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Grounding Impedance Characteristics for Two-Layer Soil of Vertical Rod Configuration with Variation of Length and Diameter

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Abstracts: Grounding impedance is an important component of electrical power systems especially for protection for human safety and the continuity of the operation of power systems. At low frequency current injection the characteristics of grounding impedance is very resistive, however at high frequency it may be capacitive or inductive depending on the frequency. In order to build a grounding system used for lightning protection, it needs a careful and accurate design. It will receive high current and high frequency around hundred kilos up to mega hertz, otherwise it is simple grounding for low frequency. This paper reports the modification of a grounding system with vertical layers configuration. This is the novel issue because the other researchers use horizontal layers configuration. In this experiment, the grounding rod is injected by using low to high frequency AC source The modification is made by filling the soil into a grounding rod (cylinder rod) and therefore it created two soil layers of grounding system, and by using three size variations of cylindrical layers of length (L) of 40, 60, and 100 cm; and three size variations of diameter (D) of 20, 30, and 40 cm. These variations will allow us to understand the characteristic of the grounding impedance at low and high frequency, where usually the composition of inner layer soil have lower resistance than the outer soil. The composition of the outer soil consist of 16.85 % clay, 66.18 % silt, 15.48 % sand, and 1.49 % gravel whereas the composition for the inner/filling soil consist of 34.98% clay, 49.55% silt, 15.35% sand, and 0.16% gravel. The value of soil permittivity and resistivity affect the value of grounding impedance at low and high frequency. In general, the results indicated that the grounding impedance at high frequency was higher than at low frequency, but the fluctuation of grounding impedance depended on the condition of inner soil, length and diameter of cylindrical rod. In this research, the grounding impedance was plotted as the function of the frequency and until now the value of this fluctuation cannot be determined accurately.

Keywords: grounding impedance, vertical grounding system; soil resistivity; type of soil; soil permittivity

1. Introduction

Electrical grounding system is the simple component in a power system, yet it plays a very urgent and important role in protecting human, equipment, and system safety. NEC defines grounding system as *"a relationship (conduction) either intentionally or unintentionally between the electrical circuit and the ground or connect with conductive objects that are on the ground"*. The grounding impedance depends on the shape and the quantity of current injection, material condition of soil, and grounding configurations [1]. The environment condition determines the grounding configuration design, where in arid or dry soil condition the grounding impedance is usually high. This problem can be solved by modifying the configuration of the grounding system or by treating the soil [2]. The grounding impedance is influenced by several factors,

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which are a) electrodes configuration, b) material composition of soil, and c) shape of current injection. So the general function of grounding impedance is [3]:

$$Z = Z(C, S, I,) \quad (1)$$

Where Z: grounding impedance

C: electrodes configuration (vertical, horizontal, grid or mesh, and combination of grid - vertical)

S: soil material composition (resistivity ρ, permittivity ε, permeability μ)

I: injected current shape (DC, AC or impulse current)

The electrode configuration depends on the soil surface. For narrow soil, the electrode configuration is made by using vertical configuration. For wide soil, the configuration is designed using horizontal or grid configuration. The horizontal or grid grounding impedance has a more stable value than the vertical configuration because the area of grounding space is very large[4].

The electric constants of soil such as resistivity ρ, permittivity ε, and permeability μ depend on the type of soil such as clay, silt, sand, and gravel. These electric constants of different types of soils will be tested to understand its impact to the grounding impedance.

Furthermore, the type of injected current such as DC, impulse, or AC with variety of frequency, affects the grounding impedance. The grounding system used in the power system must be tested using DC or AC with low frequency. The grounding system used for lightning protection must be tested by using impulse or AC with high frequency. It is known that lightning current has high frequency up to mega hertz.

The grounding impedance may be reduced by lengthen the grounding rod. It reduces the resistance but increase the inductance of the grounding rod. The grounding impedance may also be reduced by enlarging the rod diameter. It can be made by modifying the grounding rod with two layers of soil, where the resistivity of inner layer is lower than one of outer layer. In this experiment, the grounding rod is injected by using low to high frequency AC source [5,6].

