Full Length Research Paper

The impedance characteristics and equipotential pattern in ground surface of horizontal and grid configuration of grounding systems which are injected by frequency variable alternating currents

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INTRODUCTION

Background

The first functions of the grounding systems is for personal safety if some one touch the body of electrical equipments that the touch voltage is not more than 50 volt. The good electrical installation can be done by installing the small impedance of grounding systems. How to make small impedance of grounding systems ? a. To choose the soil of land that have the small resistance or to treate that soil so tobe the good resistance b. To make the good configuration (gird, paralel etc) so the grounding impedance is small c. To burry the electrode more deeply so to make the contact volume in the ground is large.

In this paper we made experiments by grounding simulation of horizontal and grid configurations with several depth of electrodes burried. In the same configurations for electrode is burried in more deep will make the grounding impedace smaller than the electrode is burried shorter. Personal accidence is caused by touch voltage or step voltage occur if the grounding impedance is too high , so if we want to avoid the high touch voltage so the grounding electrode must be burried in long depth under the ground surface. .

The laboratory experiments use the black soil from Bandung – Indonesia near thr transmission line and lay in the box with the dimension 1.5 x 1.5 x 1 and the grounding electrode with horizontal and grid
configuration were buried in several depth. The method of measurement is used *fall of potential* by injection the current to the current rod and measure the voltage drop at the potential rod.

**Condition of experiments**

1. Range of frequency for measuring voltage drop is 50 Hz – 200 KHz.
2. The diameter electrode rod is 2.5 mm.
3. There are 4 types of configuration electrode are used at these experiments: 2 horizontal electrodes, 4 horizontal electrodes, grid, dan combination of grid + vertical electrode.
4. The condition of soil is assumed homogenous so the conductivity; resistivity and permeability are assumed all same.
5. The result of this experiments only measure the impedance and phase angle of the impedance for indicating the state of impedance.

**The characteristics of grounding systems**

**Configuration**

In general the type of configurations are:

- Vertical single rod or paralel
- Horizontal single rod or paralel
- Grid
- Combination of grid and vertical
- Plate vertical or horizontal

Although there are many configuration of grounding systems, but in this experiment we chose only 2 types, horizontal and grid.

**Horizontal configuration of 1 rod**

The grounding systems with horizontal configuration can be made by bury the electrode under the ground surface with the depth variable. The electrode also may be laid parallel with the effective distance. If the electrode are laid parallel must have the distance so make the effect of parallellism is effective. Several transmission tower use the grounding horizontal and it’s called *counterpoise*. Usually *counterpoise* is used at the mountain or the land with high resistivity (Figure 1 and 2)

The value of R, G, L and C are:

\[
R = \frac{\rho}{2\pi l} \ln \frac{l}{185bd}
\]

\[
G = \frac{2\pi}{\rho} \left( \ln \frac{2l}{\sqrt{2hr}} - 1 \right)
\]

\[
L = \frac{\mu}{2\pi} \left( \ln \frac{2l}{\sqrt{2hr}} - 1 \right)
\]

\[
C = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln \frac{2l}{\sqrt{2hr}} - 1}
\]

where:

- R = Grounding Resistance (Ohm/m)
- G = Grounding conductance (Ohm.m)⁻¹
- L = Grounding Inductance (H/m)
- C = Grounding Capacitance (F/m)
- \(\rho\) = Resistivity of soil (Ohm-m)
- r = Grounding Conductor Radius (m)
- l = Conductor length (m)
h = Depth of conductor buried (m)  
d = Diameter of electrode (m)

**Horizontal configuration of 2 rods**

2 Electrodes are laid parallelism under the ground surface, with about 1 – 1.5 meter depth. (Figure 3)

$$R = \frac{\rho}{2\pi L} \left( \ln \frac{L^2}{163.42hd.aA} \right) \text{ Ohm}$$

Where:
- h = Depth of laid electrode (s) (m)
- L = Electrode Length (m)
- a = Electrodes Distance of each other (m)
- d = Diameter of electrode (m)

$$A = \sqrt{a^2 + 4h^2}$$

**Grid configuration**

The Grid / Mesh configuration of electrical grounding systems is several electrodes are laid horizontal and crossing each other to make the mesh. The distance between two conductors must be enough so there’s no interference each other. The depth of the electrodes layer is about 1 – 1.5 meters under the ground surface. (Figure 5)

The Resistance of grid configuration can be done by this formulation:

$$R = \frac{\rho}{2 \cdot D} + \frac{\rho}{L}$$

Where:
- R = Grounding Resistance (Ohm)
- \(\rho\) = Soil Resistivity (Ohm meter)
- D = Total length of conductors. (meter)
- L = Distance between the centre of electrode to the end of conductors (meter)
- h = Depth of laid electrode (s) (m)
- h<<D

The characteristics of the grounding impedance (resistance) is small enough but rather not stable, for making the stability of grounding impedance the grid
configuration is added by several vertical rods at several junctions. (Figure 6)

