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On the HF Performance of Vertical Ground Electrodes and LRM Application

O. Kherif, *Member, IEEE,* S. Robson, *Member, IEEE,* H. Griffiths, *Member, IEEE,* N. Harid, *Member, IEEE,*
D. Thorpe, and A. Haddad, *Member, IEEE*

***Abstract*—This paper addresses the critical need to reduce grounding impedance for the protection of both individuals and electrical equipment under normal and faulty conditions. While numerous techniques exist for low-frequency applications, challenges arise at higher frequencies due to the inductive behavior inherent in grounding systems. The efficacy of Low Resistivity Material (LRM) as a solution to decrease grounding impedance at high frequencies is investigated. Through experimental studies using vertical ground electrodes with varied lengths and some backfilled with a commercial conductive aggregate compound, grounding impedance is analyzed across the frequency range between 10 Hz and 10 MHz. A considerable reduction in grounding impedance is achieved. Based on these findings and other published results, practical insights for designing effective grounding systems are derived, where alternative arrangements are proposed, exhibiting promising results for further enhancing high-frequency performance.**

***Index Terms*—Grounding, grounding impedance, reduction techniques, high frequency, low resistivity materials.**

I. INTRODUCTION

GROUNDING systems play a critical role in electrical installations and power systems. Alongside other protective measures, they ensure the safe operation of power systems and offer a high level of protection against fault and lightning currents [1]. The behavior of grounding systems in power systems has been studied extensively and the contributions from different researchers have greatly improved our understanding of the factors influencing their performance. These include geometrical electrode design, soil electrical parameters and the non-linearities affecting conduction phenomena in soil. Field and laboratory tests have been prevalent in these studies (e.g., [2]–[4]), demanding considerable investments and facing experimental challenges that hinder their development. Studies based on theoretical modeling of grounding have also been conducted by many researchers (e.g., [5]–[8]). Utilizing such models can aid in comprehending the mechanisms of discharge in the ground and contribute to the design of cost-effective grounding systems.

Certain characteristics, parameters, and phenomena related to the dissipation of transient and lightning currents into the soil were often ignored or overlooked in lightning protection applications until recently. With the advancement of measurement methodologies and computer tools, the frequency dependence of soil parameters has become a critical consideration. Experimental results from numerous researchers have shown a significant frequency dependence of these parameters within the range of lightning current components. CIGRE Technical Brochure [9] delves into this aspect thoroughly, detailing the frequency dependence and its implications for the behavior of grounding systems, among other engineering applications. It demonstrates that this frequency dependence can enhance the performance of grounding electrodes, especially in high-resistivity soils. It should be noted that the main performance parameters used for ground electrode design are ground impedance and the safety voltages (touch and step voltage) arising from the flow of fault currents or lightning currents. Various impedance parameters are studied to assess the transient of grounding systems under impulse currents [10]. Minimising the impact of grounding systems on other installations, such as buried pipelines and communication cables or above-ground structures, should also be taken into account [11]. Cost-effective designs of grounding systems under high-frequency and transient conditions must also consider parameters like effective length and area [12].

In the literature, several studies have been conducted to explore the behavior of grounding systems under high-frequency and transient currents (e.g., [13]–[18]). In [13], the authors presented experimental results that visualize the current distribution in the horizontal branches of a grounding grid. They also investigated the performance of the same grid with bonded vertical rods at its corners, aiming to reduce the grounding impedance. Various techniques have been developed or proposed to enhance the performance of grounding systems. For instance, additional conductors were employed to decrease the impulse impedance of vertical ground electrodes [14]. To increase the effective length, the authors in [15] connected an insulated conductor in parallel to an underground bare horizontal electrode, resulting in an improvement in grounding system performance. In other studies [17], [18], researchers explored the behavior of additional low-resistivity materials used for soil treatment, such as Bentonite and soil mixed with NaCl.

Indeed, various techniques have been proposed to reduce grounding resistance, primarily involving the enhancement of the system with additional ground conductors. At high frequencies, grounding systems may exhibit inductive behavior, leading to a significant increase in grounding impedance,

O. Kherif, S. Robson, H. Griffiths, and A. Haddad are with the Advanced High Voltage Engineering Research Centre, School of Engineering, Cardiff University, Cardiff CF24 3AA, UK. e-mail: (KherifO@cardiff.ac.uk ; robsons1@cardiff.ac.uk ; griffithsh@cardiff.ac.uk and haddad@cardiff.ac.uk).

N. Harid is with the Electrical Engineering and Computer Science Department, Khalifa University, P O Box 127788, Abu Dhabi, UAE. e-mail: (noureddine.harid@ku.ac.ae).

D. Thorpe are with Kingsmill Industries (UK) Limited, Pinxton, Derbyshire NG16 6NS, UK. e-mail: (dt@kingsmillearthing.co.uk).

particularly for large-scale systems and soils with low resistivity [16]. Therefore, it becomes crucial to reduce grounding impedance under high-frequency conditions to ensure the proper functioning of lightning protection and surge arresters, which require effective grounding at both low and high frequencies. Further investigations are needed to explore the high-frequency and impulse performance of grounding systems buried in soils with LRM compounds, as studies in this area are limited and some only restricted to DC and power frequency behavior (e.g., [19]–[22]). Additionally, the benefits of exploring the high-frequency behavior of LRM compounds will become more evident in future applications such as grounding of EV charging stations, compact substations and areas prone to severe soil contamination such as acid rain [23].

