Characteristics of Earth Electrodes Under High Frequency Conditions: Numerical Modelling

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Abstract. The earthing segments of electrical power systems play an important role in ensuring human safety. A core function of these earthing systems is to maintain reliable operation and ensure safety for personnel and apparatus during fault conditions. Earthing electrodes can be buried in the soil to dissipate lightning and fault currents into the earth and limit the effect of any magnitude of voltage and current generated between different contact points to earth structures that may be occupied by people or sensitive electrical equipment. In order to obtain the best design of an electrical system to protect power system installations and ensure human safety against abnormal conditions, it is useful to clarify the behaviour of earthing systems subjected to variable frequency currents. In this paper, a numerical study is thus implemented to investigate the behaviour of earthing electrodes subjected to variable frequency current using the computational software program HIFREQ/FFTSESCDEGS with a uniform equivalent soil model. The effect of soil resistivity and permittivity on the behaviour of earthing electrodes is thus obtained, and the relationship between the length of earthing electrodes and their earthing responses over a wide range of frequencies from DC up to 1MHz is identified.

1. Introduction:

Earthing systems are essential to electrical power systems and must be considered within electrical power system design to ensure maintenance of a reference point for earth potential to preserve the safety of both equipment and personnel; they provide a conductive path for current to dissipate to the earth under transient conditions and ensure a return path for fault currents, limiting hazardous overvoltage generation in the power system under transient and fault conditions.

To achieve satisfactory performance of an earthing system, proper design, installation, and testing of earthing electrodes is required. The ideal earthing system is designed to exhibit zero-ohm earth resistance; however, this value cannot be achieved in reality. Thus, to limit the generated voltages to a safe level in working zones, different techniques are used to specify the required maximum value of earth resistance [1] – [7]. Under transient and fault conditions, high magnitude current is passed to the earth, and a large potential gradient will result, such that the earthing system will exhibit a potential voltage generated between the earthing system and the reference earth [8]; this voltage is defined as the potential rise [9].

High magnitudes of current may be injected in the earthing system under transient conditions such as direct lightning strikes. The function of the earthing system is to discharge such high fault currents to the earth. However, the dissipation of a high fault current may result in a high magnitude of generated potential rise, which threatens the safety of workers and may cause damage to the ancillary equipment. Intensive investigations should thus be undertaken to determine the risks of such generated earth potential rise and to find ways to control its value, particularly inside and near substations.

The main components responsible for earthing system behaviour under abnormal conditions can be classified into three categories: the connection between the power system and the electrodes, which should be as short as possible according to standards [10],[11]; the configuration of the earthing electrodes including electrode type, the material used, and the dimensions; and finally, the characteristics of the earth where the electrodes are installed. Investigations of the behaviour and performance of earthing systems began around a century ago [12],[13], and the results of these investigations have provided useful guidance for the effective design of earthing systems, for installing...
earthing electrodes, and for measuring and testing earthing systems’ impedance. In addition, useful knowledge on soil resistivity measurements and their effect on the behaviours of earthing systems at various power frequencies and under certain transient conditions has been obtained. The descriptions of variations in earthing systems’ responses under normal and transient conditions, and the factors responsible for such behaviours, can thus be considered the most important outcomes of these previous studies [14]-[22]. In addition, the rapid growth in computer technology has helped with the development of powerful numerical computational models that are capable of performing rapid evaluations of the responses of complex earthing system configurations.

This paper focuses on the frequency response of the earthing electrodes. The effect of soil parameters on the behaviour of earthing electrodes (vertical and horizontal) subjected to variable frequencies is calculated using the computational software program HIFREQ/FFTSES-CDEGS, and the effect of electrode length on the performance of earthing systems under power and high frequency is explored.

2. Computer Model and Earth Electrode Configurations

Appropriate computer models were set up in CDEGS-HIFREQ [23] to obtain the frequency responses of both vertical and horizontal earth rods buried in homogeneous soil, as seen in figure 1 and figure 2, which represent the test set up for both electrodes. The dimensions and properties of the simulated electrodes are shown in Table 1, together with the assumed electrical properties of the conducting medium. Simulations were carried out by injecting 1A AC current at the top of the 0.5m downlead and the earthing impedance magnitude and phase angle at the injection point were calculated.