According to IEEE standard 142-2007 [7-10], the impedance grounding system are proposed for:

a. The current flow of undesirable conduction between grounding systems and conductor must be provided.
b. The permitted potential between earths to boundary must be limited.
c. The value of the grounding impedance needs to be as low as possible.

Transient voltage and electric shock commonly are caused by electrostatic discharge, short circuit, and circuit switching. An effective grounding system can minimize these effects, and grounding system must comply with these requirements [8,10].

a. Use noncorrosive materials of soil and chemical to ensure equipment long-life time.
b. Low impedance path from ground to equipment safety must be effective.
c. Mechanical system is used to repair and maintain when damage happens.
d. The spread of fault and surge current must be detected accurately and timely
e. Large grounding system must be protected physically.

This paper reports the modification of a grounding system with vertical layers configuration. This is the novel issue because the other researchers use horizontal layers configuration. In this experiment, the grounding rod is injected by using low to high frequency AC source The modification is made by filling the soil into a grounding rod (cylinder rod) and therefore it created two soil layers of grounding system, and by using three size variations of cylindrical layers of length (L) of 40, 60, and 100 cm; and three size variations of diameter (D) of 20, 30, and 40 cm. These variations will allow us to understand the characteristic of the grounding impedance at low and high frequency, where usually the composition of inner layer soil have lower resistance than the outer soil. The composition of the outer soil consist of 16.85 % clay, 66.18 % silt, 15.48

impedance fluctuates towards frequency change, hence the equivalent circuit is distributed with several peaks at its resonance frequency.
RLC Formulation for 2 Layers Ground Rod
Calculation of R, L, C for 2 layers ground rod can be calculated using formula on Figure 2.

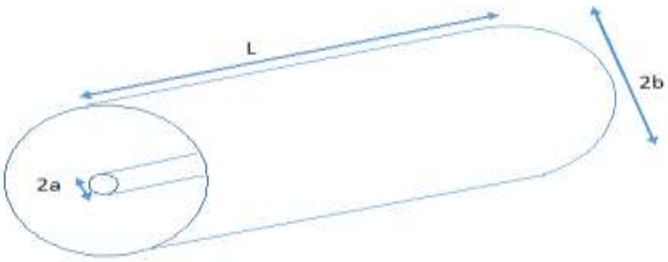

Figure 2. Two-cylinderModel[7]

$$R = \frac{\rho}{2\pi l}\ln\frac{b}{a} \tag{5}$$
$$C = \varepsilon_0\varepsilon_r\frac{2\pi l}{\ln\frac{b}{a}} \tag{6}$$
$$L = \frac{\mu_0 l}{\pi}\ln\frac{b}{a} \tag{7}$$

Where:
R =soil resistance (Ω)
C =soil capacitance (F)
L =soil inductance (H)
ρ =soil resistivity (Ωm)
ε_0 =permittivity(F/m)
b =radius of outer cylinder (m)
ε_r =soil permittivity (F/m)
a = radius of inner cylinder (m)
μ_0 =air permeability (H/m)
l= length of electrode (m)

Based on the equivalent circuit of grounding systems (figure 1c above) the impedance characteristics can be expressed by the equation below .

$$Z = j.\omega.L + \left(\frac{R \big/ j.\omega.C}{R + 1\big/ j.\omega.C} \right) \tag{8}$$

$$Z = \frac{R}{1+[\omega.R.C]^2} + j\varpi\left\{ \frac{L - R^2C + (\omega.R.C)^2 L}{1+[\omega.R.C]^2} \right\} \tag{9}$$

$$Z.\cos\varphi = \frac{R}{1+[\omega.R.C]^2} \tag{10}$$

$$Z.\sin\varphi = j.\omega.\left\{ \frac{L - R^2C + (\omega.R.C)^2 L}{1+[\omega.R.C]^2} \right\}. \tag{11}$$

Above equation can be explained as when the injection of current frequency is very low or equal to zero (Direct Current) then the grounding impedance is:

$$Z_0 = R_0 \tag{12}$$

And at resonance frequency, only the real component of impedance is a dominance but not at zero frequency (f = 0), so the grounding impedance is :

composition and properties study has been almost entirely on the mineralogy and structure of the soil phase, with very little regard for the properties of the liquid phase. The properties and structure of water in soil are not well known in detail, there is no rigorous theory for the structure of pure, liquid water, only a hypothesis. Since neither water nor soil surface are inert chemically, water and soil particles interact with each other. These interactions can be expected to influence the physical and physical-chemical behaviour of the material.