This paper investigates the reduction of grounding impedance of vertical ground rods subjected to low-magnitude currents across a variable frequency ranging between 10 Hz and 10 MHz. Experimental investigations were conducted using vertical electrodes buried in untreated soil and others backfilled with LRM. Analysis of the measurement results focuses on assessing the impact of electrode length on grounding impedance, employing two distinct vertical ground electrodes. Additionally, the study examines the effect of a commercial conductive aggregate compound covering on grounding behavior across both low and high frequency domains. Electrodes fully or partially embedded in the conductive aggregate compound, were explored. The emphasis is put on grounding impedance and normalized impedance used as metrics to evaluate the grounding system's efficacy. Essential factors for devising resilient grounding systems capable of mitigating low and high frequency interference are elucidated. Two proposed grounding systems undergo rigorous testing, revealing encouraging prospects for advancing the HF performance of grounding installations.

II. EXPERIMENTAL SETUP AND SYSTEM ARRANGEMENTS

A. *Experimental Setup*

Experimental tests were carried out in an outdoor environment at the testing facilities of Cardiff University situated in Cardiff, UK. Fig. 1 presents a graphical representation of the experimental setup for grounding impedance measurement.

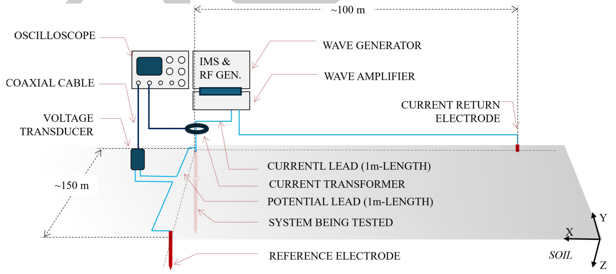


Fig. 1. Representation of the experimental setup

Current measurement employed a current transformer with a sensitivity of 0.1 V/A and a bandwidth of 20 MHz, while voltage measurement was achieved using a differential voltage transducer with a bandwidth of 25 MHz and attenuation ratios of 1/20, 1/50, and 1/200. Throughout each test, the GPR and injected current waveforms were monitored and recorded to ensure control over the measured results where an oscilloscope (LeCroy WaveJet 314) was used. For the AC low voltage tests, the variable-frequency sinusoidal current was injected using two high-frequency sources : (i) the impedance measurement system (IMS) [24] for frequencies from 10 Hz to 8 kHz, and (ii) the radio-frequency generator (RF) for frequencies up to 10 MHz. Fig. 2 presents a photograph of the experimental setup and a description of the components.

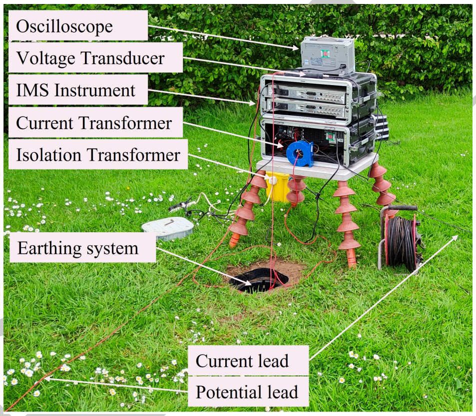


Fig. 2. Photograph of the experimental setup

The potential reference lead is oriented perpendicular to the current return lead to mitigate mutual coupling effects. Specifically, the reference potential electrode is positioned 150 m away from the injection point. Furthermore, the instrument test sources were powered by an AC petrol generator, in conjunction with an isolation transformer, as illustrated in Fig. 2. This arrangement was devised to minimize external interference from the power supply. Additionally, employing the same configuration, DC grounding resistance tests were carried out using two distinct grounding testers (Megger DET2/2 and Chauvin Arnoux C.A.6472).

B. *Soil Resistivity Test and Results*

For soil resistivity measurement, the ABEM Terrameter SAS 1000 ground tester was utilized in conjunction with the Lund Imaging System (LIS). Fig. 3 illustrates the experimental setup for soil resistivity measurements.

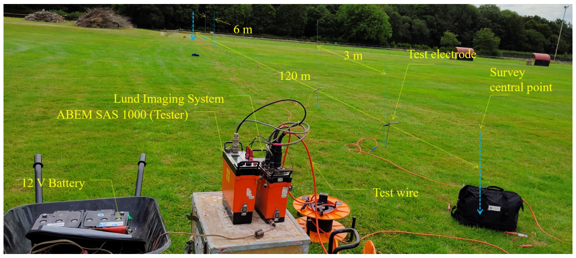


Fig. 3. Experimental setup of soil resistivity test

The Wenner configuration was used, where an array of electrodes arranged in a straight line was place at equal intervals along the survey line. An automatic measurement process and data storage are facilitated by the LIS through its switched sequential measurement process. The system injects a current between a pair of electrodes and measures the potential between two electrodes within the current boundary. This procedure rolls over all electrodes having the same distance, and then repeats with another pair of electrodes with increased distance until all electrode distances are used. In this study, a survey length of 240 m was used. For the inner 120 m of the survey line, the electrode spacing distance was set at 3 m, while for the remaining section, it was set at 6 m.

To obtain resistivity values at different depths, the survey was conducted at multiple positions, denoted as ”i.” By fixing the position ”i” and varying the electrode spacing distance, resistivities were estimated for each depth ”j.” Similarly, by fixing the electrode spacing distance ”j” and varying the position, resistivities were obtained. Usually, a 2-D soil model is generated through this process. However, for grounding purposes, the measured soil apparent resistivity and the average values over the inter-electrode spacing, regardless of lateral variation, are illustrated in Fig. 4.