Table 1. Dimensions and properties of simulated vertical rod and soil medium.

| Earthing Electrodes | Conducting Medium |
|---------------------|-------------------|
|                       | Material | Resistivity | Relative permittivity |
| Vertical Electrode   | Copper    | 1.7 $\times$ 10^{-8} Ωm | 1 |
| Horizontal Electrode| Copper    | 1.7 $\times$ 10^{-8} Ωm | 1 |
| Length               | 1, 3, and 6m  | 100, and 50m  |                |
| Dimension            | 14mm      | 14mm         |                |

Figure 1. Simulation arrangements for vertical earth electrode.

Figure 2. Simulation arrangements for horizontal earth electrode.
3. Frequency Response of Vertical Electrode

3.1 Resistivity and Permittivity

The frequency response of a 1m vertical earth rod was predicted for three values of soil resistivity, 10 Ωm, 100 Ωm, and 10 kΩm. For a low soil resistivity of 10 Ωm, the earthing impedance exhibited a constant value approximately equal to the DC resistance up to specific frequency, known as the characteristic frequency or cut off frequency. The cut off frequency value for the electrode thus depends on the resistivity value. The simulated electrodes with resistivity 10 Ωm, and 100 Ωm show different characteristic frequencies under identical conditions, as shown in figure 3. At low frequencies, the earthing impedance is approximately equal to the DC resistance up to the cut off frequency. After this point, the earthing impedance exhibits an increase in its value. Such a response is explained by the inductive effect. Although the earth rod shows a similar response at low and high frequencies, the earthing impedance of 100 Ωm is ten times the earthing impedance of 10 Ωm. At 10 kΩm resistivity, the simulated earth rod exhibited a constant value up to the characteristic frequency, then a reduction in earthing impedance was observed. Such a response is explained by capacitive effect. 

The soil resistivity value is also greatly affected by the impedance angle, exhibiting the same variation of earthing impedance over frequencies, as shown in Figure 4. At low frequency and low soil resistivity 10 Ωm, and 100 Ωm, a positive and almost constant impedance angle was observed that began to increase remarkably after the characteristic frequency was reached. However, high soil resistivity and low-frequency current lead voltage generated a small and almost constant angle up to the characteristic frequency, at which point the angle started to increase with the increase in frequency. 

To quantify the effect of permittivity on the performance of the earthing system, the frequency response of the vertical earth rods was examined under different values of soil relative permittivity from 1 to 50, over frequencies DC to 10MHz. The variation of permittivity value did not exhibit a marked effect on the impedance magnitude at low frequencies in either condition of soil resistivity. However, at a high frequency, there was a marked reduction in impedance magnitude as the permittivity increased, with this reduction becoming more evident at high soil resistivity; the cut off frequency also occurred earlier as permittivity increased, as shown in figure 5.

![Figure 3. Earthing Impedance of simulated vertical earth rod.](image-url)
3.2 The Effect of Electrode Length

The length of the electrode has a major effect on the performance of the earthing system. Figure 6 shows the effect of simulated electrode length on the earth potential rise (EPR). The EPR is defined as the maximum electrical potential that an earth electrode may attain with respect to a distant earthing point, assumed to be at the potential of remote earth, under different soil medium conditions. The generated EPR at the injection point of the simulated rod exhibited a reduction in value with the increase in electrode length at both low and high frequencies. The longer earth rod exhibited a greater reduction in EPR. In addition, as shown in the figure, the transition point in the electrode response from low frequency to high frequency behaviour, was smaller for the longer electrode at the same soil resistivity value [24]. Therefore, electrode length should be considered a key factor to achieve satisfactory earthing system performance.
4. Frequency Response of Horizontal Electrode

