Performance of Aligned Earth Rods under Low-magnitude Variable-frequency Current

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Abstract

This paper analyses the behaviour of earthing systems under low and high frequency ranges, aiming to provide effective design and mitigating risk associated with fault current inducted potentials. A parametric analysis is carried out to study the behaviour of two interconnected earth rods under different conditions by varying the length of rods, separation distance, soil resistivity and frequency of the injected current. For long separation distances, the effect of current injection point is studied where above- and under-ground insulating conductors are selected and compared to the case of and bare conductors. Simulations using HIFREQ module of CDEGS are conducted where earthing impedance over frequency is considered as a prime parameter. The results are grouped into several sections in order to provide a clear image on the effect of aforementioned parameters.

1 Introduction

A low value of earthing resistance is usually required to provide a better dissipation of electric currents into the soil [1]-[3]. Different techniques can be used in order to reduce this resistance such as the use of low resistivity materials and increasing the size of the earth network [4]. Increasing the quantity of conductors in an earth network is also considered where aligned earth rods is one of the commonly used techniques. In this technique, various parameters contribute to the overall earthing resistance such as the dimensions of earth rods and the interelectrode spacing [1]-[5]. Authors in [5] studied the effect of the separation distance on the thermal stress of the earthing system in order to provide recommendations as to the required separation of electrodes. This paper examines the influence of the electrode spacing on earthing impedance under low and high frequency ranges. The HIFREQ module of CDEGS software is used to simulate the system [6]. Different conditions (lengths, soil resistivity, separation distance, ..) have been considered in this investigation where the systems are buried in uniform soil. The injected current is characterised by a variable frequency of up to 10 MHz.

2 Problem and Methodology

Earth rods represent one of the most important components of the earth network, which is usually used as a main system (e.g., high frequency earth rods in electrical substation) or for enhancing the main earthing system (e.g., corners in substation earthing). The resistance R_e of each cylindrical shape vertical earth electrode, of length ℓ and diameter d, can be computed as follows [Section 9.5.3 of the BS 7430]

$$R_e = \frac{\rho}{2\pi\ell}\left[\log\left(\frac{8\ell}{d}\right) - 1\right] \tag{1}$$

in which, ρ is the soil resistivity.

From a simple calculation using the previous equation, the variation of the earthing resistance indicates that very long electrodes are not cost-effective since a slight reduction of earthing resistance may be observed at longer lengths. To overcome this issue, parallel interconnections of earth rods are required, and the interconnection of several aligned earth rods is generally considered as represented in Figure 1.

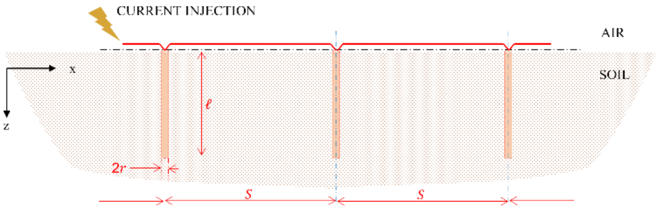


Fig. 1. Representation of aligned earth rods.

In this case, the resistance R_{tot} in ohms (Ω) of n vertically driven rods set s metres (m) apart may be calculated as follows [Section 9.5.4 of the BS 7430]

$$R_{tot} = \frac{1}{n}\frac{\rho}{2\pi\ell}\left[\log\left(\frac{8\ell}{d}\right) - 1 + \frac{\lambda\ell}{s}\right] \tag{2}$$

where, λ is a coefficient given by

$$\lambda = 2\sum\left(\frac{1}{2} + \cdots + \frac{1}{n}\right) \tag{3}$$

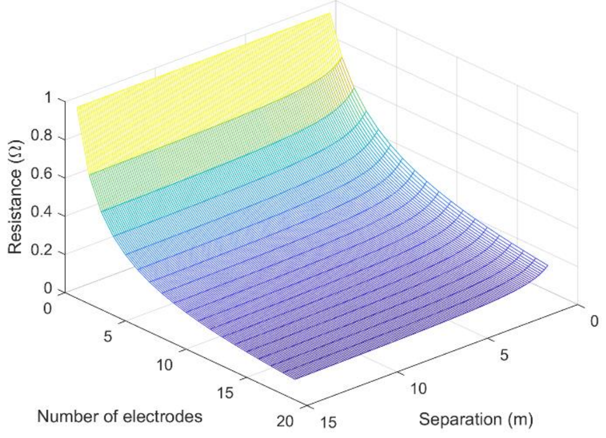
which can be approximated, for large number of electrodes, by