Table 1. Properties of Soil Sample 1 and Soil Sample 2

No.	Parameters	Soil sample 1	Soil sample 2
1.	Water content	48,27 %	41,62 %
2.	Wet density (γ_w)	1,69 t/m^3	1,73 t/m^3
5.	Dry density (γ_d)	1,14 t/m^3	1,22 t/m^3
6.	Specific gravity (G_s)	2,59	2,54
7.	void Ratio (e)	1,27	1,08
8.	Porosity (n)	0,56	0,52
9.	Saturation Degree	98,29 %	97,96 %

Table 2 shows the grain size of Soil Sample 1 and Soil Sample 2. Clays are small crystalline particles of one or more member of small group of minerals. They are primarily hydrous aluminium silicate with magnesium or iron occupying all or parts of the aluminium position in some minerals with alkalis (sodium, potassium) or alkaline earth (calcium, magnesium). Colloid chemistry provides a means for description of interaction in clay-water-electrolyte systems, and make distribution of cations and anions adjacent to clay surface, like capacitor in electrical circuit. [19].

Table 2. Grain size of Soil Sample 1 and Soil Sample 2

No.	Size Category	Soil Sample 1	Soil Sample 2
1.	Clay (< 0.005 mm)	16,85 %	34,98 %
2.	Silt (0.005-0.075 mm)	66,18 %	49,55 %
3.	Sand (0.075-4.75 mm)	15,48 %	15,35 %
4.	Gravel (> 4.75 mm)	1,49 %	0,16 %

Clays are small crystalline particles of one or more member of small group of minerals. They are primarily hydrous aluminium silicate with magnesium or iron occupying all or parts of the aluminium position in some minerals with alkalis (sodium, potassium) or alkaline earth (calcium, magnesium). Colloid chemistry provides a means for description of interaction in clay-water-electrolyte systems, and make distribution of cations and anions adjacent to clay surface, like capacitor in electrical circuit. [19]. According to Porkomenkothat the permittivity of soil and water can be expressed by this equation [20]:

$$\varepsilon_r = (1-\phi)\varepsilon_m + \phi \ \varepsilon_w \tag{19}$$

Where: ε_r = Soil dielectric Constanta; ε_m = Material dielectric Constanta

ε_w = Water dielectric Constanta; ϕ = Porosity of soil

Permittivity value of soil as the function of frequency can be expressed like the equation below

$$\varepsilon = \varepsilon' + j\ \varepsilon'' \tag{20}$$

Figure 5 shows experimental setup of the measurement of grounding rod impedance with two layers soils by using three points method. C0 is a tube as the grounding rod with 20 cm, 30 cm, and 40 cm in diameter and 50 cm in length (b). C1 and C2 are the electrodes made from the copper with a = 30 cm in length. The distance of C0-C1(6.2 meter) is 62 % of the distance of C0-C2 (10 meter).

The measurement system consist of the tube, the function generator, oscilloscope, the elektrodes, and resistor (R = 1 k ohm). The function generator injects current to the grounding measurement system with the 1Hz –15 MHz in frequency and 10 Vpp in voltage. The channel 1 of the oscilloscope displays the voltage of R (V_1). The channel 2 displays the potential difference between C0 and C2 (V_2). The phase angle between V1 and V2 is the phase angle between signals measured in Channel 1 and Channel 2. The current (I) is obtained from $I = \frac{V_1}{R}$. The voltage (V) is obtained from V_2, so $V=V_2$. Therefore, the impedance of grounding system is $Z = \frac{V}{I}$.