4.1 The Effects of Resistivity and Permittivity

The earthing impedance magnitude for a 100 m horizontal rod over a range of frequencies from DC to 10 MHz in different soil resistivities was predicted as shown in figure 7. The earthing horizontal electrode showed similar responses to the vertical electrode at low frequencies up to the characteristic frequency, though the latter value was much lower than that of the vertical electrode. After this point the earthing impedance exhibited an increase in its magnitude at 10 Ωm and 100 Ωm soil resistivity due to the inductive effect. For high soil resistivity, 10 kΩm, three intervals were observed in the response of earthing electrode. In the first interval, at low frequency, resistive behaviour dominated the electrode, with earthing impedance constant and equal to DC resistance up to the characteristic frequency. The second phase of inductive behaviour started after the characteristic frequency was exceeded; finally, an oscillation phase occurred due to the interface between inductive and capacitive effects.

The phase angle for the low soil resistivity medium of 10 Ωm was constant up to the characteristic frequency, as shown in figure 8. An inductive effect then occurred, and the phase angle showed a marked increase along with an increase in frequency. However, in the high soil medium, 10 kΩm, the electrode exhibited a capacitive effect trend accompanied by a resonant effect on the phase angle. The effect of soil permittivity on 100 m horizontal earth electrode impedance magnitude was predicted over the frequency range DC to 10 MHz for low and high soil resistivity media (ρ= 10Ωm, 100 Ωm), as shown in figure 9. There was no marked effect on the impedance value for the low soil resistivity medium. For the high soil resistivity medium, 10 kΩm, at low frequency, the performance of the earthing rod did not exhibit any response changes to permittivity variation up to the characteristic frequency, though above that frequency, increasing the relative permittivity from 1 to 50 resulted in a marked reduction in the impedance magnitude due to the capacitive effect. This response continued for a short frequency interval, after which an oscillatory behaviour was observed.
Figure 7. Earth impedance of simulated horizontal electrode.

Figure 8. Phase angle of the simulated horizontal electrode.

Figure 9. The effect of permittivity on the frequency response vertical electrode.
4.2 Effect of electrode length

To understand the effect on behaviour of electrode length, the frequency response of horizontal earth electrodes of different lengths, 10 m, 50 m, 80 m, and 100 m, were predicted for low and high homogeneous soil resistivity media. At low soil resistivity and low frequencies, the computed earth impedance magnitude was equal to DC resistance; this value depends on electrode length. The impedance magnitude showed a significant reduction as the electrode length increased up to a specific length, called the effective length. After that, there was no change in impedance magnitude, suggesting that there is no benefit in increasing the electrode length beyond this point [25] – [28]. Figure 10 shows the effect of length on the frequency response of the earthing rod over a range of frequencies. The effect of length in high soil resistivity is much greater compared with that seen in the low soil resistivity medium, as shown in the figure. The horizontal electrode exhibited a marked reduction in impedance value as the length increased from 10m to 50m, though that reduction gradually decreased with increases in the rod length up to the effective length. Generally, in high soil resistivity, a longer rod gives a lower value of earthing impedance.

![Figure 10. Effect of earth rod length on the computed impedance of a 100 m horizontal electrode.](image)

5. Conclusion

A software programme HIFREQ was used to implement intensive simulation to examine the main characteristics of frequency response based on the influence of soil medium resistivity, soil permittivity, and electrode length. The simulation confirmed the well-known low frequency responses of different electrode configuration. At low frequencies, the impedance magnitude is equal to DC resistance over a range of frequencies up to the characteristic frequency. Soil resistivity and permittivity and the length of electrode all have significant influences on the characteristic frequency, however, and above this frequency, the simulation results continue to show their effects, including an upturn in impedance with frequency in low resistivity soil (inductive effects). However, in high resistivity soil, the capacitive effects dominate the behaviour of the earthing electrode at high frequencies, causing a decrease in impedance values.

In addition, the investigations examined the effect of relative permittivity on the performance of earthing electrodes. The variation in permittivity value has no effect on the performance of the earthing system for different soil resistivity conditions at low frequencies; however, at high
frequencies and high soil resistivity, the impedance magnitude of an electrode decreases with the increase in permittivity.

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