$$\lambda = 2\log\frac{1.781\,n}{2.718} \tag{4}$$

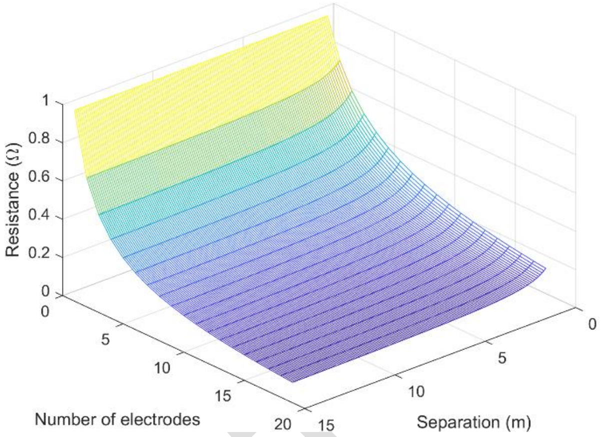
As can be seen in Equation (2), several parameters can affect the calculated value of earthing resistance because it is not only a parallel interconnection of earth rods. However, a mutual component should be considered. Indeed, the problem become more complex as the frequency of the injected current increase since the mutual component becomes considerable [4]. For this, it is worth studying the effect of the separation distance on the resistance and impedance of aligned earth rods, in particular with a variable frequency case.

3 Low Frequency Resistance

The separation distance represents a major parameter in the formulation of the resistance of aligned earth rods. In this light, the effect of such a distance at constant lengths is considered for different values of electrode length. For the same separation distance, the effect of the electrode length is studied in this section to examine the findings in the first test. In general, Fig. 2 shows the evolution of earthing resistance (normalised values) of aligned earth rods as a function of the separation distance and the number of rods. The earth rods are considered to be identical where 1.5 m (Fig. 2.a) and 4.5 m (Fig. 2.b) lengths are used for this example.



(a) A 1.5 m length earth rod



(b) A 4.5 m length earth rod

Fig. 2. Earth rod resistance for different conditions.

As can be seen in this figure, the earthing resistance of aligned earth rods decrease with the increase of the separation distance (respectively, the number of rods) for any given number of rods (respectively, separation distance). Such evolution is not linear where saturation stage exists for higher values of separation distances and/or number of rods. Such variation offer a flexibility in the selection of the pairs (number of rods, electrodes spacing) that can give the desired resistance.

Fig. 3 shows the evolution of the normalised earthing resistance of aligned earth rods as a function of the separation distance and the number of rods. The system consist of rods of 3.5 m length each that is buried in a uniform soil of 100 Ω.m.

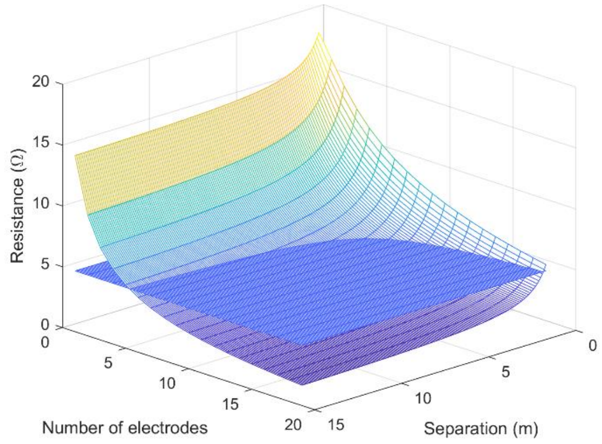


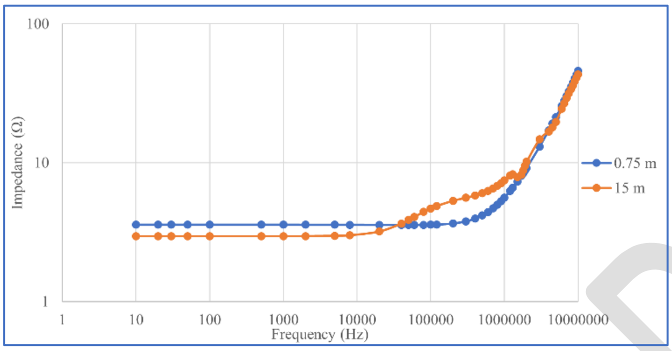
Fig. 3. Evolution of earthing resistance for different conditions using 4.5m length aligned earth rods.