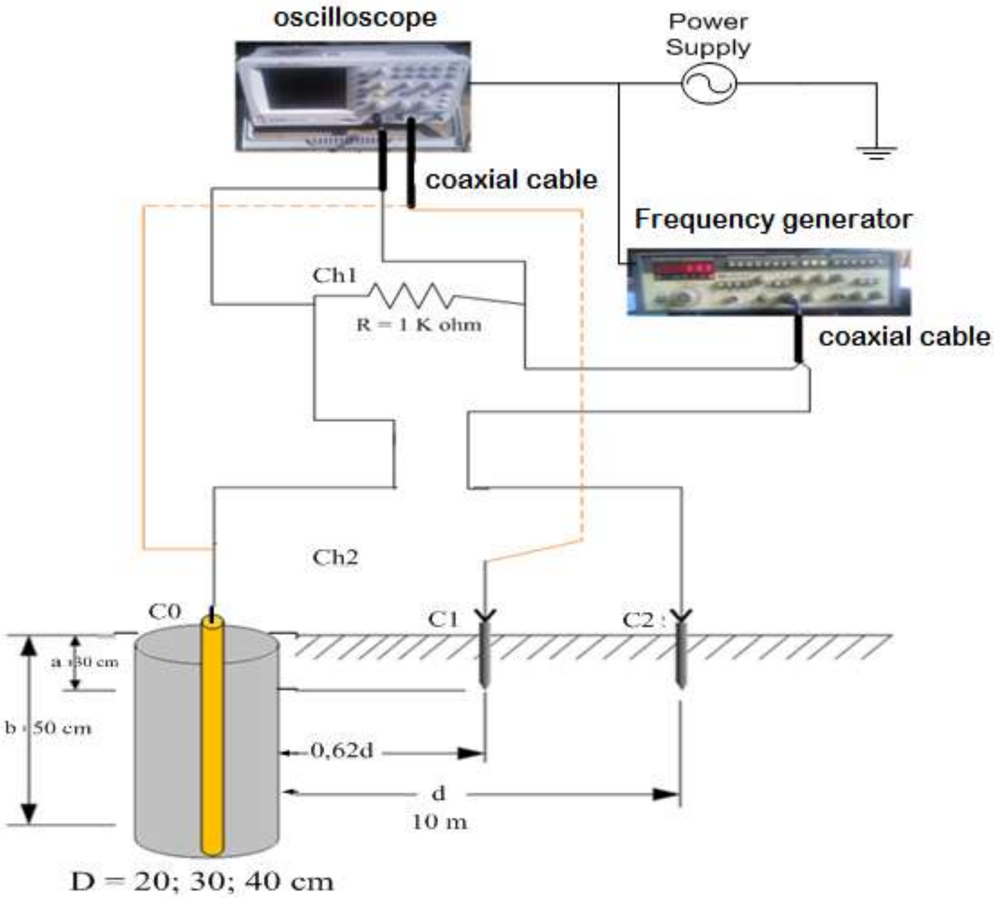

Figure 5. Measurement System of Impedance Grounding System

4. Experimental Results and Analysis

A. Experimental Result Data

In these experiments, three different lengths and diameters of two layers grounding systems were designed. The lengths are 40, 60, and 100 cm with the variation of diameters are 20, 30, and 40 cm. The results of these measurements as the function of frequency can be seen in Table 3.

no more than 40 cm. By considering the characteristic of grounding impedance and soil material compositions then the design of the grounding system can be more accurate and perfect.

The first step to analyse the results of grounding impedance and phase angle of grounding systems as the function of frequency are using dimension ratios of length to diameter (L/D) of the two layers grounding systems. Rod length is equivalent with grounding impedance inductance component, where the longer the rod the more inductive it becomes and the resistance value will be lower than the shorter rod. Soil characteristic will also affect resistivity, when first (inner) layer of rod is filled with low resistivity soil it will has lower resistance than when it filled with high resistivity soil. Therefore, in order to create lower grounding impedance of two layers system, the resistivity of the inner layer must be lower than the outer layer, in this experiment the ratio of resistivity inner / outer is 4.0, and when possible it is recommended to make the ratio of more than 10 which can be achieved by using betonite material for inner layer. Betoniteis soil material with very low resistivity.