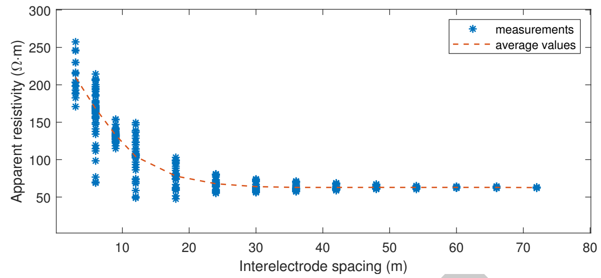


Fig. 4. Measured apparent resistivity at the testing site

It is clear that soil resistivity exhibits significant lateral variation, particularly for depths down to 30 m. The highest value, approximately 264 Ω·m, is observed at shallower depths. Beyond a depth of 30 m, soil resistivity remains relatively constant at around 61 Ω·m. The interpretation of the results was conducted using the RESAP module of CDEGS computer tool. Table I presents the measured soil resistivity results at the test site, which correspond to a two-layer soil model having a upper layer with 197 Ω·m soil resistivity and 4.85 m depth, and an infinite bottom layer of 61.05 Ω·m resistivity.

TABLE I
SOIL RESISTIVITY MODEL

LAYER	RESISTIVITY (Ω·m)	DEPTH (m)
AIR	Infinite	Infinite
TOP LAYER	196.69	4.85
BOTTOM LAYER	61.05	Infinite

C. Conductive Aggregate Compound

A commercial soil enhancement material (i.e., a granular material made of carbonaceous compound) is used in this work where specific product name is omitted for neutrality. The electrical resistivity of this compound was assessed following the standardized testing procedure outlined in IEC 62561-7 [25]. Fig. 5 depicts the testing process alongside sample details.

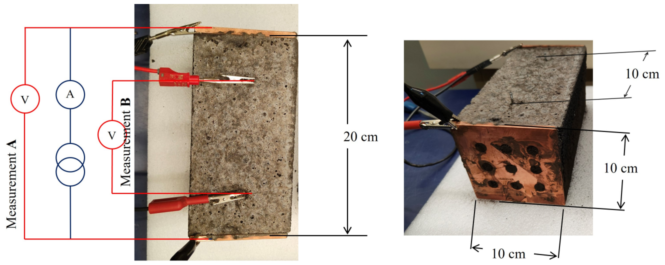


Fig. 5. Testing setup and LRM samples visualisation

The preparation of the mixture followed the manufacturer’s guidelines, which specified the combination of 6 litres of tap water with 25 Kg of the LRM to achieve the desired consistency. Samples were meticulously shaped into rectangles with dimensions of 10x10x20 cm^3, where the conductive material was mixed with water and left to dry for a period of three days. An electrical current was systematically injected, and the resulting voltage was recorded. Two-electrode and four-electrode configurations were used for measuring the impedance, as illustrated in Fig. 5. The IMS instrument was utilized for conducting these measurements. Fig. 6 shows the measured resistivity across the entire frequency range.

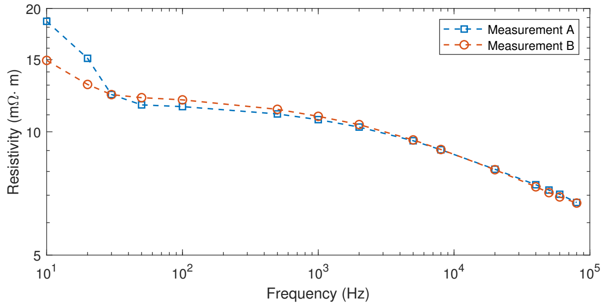


Fig. 6. Electrical resistivity of a conductive aggregate compound sample subjected to current of frequency ranging between 10 Hz and 100 kHz

Fig. 6 shows that the resistivity decreases with frequency. The figure is characterized by three distinct regions: (i) a low frequency region for frequencies below 50Hz, where a sharp decrease is observed, (ii) a plateau region between 50 Hz and about 1 kHz where the resistivity drops only slightly with frequency, and a high frequency region for frequencies above 1 kHz where the resistivity decreases at a relatively higher rate. This result is consistent with the results published by various authors on different soil and rock samples [26], [27]. As is well known, the resistivity of the LRM compound is greatly influenced by the moisture content in the compound, but other influencing factors to consider are the micro-structure of the material and the ionic concentration of salts because they also control the conduction through the medium.

Initially, at low frequencies, the material exhibited a resistivity value of approximately 0.0175 Ω·m, progressively decreasing to 0.0066 Ω·m at 100 kHz, representing a reduction rate of 42.86%. It is important to note that both measurement techniques (A and B) yielded noticeable differences at low frequencies. The electrode-medium interface effects associated with the capacitive double layer affects the measured resistivity at low and very low frequencies. The decrease in the compound's resistivity with frequency is a well known phenomena for dielectrics and semi-conductive media, and can be explained using Debye's or Cole-Cole models for example. However, it will be useful to characterize the sample's dielectric properties and extract resistivity and permittivity variations from these studies. The increase in resistivity at low frequency is attributed to electrode interface effects and can be corrected for by conducting combined two- and four-terminal measurements under similar test conditions or using special electrode material such as platinum electrodes. However, it can be concluded that for power frequency grounding applications, the resistivity of the LRM under study for a given moisture content can be considered constant. At high frequencies, the resistivity starts to decrease and is expected to decrease further at frequencies within the lightning current range, as was already established by various researchers (e.g., [8]).

D. Grounding System Configurations

Cylindrical-shaped ground electrodes are frequently utilized for grounding installations, either as the main system or for reinforcement purposes. Vertical rods, in particular, have received significant attention from researchers and engineers due to their ability to be buried in stratified soils, achieving lower resistivity values [10]. In this study, a total of seven ground electrodes, with and without a conductive aggregate compound coverings, have been included in this study. Firstly, the frequency response of vertical electrodes with lengths of 1.2, 1.5, 2.4 and 4.8 m (designated as Rod-1, Rod-2, Rod-3 and Rod-4, respectively) is analyzed to examine the inductive effect associated with the electrode length. All electrodes are made of copper and have a radius of 8 mm.