For the same earthing resistance (5 ohms in the example), various pairs (number of rods, electrodes spacing) can be considered. This means that the increase of the number of rods can help with the decrease in the electrodes spacing and vice versa. It is obvious that the final selection shall depend on the site where the earthing system will be installed and on the system cost.

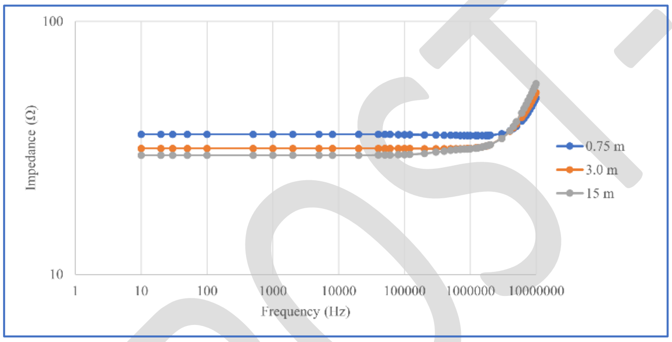
In most cases, one is limited by a well-defined area and the electrodes pacing cannot take very large values. In this situation, one sometimes considers a short interelectrode spacing with a large number of rods in order to achieve the desired earthing resistance. However, short separations between electrodes can result in an inductive component of the system, especially under higher frequencies.

4 High Frequency Impedance

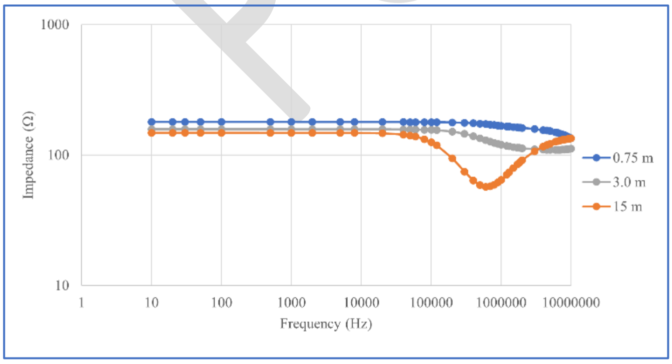
In this section, the effect of the interelectrode spacing is considered where uniform soil model of resistivity varies between 10 and 500 Ω.m is employed. A low magnitude variable frequency current is injected to two aligned earth rods of 1.5 m length each. The system is simulated using HIFREQ module of CDEGS software, and Figure 4 shows the obtained results.



(a) 10 Ω.m soil resistivity



(b) 100 Ω.m soil resistivity



(c) 500 Ω.m soil resistivity

Fig. 4. Impedance as a function of frequency of the injected current for two aligned earth rods of 1.5 m length each.

From the results in Figure 4, it is shown that the separation distance considerably affects the impedance of the earthing system at low and high frequency ranges. Under low frequencies, it was found that the impedance of the earthing system is directly proportional to the electrode length, and interelectrode spacing (similar to the analytical calculations in the previous section). This impedance is inversely proportional to soil resistivity. However, the process is more complicated at high frequency range.

Any earthing combination presents resistive, inductive, and capacitive effects. For any given earthing system, its behaviour is practically resistive up to a certain frequency, which is called the characteristic or the break frequency [7]. Above such a frequency, the earthing behaviour is governed by the conductance since the capacitive current dispersed into the soil are negligible. Beyond this characteristic frequency, the electrode has either an inductive and/or a capacitive response based on numerous factors such as the electrode length and soil electrical parameters. The inductive component increases with the length of the conductors and the electrodes length. It becomes more pertinent for soils with low resistivities. The capacitive behaviour increases with the soil resistivity and the effect of soil electrical permittivity can be neglected in low resistivity soils.

In order to understand the effect of the electrode length, two earth rods of different lengths are considered. These rods are buried in a soil of 500 Ω.m resistivity where a 15 m distance is considered between them. Figure 5 illustrates the variation of the impedance over frequency.