- Phase angle for L = 40 cm

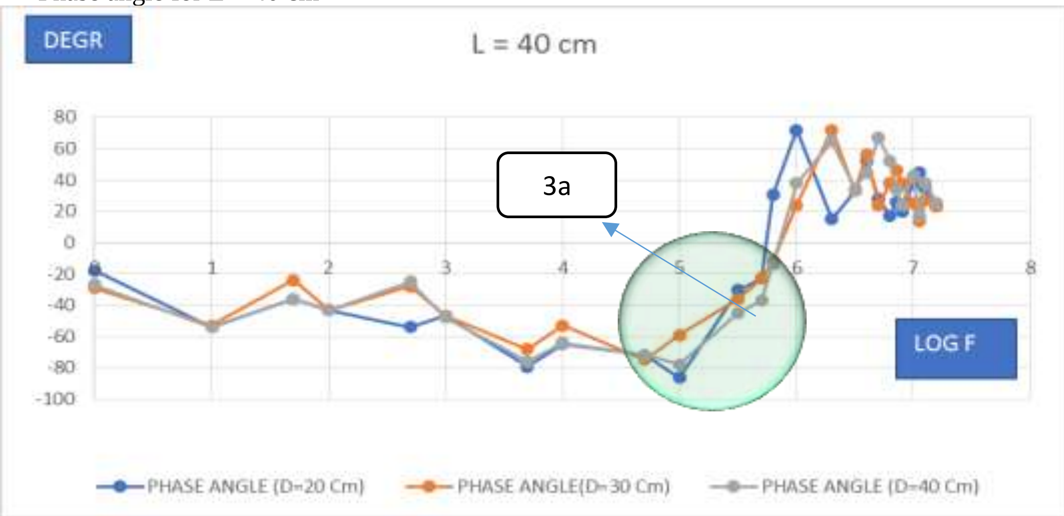

Figure 7. Phase angle Vs Log Frequency for L = 40 cm

Figure 7 shows fluctuation curves of phase angle as the function of frequency for rod with L = 40 cm, it can be seen that at low frequency to several kHz the trend of the phase angle is capacitive or leading. The values of phase angle for D = 20, 30, and 40 cm cannot be compared as it is similar to one another where all diameters show the same trends of gradually increasing from low to high at f=8kHz – 100 kHz and zero "0" at f = 5 – 7 kHz. This frequency is known as resonance frequency and at this frequency the grounding impedance is pure resistive impedance. Above the resonance frequency the phase angle trend is to fluctuates in inductive or lagging mode, and there is some differences the phase angle values for D = 20, 30, and 40cm. The resonance frequency for D = 20 cm is smaller than for D = 30 cm, and for D = 30 cm is smaller than for D = 40 cm, see circle "green" 3a. The fluctuation of phase angle at high frequency is very difficult to predict and also it is different for D = 20 cm, D = 30 cm and D = 40 cm, sometimes the phase angle for D = 20 cm is bigger than for D = 30 and D = 40 cm, but sometimes it is smaller.

There is very importance “thing” to design the 2 layers grounding systems to make very low at high frequency special for lightning protection [23]