Moreover, the impact of soil treatment using low-resistivity materials on reducing grounding impedance is considered by partially or fully covering them with the conductive aggregate compound. The LRM was prepared by mixing it with a specified percentage of water content, transforming it into a slurry mixture, which was then poured into the hole. Fig. 7 illustrates a representation of electrodes with or without a conductive aggregate compound coverings, specifically in the partially covered case.

In this configuration, the ground electrode (referred to as LRM-R) is covered by a cylindrical shape of a conductive aggregate compound with a radius of 0.2 m and a length of 0.45 m. The conductive aggregate compound is characterized by a DC resistivity of 0.02 Ω.m. For electrodes fully embedded in a conductive aggregate compound, two short electrodes with lengths of 0.45 and 0.35 m are considered, both having radii of 0.004 m. Fig. 8 provides an illustration of the systems under consideration.

In Fig. 8, the first system, denoted as LRM-C, comprises a 0.45m-length electrode with a conductive aggregate compound arranged in a cylindrical shape measuring 0.05 m×0.4 m. The second system, LRM-S, involves a 0.35m-length electrode with a conductive aggregate compound covering forming approximately a cubic volume measuring 0.2 m×0.2 m×0.25 m.

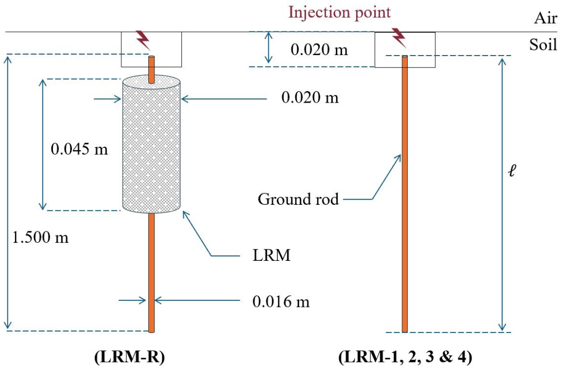


Fig. 7. Representation of vertical ground electrodes with and without LRM

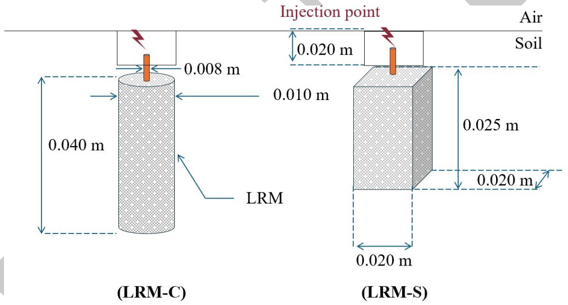


Fig. 8. Configurations of vertical ground electrodes fully backfilled with a conductive aggregate compound

It is worth noting that all systems were installed practically at the same time and buried in the same area. The measurements were carried out three months after the installation date to ensure a good contact between all the systems and the ground.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

The impedance, also known as harmonic impedance, is calculated using the following formula:

$$Z(\omega) = \frac{v(\omega)}{i(\omega)} \tag{1}$$

Here, $i(\omega)$ represents the current of frequency ω injected into the grounding system, and $v(\omega)$ is the voltage measured between the injection and potential reference points. Additionally, the impedance normalized to the DC resistance value is considered, expressed by the ratio Z/R. In this context, the response of the grounding electrode is regarded as dominantly resistive when $Z = R$, capacitive when $Z < R$, or inductive in the case of $Z > R$ for any given frequency of the injected current.

The discussion that follows relates only to the results obtained in the test site described in this paper and is hence valid for the specific soil structure and resistivity at the site, as defined in Table I and for the LRM compound prepared for this study.

A. Grounding DC Resistance

As is well known, the impedance of grounding systems is affected by several factors, including the system dimensions and prevailing seasonal conditions such as temperature and rain. To avoid the effect of seasonal variation on the grounding systems under test, all measurements were carried out during the same period. Table II provides the measured DC resistance of the proposed grounding systems.

TABLE II
DC RESISTANCE (IN Ω) OF THE PROPOSED GROUNDING ELECTRODES MEASURED USING TWO INSTRUMENTS

SYSTEM	CHAUVIN ARNOUX	MEGGER DET 2/2	
		LOW	HIGH
Rod-1	151.4		
Rod-2	109	112	110
Rod-3	53.3		
Rod-4	19	19	19
LRM-R	84.5	84.7	84.3
LRM-C	146	146.8	146.3
LRM-S	256	256	256