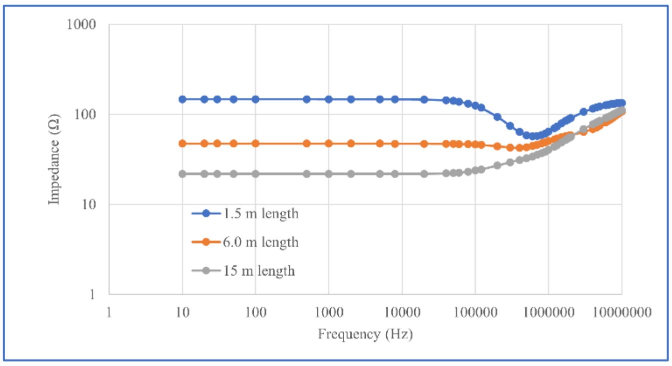


Fig. 5. Evolution of earthing impedance for different lengths (500 Ω.m soil resistivity and 15 m separation distance).

As can be seen in this figure, the effect of the electrode length at a given separation distance is important since approximately the same value of earthing impedance is obtained at very high frequency. This can be explained by the fact that the dissipation of current is local under high frequency and the separation distance does not affect the performance of the system in the same it does under low frequencies.

5 Conclusion

Under low frequencies, it was found that the impedance of the earthing system is directly proportional to the soil resistivity, and inversely proportional to the electrode length and the separation distance. This can be explained by the fact that the electrodes are made of highly conductive materials to have a better dispersion of excessive currents into the soil, and the dissipation increases as long as the soil resistivity decreases. At higher frequencies, overall, the capacitive behaviour of grounding systems increases with soil resistivity while inductive behaviour is proportional to the electrode length.

Increasing the electrode length is a widely used technique to reduce earthing impedance, but it may result in an inductive component that increases the system impedance. This increase will be considerable for shorter interelectrode spacings since the current dissipation is getting more local as the frequency of the injected current increases.

The effect of the separation distance is a complex topic and complementary in-depth studies are essential to define the requirement of such a parameter to provide the better dissipation of current into the soil. In general, the results provide an introductory study that can help defining or outlining the best practices and limits for the electrode length, separation distance and interconnection method in accordance with the characteristics of soil and the injected current.

6 References

[1] BS 7430:2011+A1:2015 Code of practice for protective earthing of electrical installations.

[2] H. E. Messaoudi, O. Kherif, S. Chiheb, M. Teguar and A. Mekhaldi, "Modelling of Vertical Ground Electrode under Lightning Transient," 2019 19th International Symposium on Electromagnetic Fields in Mechatronics, Electrical and Electronic Engineering (ISEF), Nancy, France, 2019.

[3] S. Chiheb, O. Kherif, M. Teguar and A. Mekhaldi, "Incorporation of soil ionization and mutual coupling in transient study of horizontal grounding electrode using TLM," 2017 5th International Conference on Electrical Engineering - Boumerdes (ICEE-B), Boumerdes, Algeria, 2017.

[4] O. Kherif, S. Robson, A. Haddad and D. Thorpe, "On the optimization of Grounding Design of Rods Covered by Low Resistivity Materials," 2022 57th International Universities Power Engineering Conference (UPEC), Istanbul, Turkey, 2022, pp. 1-6, doi: 10.1109/UPEC55022.2022.9917937.

[5] N. Noorudheen and P. Wolfs, "Relative Influence of Rod Spacing and Length on the Thermal and Resistance Properties of Continuously Loaded Earthing Electrodes," 2018 Australasian Universities Power Engineering Conference (AUPEC), Auckland, New Zealand, 2018, pp. 1-6, doi: 10.1109/AUPEC.2018.8757919.

[6] Current Distribution, Electromagnetic Interference, Grounding and Soil Structure Analysis (CDEGS), Safe engineering services, Canada, 2020. [Online]. Available: http://www.sestech.com/products/softpackages/ cdegs.htm

[7] O. Kherif, S. Robson, N. Harid, D. Thorpe and A. Haddad, "On the Behaviour of Vertical Ground Electrodes under High Frequency Currents," 2022 2nd International Conference on Advanced Electrical Engineering (ICAEE), Constantine, Algeria, 2022, pp. 1-5, doi: 10.1109/ICAEE53772.2022.9961998.