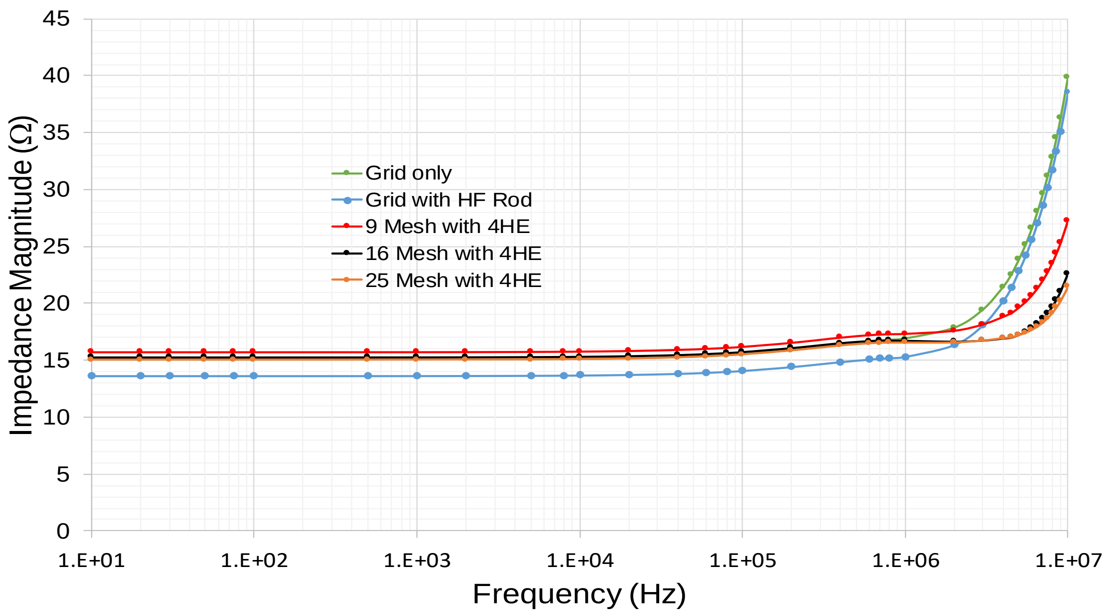


Fig. 10: Effect of dense mesh on frequency response of a 5m x 5m earth grid

8. Conclusion

The computer simulation has been employed to investigate the behavior of vertical earthing electrodes and an earth grid. The findings indicate that the impedance magnitude increases considerably at high frequencies due to inductive effects, particularly in conditions of low soil resistivity or with long length of electrodes. Capacitive effects become increasingly significant at high frequencies in soils with resistivity greater than 1000 Ωm. The influence of the effective length was conducted under low and high frequency and transient performances and was shown to be dependent on the soil parameters and impulse rise time rather than purely on physical dimension. The effect of the above ground downlead for two arrangements straight and bent was also simulated under variable frequency and transient energisation conditions. The investigation also demonstrates that soil permittivity plays a significant role in high-resistivity soils, where capacitive effects can reduce impedance magnitude and introduce resonant behaviour at high frequencies. Analysis of transient responses further reveals that the effective length of vertical electrodes varies with impulse waveform, emphasising the need to consider both inductive and capacitive components when assessing lightning performance. The use of horizontal enhancements is shown to be particularly beneficial at frequencies above 1 MHz by providing additional parallel current paths and reducing inductive effects.

Overall, the findings underline the necessity of frequency- and transient-aware design methodologies for modern earthing systems. The results provide valuable guidance for the optimisation of electrode geometry, grid layout, and downlead arrangements to ensure safe and effective performance under lightning and other fast transient conditions.

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