- *Phase angle for L = 60 cm*

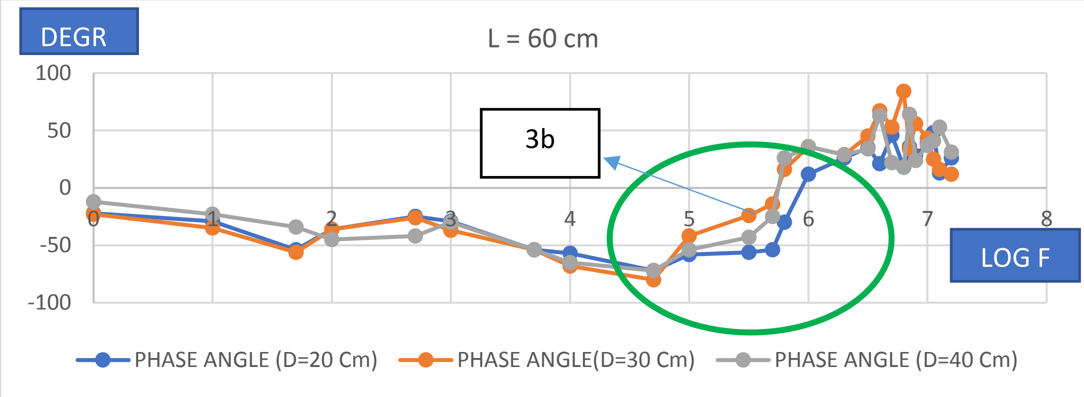

Figure 9. Phase angle Vs Log Frequency for L = 60 cm

Table 5. Impedance and Phase angle for L = 100 cm

		L = 100 Cm ; D = 20 Cm		L = 100 Cm ; D = 30 Cm		L = 100 Cm ; D = 40 Cm	
Frekuensi (Hz)	LOG F	PHASE ANGLE(DEG)	IMPEDANCE (Ohm)	PHASE ANGLE (DEG)	IMPEDANCE (Ohm)	PHASE ANGLE (DEG)	IMPEDANCE (Ohm)
1	0	-15	35	-15	35.9	-23	8.9
10	1	-25	43	-25	43.6	-25	19.6
50	1.7	-8	24	-8	35.2	-8	25.2
100	2	-10	45	-18	54.6	-12	40.6
500	2.7	-29	35	-30	36.4	-29	18.4
1k	3	-27	33	-42	35.7	-34	11.7
5k	3.7	-54	45	-56	46.3	-56	30.3
10k	4	-64	89	-51	89.6	-62	54.6
50k	4.7	-75	135	-68	137.4	-75	98.4
100k	5	-45	122	-42	145.8	-36	68.8
300k	5.5	-22	345	-38	257.3	-22	144.3
500k	5.7	-14	321	-14	342.7	-12	236.7
700k	5.8	-11	475	10	457.5	-23	412.5
1M	6	15	348	25	368.4	26	172.4
2M	6.3	36	462	36	479.2	43	345.2
3M	6.5	26	574	48	586.4	28	478.4
4M	6.6	23	429	26	436.7	37	300.7
5M	6.7	12	347	37	435.7	48	363.7
6M	6.8	48	574	58	587.3	63	391.3
7M	6.85	23	643	29	634.2	51	520.2
8M	6.9	32	358	38	321.4	29	183.4
9M	7	45	321	48	298.6	35	208.6
10M	7.05	34	475	26	378.5	42	232.5
12M	7.1	23	548	18	452.8	13	258.8
14M	7.2	14	672	38	573.8	21	399.8

Figure 9 shows the curves of phase angle as the function of frequency for rod with L = 60 cm. The changes of phase angle at low frequency to f = 1 kHz is relatively small but from f = 1 – 80 kHz the phase angle has a tendency to increase in capacitive mode. Above f = 80 kHz the phase angle tends to decrease to 500 and 700 kHz where then the phase angle is equal to zero = “0”, t this frequency is called as a resonance frequency. D = 30 cm and D = 40 cm have relatively smaller resonance frequency than D = 20 cm, see “green” circle 3b. In this case there is a difference between L= 40 cm and L = 60 cm, where L = 60 cm have inductance value bigger than L = 40 cm, so the lagging mode occur “faster” for L = 60 cm. When tested with frequency above resonance, the phase angle for all diameters are very fluctuated and the value of phase angle cannot be predicted accurately, it is identified that for D = 40 cm and D = 30 cm the phase angle are bigger than for D = 20 cm in inductive mode, it means that the grounding system with long rod have more inductance than resistance component. This fluctuation of the phase angle

10, and 11 are compared it can be assumed that phase angle of grounding impedance are affected significantly by a rod length of the inductive part of grounding impedance and soil mineralogy. This experiment proves that the equivalent circuit for grounding system for high frequency is a distributed circuit, which also has been presented by Dawalibi and Mukedar [12]Please refer to Figure 7, 9, and 11 to see all of the peaks at different frequencies and above 1 MHz, circled "green" 3a, 3 b, and 3c.