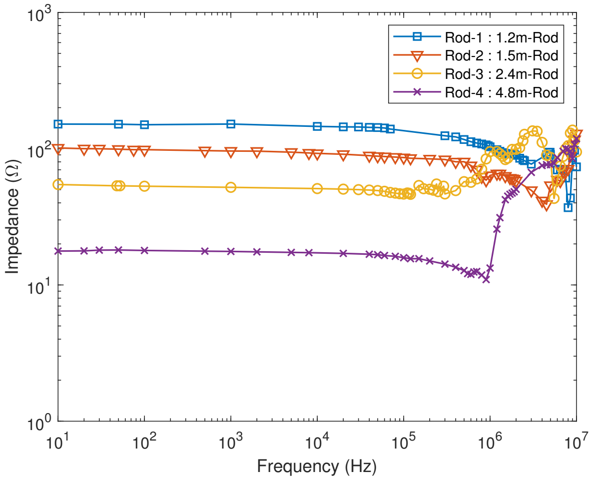
These results affirm that the grounding DC resistance is proportional to the electrode length; longer electrodes exhibit lower resistance. For instance, Rod-1, with a length of 1.2m, has a 130 Ω resistance, while Rod-4, measuring 4.8 m, registers 19 Ω. This translates to an 85.42% reduction in grounding resistance when the length is increased fourfold. This reduction rate emphasizes the effectiveness of augmenting electrode length in diminishing DC resistance. However, this enhancement comes at a cost, as installation expenses are roughly quadrupled due to the increased quantity of grounding material (excluding coupling accessories). In certain situations, constraints such as depth limitations may make it challenging to employ longer rods, prompting engineers and researchers to explore cost-effective reduction techniques. One approach involves using multiple electrodes or a ground grid. For sites with limited space, these techniques may not be practical, and a common alternative is the use of low-resistivity materials. This approach, solely or in combination with the aforementioned techniques, is also favored in rocky areas where deploying longer or multiple rods is challenging and may not yield satisfactory resistance due to the relatively high resistivity.

The findings presented in Table II reveal that the dc resistance can be reduced by up to 22%, which shows the effectiveness of LRM. For short electrodes fully covered with the conductive aggregate compound, the grounding resistance depends on the geometrical configuration of the studied system (146 and 252 Ω for the LRM-C rod and LMR-S rods, respectively). Both electrodes display higher resistance levels compared to other systems. However, it might be cost-effective to install multiple systems (LRM-C or LRM-S) connected in parallel to achieve lower resistance values.

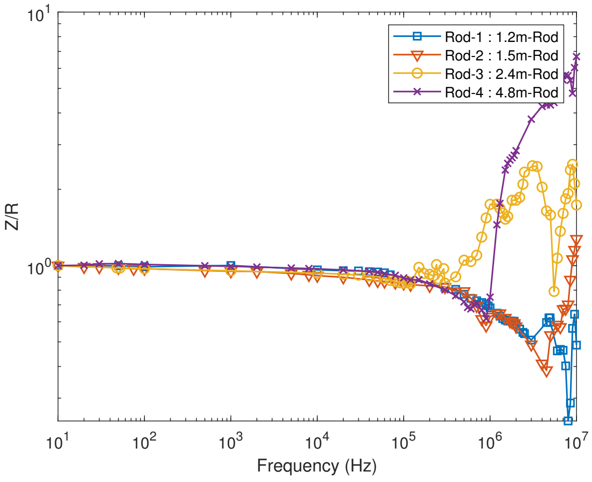
In practical applications, a cost analysis should be conducted to determine the most suitable grounding system configuration. This is imperative due to the relatively high cost of some commercially available LRM-S compared to conventional electrodes, especially in areas with low soil resistivity and/or no space limitations. Moreover, it is crucial to recognize that a comprehensive grounding study should consider safety parameters, as relying solely on a single electrode cannot guarantee a safe GPR in substations for example.

B. Electrode HF Performance

HF performance of vertical ground electrodes of 1.2, 1.5, 2.4 and 4.8m lengths are considered, all buried in the two-layer soil. Fig. 9 illustrates the measured impedance of the studied ground electrodes, including the normalised impedance of each system.



(a) Grounding impedance



(b) Normalised impedance (Z/R ratio)

Fig. 9. Impedance of vertical ground electrodes subjected to current of frequency between 10 Hz and 10 MHz

From Fig. 9a, one can assume that the rods show the same trend. Generally, all of them are constant at low and medium frequencies up to a ”cut-off” frequency that varies with the electrode length. For frequencies higher than the cut-off frequency, the impedance starts to fall non-linearly, consistent with the reduction in resistivity with frequency shown in Fig. 6. Some electrodes present more complex behavior at higher frequency, where the impedance shows resonant peaks and troughs occurring at certain resonant frequencies that are dependent on electrode length. Analysis of this behavior requires knowledge of the variations with frequency of the soil resistivity and permittivity, both behaving non-linearly, and depend on the subsurface soil layers.

At higher frequencies, all rod electrodes exhibit an inductive behavior, mostly apparent in the 4.8-m rod characteristic, rising from 10 Ω at 1 MHz to around 120 Ω at 10 MHz. Regarding the 1.5m-length electrode, for comparative purposes, the capacitive behavior lasts longer compared to the 4.8m-length electrode. In this case, the inductive behavior becomes dominant at frequencies higher than approximately 5 MHz, and the grounding impedance increases from 40 to 130 Ω at 10 MHz.

In general, a significant reduction in grounding impedance can be achieved in the low-frequency range by increasing the electrode length. However, this length increment may lead to the emergence of high-magnitude inductive behavior at high-frequency currents. As depicted in Fig. 9b, the impedance increased by 30% for the shorter electrode against 500% for the longer electrode under frequencies up to 10 MHz. This outcome underscores the importance of developing or finding a technique that can be used to mitigate grounding impedance at this frequency range without compromising its performance under lower frequencies. This becomes essential in application that involve an effective protection against transient currents originated from various sources (e.g., lightning transients).

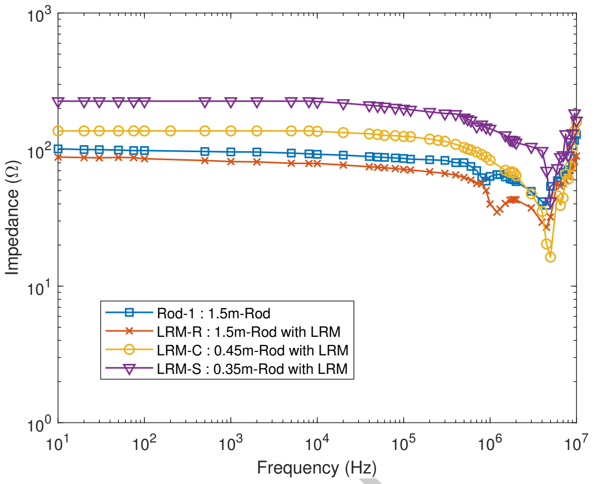
C. Electrodes with LRM

A variable-frequency current up to 10 MHz is injected into the four vertical ground electrodes, namely; Rod-1, Rod-R, LRM-C, and LRM-S. For each of them, the grounding impedance is measured and presented, in Fig. 10, as a function of frequency. The normalized impedance is also presented.

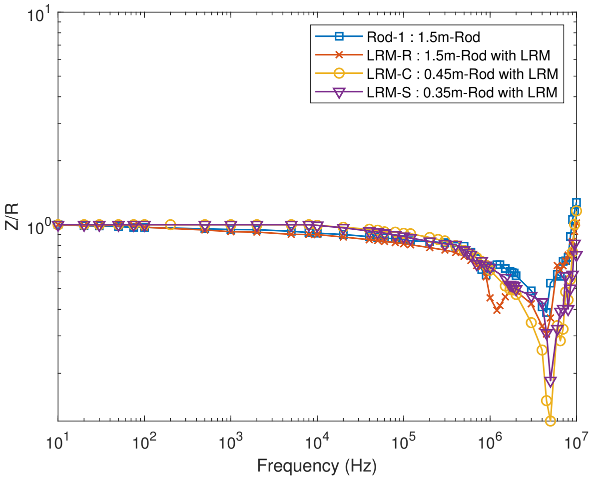
In Fig. 10a, a resistive behavior is observed at low frequencies up to 1 kHz. For high frequencies up to 5 MHz, the behavior becomes mostly capacitive, reaching its lowest impedance. An inductive behavior is noted for the systems when the injected current frequency exceeds 5 MHz, leading to the highest grounding impedance in the considered frequency range. In the case of a rod partially backfilled with a conductive aggregate compound (LRM-R), an impedance of approximately 80 Ω is achieved at low frequency. This value corresponds to a reduction of over 20% compared to an electrode of the same length without a conductive aggregate compound covering.

From Fig. 10b, the Z/R ratio is around or below unity for LRM-R all over the selected frequencies. This indicates that, under the given test conditions, the increase in grounding impedance at high frequency is practically below or equal to that due to the capacitive effect of the grounding impedance. An impedance equal to that observed in low-frequency measurements is achieved, contrary to a long electrode without LRM coverings, as illustrated in Fig. 9b.

Both systems are fully covered with LRM, and characterised by copper electrodes of lengths less than 0.5 m and a very small radius of 0.004 m. This is why they show an impedance higher than that obtained for 1.5m-length vertical ground electrodes, either with or without LRM coverings. For frequencies higher than the characteristic one, the impedance shows a slight decrease for all the proposed systems. This decrease becomes important for frequencies between 0.6 and 7 MHz, where the impedance reaches its lowest value. For higher frequencies up to 10 MHz, the impedance shows a considerable increase of less than 10% as can be seen in Fig. 10b. Regarding the normalised impedance (Z/R ratio), values below 1.2 are obtained for both systems, indicating an acceptable amount of increase within the impedance under high frequency condition (i.e., impedance around the DC resistance).



(a) Grounding impedance



(b) Normalised impedance (Z/R ratio)

Fig. 10. Impedance of the four grounding systems subjected to current of variable frequency up to 10 MHz

From the above results, it can be concluded that while inductive behavior is prominent in soils of low resistivity, using low-resistivity materials can be an effective solution also for high-resistivity soils. The contribution of low-resistivity material is not only to reduce the impulse impedance but also to make the cut-off frequency at which inductive effects start to appear approximately the same for all rod lengths as shown in Fig. 10b. This is of great benefit for the design engineer where a more uniform HF frequency behavior is obtained for rods backfilled with LRM compared to rods buried directly in the soil.

IV. RESULTS EXPLOITATION AND DISCUSSION

Grounding impedance behaves distinctly across frequency ranges, influenced by factors like injected current and soil characteristics. Lightning discharges, for instance, induce transient effects due to fast rise-time of impulse currents, presenting stark differences from low-frequency behavior. Additionally, soil ionization is another aspect that impact the grounding impedance. Notably, shorter electrodes may outperform longer ones, sparking discussions on effective lengths in various studies. While this paper does not delve into these topics, recognizing their importance suggests avenues for different research. Effective surge arresters are crucial for personnel safety and equipment protection during lightning and switching transient events, highlighting the necessity of efficient grounding systems. This section offers considerations and cost-effective solutions for grounding system design, drawing from diverse research, including experimental tests comparing different configurations with a 1.5m-length ground electrode.

A. Considerations in Grounding Design

Drawing from both the measured results in this investigation and insights gleaned from pertinent literature ([10], [14], [16], [17], [28]–[32]), the design of effective grounding systems under high-frequency conditions should prioritize several key considerations for cost-effective performance. These considerations should be taken into account in addition to those already established in international standards for the low-frequency range.

1) **Electrode disposition :** Compared to other grounding arrangements, vertical electrodes are practically more efficient under high frequency and transient currents leading to considerably a smaller inductive component [10], [28]. In addition, arrangements of inclined electrodes can be more efficient than the horizontal ones [28].