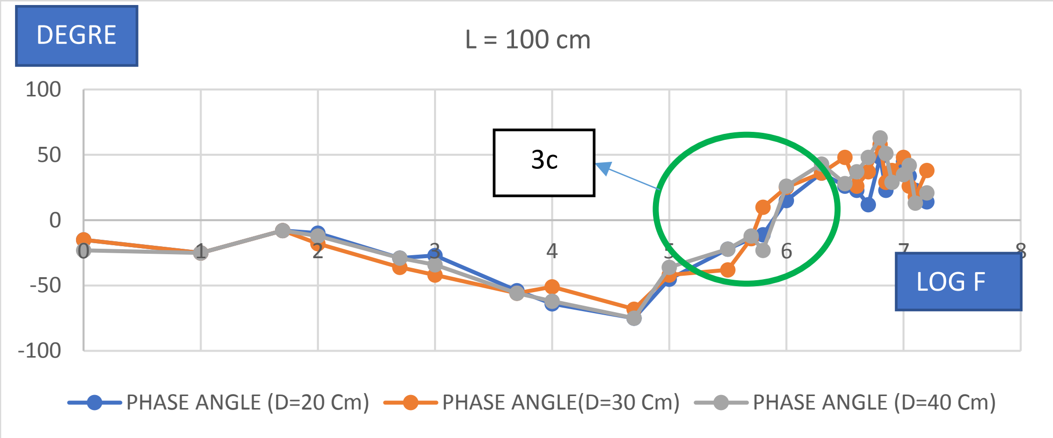

Figure 11. Phase angle Vs Log Frequency for L = 100 cm

If the grounding impedance have more than one peak it means that the value is highly dependent on the frequency which makes it difficult to predict the real value of grounding impedance. The equivalent circuit of grounding impedance of Z = L + (R//C) is not a "lumped circuit" as shown in Figure 1c but rather a "distributed circuit" as Figure 1d that have been proposed byDawalibi and Mukedar [12]. It is known that the grounding impedance $Z = Z_1 + Z_2 + \ldots + Z_n$, $Z_1 = L_1 + (R_1//C_1)$ …… $Z_n = L_n + (R_n//C_n)$ and every segment of Z $_{(1,2..n)}$ have one (1) resonance frequency, therefore the reason why grounding impedance at high frequency have many peaks is still in question. To date there is no experiment that has mention how to divide the total impedance Z into several impedance of segment $Z_1 \ldots Z_n$ and what is the requirement to make equivalent impedance to be "lumped" or "distributed" including the ratio of dimension or ratio of resistivity and permittivity of soil. All of these conditions are caused by the grounding configuration and material conditions.

If the analysis of soil material components, porosity, water content be done accurately and the configuration can be defined well then it is possible to predict the "real" value of grounding impedance at many frequencies. During this experiment the resonance frequency occurs at about 400 – 800 kHz as stated in equation 15 above, and the value of grounding impedance equal to the resistance (Z = R). However, at high frequency the grounding resistance is higher than when at low frequency. The reason why this condition occurs in this experiment is because at high frequency resonance the permittivity of soil has ε" which is in the same direction of resistance (Cole-Cole diagram) see figure 3 and equation (20), therefore it will add to the value of the resistance of grounding impedance.

5. Conclusion

This paper reports the modification of a grounding system with vertical layers configuration. This is the novel issue because the other researchers use horizontal layers configuration. In this experiment, the grounding rod is injected by using low to high frequency AC source The modification is made by filling the soil into a grounding rod (cylinder rod) and therefore it created two soil layers of grounding system, and by using three size variations of cylindrical layers of length (L) of 40, 60, and 100 cm; and three size variations of diameter (D) of 20, 30, and 40 cm. These variations allow us to understand the characteristic of the grounding impedance at low and

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