2) **Electrode length :** Grounding resistance typically scales with electrode length, indicating that longer rods offer lower resistance in low-frequency settings. However, this research uncovers a notable inductive element for lengthy electrodes exposed to high-frequency currents. Consequently, long electrodes are best suited for low-frequency tasks, while shorter ones are preferable for high-frequency applications to curb the influence of this inductive element in grounding impedance. Determining the boundary between short and long electrodes should hinge on soil resistivity and fault characteristics.

   Moreover, designing and installing effective grounding systems in densely populated regions with restricted access pose considerable challenges for both individuals and power utilities. Short electrodes may be essential to navigate space constraints while upholding safety and performance standards.

   Based on the experimental results in [14], the effective area of the grounding system can be increased by utilising small enhancement electrodes, improving the grounding performance at frequencies in excess of 2 MHz. It should be noted that the number of the additional arms should be optimal since it was found, from calculations in [28], that the mutual resistance between the electrode arms increases with the number of additional arms. For this reason, authors in [28] proposed a few steps that can be considered when searching for a grounding electrode arrangement with the smallest total conductor length and minimal voltage peaks. A concept of ”effective volume” was introduced to visualise the process of effective length increase by adding electrodes connected to the current injection point.

3) **Electrode backfilled with LRM :** Covering electrodes with LRM is a widespread method to decrease grounding resistance, particularly effective in high resistivity soils and at industrial frequencies as noted by Meng et *al.* [29]. This paper further confirms the efficacy of this approach, demonstrating that using a commercial conductive aggregate compound to cover electrodes enhances the high-frequency performance of grounding systems. Moreover, a couple of experimental works were conducted on the LRM behavior at the high frequency range, and the results were generally positive. For instance, experimental works in [17] found that the electrical resistivity of LRM decreases with both the moisture content and the frequency. At a given moisture content, it was found that electrical resistivity shows a considerable decrease with frequency up to the range 600-700 Hz. For higher frequencies up to 100 kHz, the resistivity shows a slight decrease. Authors in [17] used different combinations of materials, and the reduction rate reached more than 50%.

   Numerical results in [30] showed the existence of LRM, in grounding systems, can reduce temperature rise on the system electrodes. This may be explained by the fact that the additional materials (of resistivity lower than that of the soil) facilitate the current dissipation into the soil (in a short duration), avoiding the rise of temperature and improving the performance of the grounding system. In addition, these materials may be useful in protecting the grounding conductors from corrosion. Such information should be examined to provide a clear vision about other benefits of such materials.

   Given the benefits outlined, integrating additional LRM into grounding designs is advisable across both low and high-frequency ranges, regardless of soil resistivity levels. This becomes particularly relevant in scenarios involving rocky soil or constrained project spaces where multiple aligned rods are impractical for achieving lower resistance or impedance. However, it is essential to conduct a cost analysis as certain LRM options may be relatively expensive compared to traditional rods.

4) **Multi-layer soil :**
A horizontally stratified multi-layer soil with plane boundaries is usually considered in grounding studies. In such soil structures, it was found in literature (e.g., [31], [32]) that the characteristics of the lower layer have a dominant influence at lower frequencies. At higher frequency, however, the electric fields become more localised, and the upper layer becomes dominant. Considering these results, it is clear that electrode location in multi-layer soils should be considered when designing grounding systems.

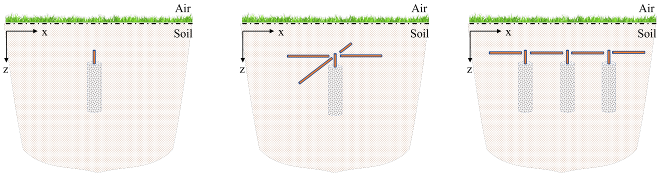
The final consideration pertains to the necessity of testing, measuring, and periodically inspecting the grounding system to ensure both its physical integrity and low impedance. For large-scale projects like substations, grounding takes on added complexity, involving safety parameters such as touch, step, and transfer voltages. Understanding the behavior of individual rods in such contexts aids in grasping the broader principles of substation grounding system. Furthermore, flexibility in designing grounding systems allows for various arrangements and configurations to be considered, necessitating cost analysis to select the most suitable option that aligns with project requirements and navigates site constraints effectively.

B. Design Arrangements and Example Results

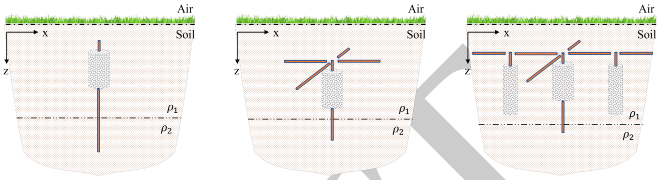
It is clear that several cost-effective designs of grounding systems (for application at low and high frequency ranges) can be suggested by taking the previous considerations into account. Such designs can also consider many other factors such as the total covering area where the system should be installed. In small areas, for instance, Figs. 11a and 11b show some possible combinations of grounding electrodes buried in single- or two-layer soil, respectively.

For soils with an upper layer of low resistivity, it would be better to use a combination of short electrodes enhanced by additional arms and/or covered with LRM as represented in Fig. 11a. In this combination, the effective volume should be considered as discussed in [28]. For soils with an upper layer of high resistivity, one electrode or more can be driven into the ground in order to reach the layers of low resistivity as represented in Fig. 11b. These longer electrodes, partially or fully covered with LRM, can help reduce the impedance furthermore without increasing the occupied area by the grounding system.

In principle, additional short electrodes along with LRM coverings can help improve the overall impedance at low and high frequency ranges, and this in soils having either low or high resistivity. For this, further combinations are considered in this section. Fig. 12 illustrates two selected grounding systems.

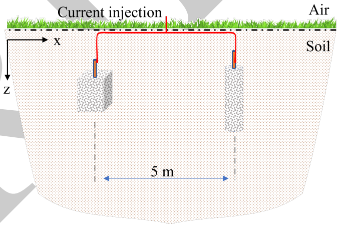


(a) Upper layer of low resistivity

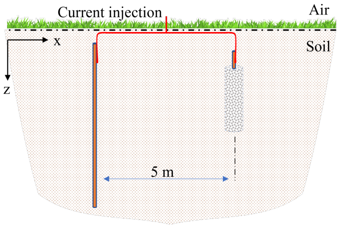


(b) Upper layer of high resistivity

Fig. 11. Combinations of grounding electrodes in uniform and two-layer soils



(a) Combination 1



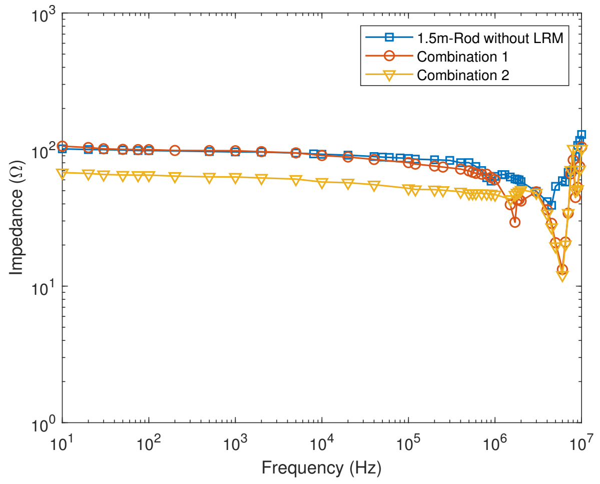
(b) Combination 2

Fig. 12. Representation of two selected combinations of grounding electrodes with a conductive aggregate compound covering

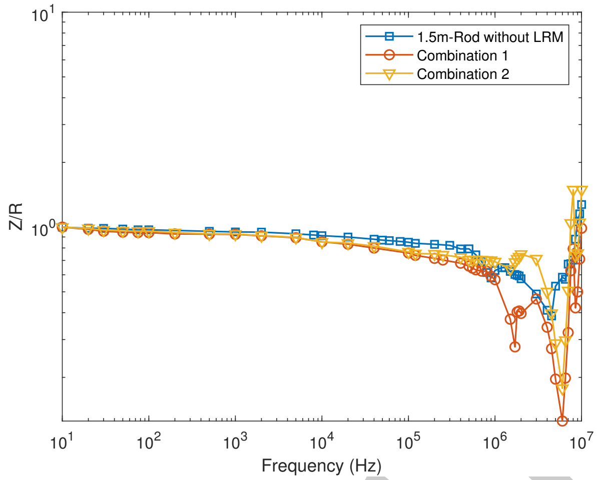
As shown in Fig. 12a, the first combination consists of two short electrodes fully covered with LRM, those presented previously (LRMC and LRMS). The second combination in Fig. 12b groups a vertical electrode of 1.5 m length enhanced by a short electrode fully covered with a conductive aggregate compound (Combination 2 is Rod-1 connected with LRM-C). In both combinations, the distance between each system is 5 m as indicated in Fig. 12.

Fig. 13a shows the measured grounding impedance for the proposed combinations. In Fig. 13b, the impedance-resistance ratio is presented in order to quantify the amount of variation in the impedance components. In both figures, the results of 1.5m-rod have been included for a comparison purpose.

In general, both combinations provide good impedance variation over frequency compared to the results of a single vertical rod. Even though the total length of used electrodes is 0.8 m in combination 1, it provides approximately the same impedance as the 1.5m-rod at low frequency range. At high frequency range, combination 1 presents better performance



(a) Grounding impedance



(b) Normalised impedance (Z/R ratio)

Fig. 13. Impedance and normalised impedance as a function of frequency obtained for the two proposed combinations

compared to the 1.5m-rod, confirming the capability of LRM to reduce the impedance and provide an economic grounding system. Regarding the second combination, it provides the best performance compared to the other proposed systems. The impedance of the single grounding rod is decreased by 30% when it is enhanced by LRM-C. Such findings prove the possibility to design cost-effective grounding systems using LRM instead of enlarging the size of the grounding system.

V. CONCLUSION

The performance of grounding systems with and without a conductive aggregate compound covering was analysed in this paper in order to examine the LRM use as a minimisation technique of grounding impedance. Experimental investigations were conducted by employing several vertical ground electrodes subjected to current of variable frequency up to 10 MHz. The following conclusions are also drawn.

1) It was found that increasing electrode length represents an effective tool to reduce the grounding impedance at low frequencies, which is not the case for higher frequencies where an inductive behavior is observed with the electrode length.
2) The use of a conductive aggregate compound represents an effective technique to reduce the grounding impedance and provide an economic system. A reduction rate of more than 20% was obtained over frequency for the electrode partially covered with a conductive aggregate compound.
3) The normalised impedance (Z/R ratio) is around the unit for electrode covered (partially or totally) with a conductive aggregate compound, leading to conclude that the material helps obtain a reduced grounding impedance and avoid the significant impedance rise at higher frequencies.

It is envisaged, for the future, to complement the findings of the present work by an extensive computer simulation study. In addition to making a comparison between the theoretical and experimental results for validation, the study would explore the effect of major influencing parameters such as the frequency-dependence of soil parameters, the non-linear effects related to current density, and soil and LRM structure and the geometry and configuration of the grounding system. Exploring how these materials can mitigate temperature rise in grounding conductors and protect the system against corrosion are among the various aspects that could contribute to the understanding of LRM benefits.

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