The grounding resistance for one vertical electrode can be calculated by this equation

$$ R_v = \frac{\rho}{2\pi l} \left( \ln \frac{3l}{d} \right) \quad \text{Ohm} $$

For multi vertical electrodes of grounding systems, the resistance can be calculated by this formula

$$ R_v = \frac{\rho}{2\pi NL} \left( \ln \frac{8l}{d} - 1 + \frac{2l}{s} \ln \frac{2N}{\pi} \right) \quad \text{Ohm} $$

Special for vertical parallelism and rectangular shape of grid, the resistance can be calculated by equation below:

$$ R_A = \frac{R_v}{N} \quad \text{Ohm} $$

For the grid electrodes and laid horizontal under the ground surface, the resistance can be calculated by this equation.

$$ R_t = \rho \left[ \frac{\sqrt{\pi}}{4\sqrt{A}} + \frac{1}{Lt} \right] \quad \text{Ohm} $$

The combination of grid and vertical configuration of grounding systems so the resistance can be calculated by the combination these two systems with formulation:

$$ R = \frac{R_k \cdot R_A - R_m^2}{R_k + R_A - R_m} \quad \text{Ohm} $$

Where

$$ R_m = \text{Combination grid and vertical resistance.} $$

$$ R_m = \frac{0.73 \rho}{Lt} \log 10 \left( \frac{2Lt}{\sqrt{2r_g \cdot h}} \right) \quad \text{Ohm} $$

The result of the above calculation is

$$ R_o > R_N > R_A > R_g > R_t $$

Note:

- $R = \text{Grounding Resistance (Ohm)}$
- $\rho = \text{Soil Resistivity (Ohm meter)}$
- $N = \text{Number of Vertical Rods}$
- $l = \text{Vertical Electrode Length (rod) (meter)}$
- $d = \text{Diameter of electrode (rod) (meter)}$
- $s = \text{Space between 2 electrodes (meter)}$
- $h = \text{Depth of layed electrode (s) (m)}$
- $A = \text{Total Grid Area (m}^2\text{)}$
- $r_g = \text{Electrode radius of grid}$
- $Lt = \text{Total wide of grid}$

Potential calculation on and under ground surface area

In this experiment we need special potential prob that can measure voltage / potential in all of the ground area. By knowing the potential of position or coordinate in and on the ground surface so can make the potential pattern and electric field. For identifying the ground potential at each position we can use the La Place Equation for 3 dimensions

$$ \nabla^2 \phi(x, y, z) = 0 $$

$$ \nabla^2 \phi(x, y, z) = \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = 0 $$

With the differential equation and the La Place equation for 3 dimensions, so can calculate the potential of all the position in and on ground surface. (Figure 7)
Figure 7. 3 Dimensions for La Place quations.

\[
\frac{\partial^2 \phi}{\partial z^2} = \frac{\phi_s + \phi_e - 2\phi_0}{h^2} \\
\n\n\n\text{from this equation above , so:} \\
\phi_0 = \frac{\phi_1 + \phi_2 + \phi_3 + \phi_4 + \phi_5 + \phi_6}{6} \\
\text{Where :} \\
\phi_1, \phi_2 \text{ are potentials at X ordinate} \\
\phi_3, \phi_4 \text{ are potentials at Y ordinate} \\
\phi_5, \phi_6 \text{ are potentials at Z ordinate} \\
\phi_0 \text{ Calculated potential} \\
\text{The calculation be done iterative until the potential error at each coordinate is less than the tolerance value.}
\]

\[\text{Experimental equipment}\]

In this experiment use several equipments that they are for indicating the quantity of measurement. 

1. Grounding Electrodes 

The simulated electrodes that's used in this experiment are the copper electrodes with diameter 2.5 mm. The configurations of grounding systems are 2 (two) rods parallel, 4 (four) rods parallel, rectangular and combination of rectangular and rods. All of these configuration of grounding systems are buried under the
ground surface about 5 mm depth.
2. Box
The box dimension is 1,5 m x 1,5 m x 0,75 m which is filled by the soil that will be analyzed it's characteristics.
3. Frequency Generator
Frequency Generator as the power supplies which generate sinusoidal current about 0.01 A and frequency range are 50 Hz-200 KHz. The current will be injected to grounding systems
4. Digital Oscilloscope
Digital oscilloscope for measuring the voltage drop and the injected current included the phase angle between them

**EXPERIMENT RESULTS**

**The influence of frequency to Grounding Impedance**

The grounding impedance can be calculated from several experiment data and use the formula of equation:

\[ Z = \frac{V}{I} \]

Where:
- \( Z \): Grounding Impedance (Ohm)
- \( V \): The Voltage at the measuring point (Volt)
- \( I \): Injected current (Ampere)
### Tabel 1. Grounding Impedance for 2 Rods Paralel

<table>
<thead>
<tr>
<th>( f(\text{Hz}) )</th>
<th>( z = 5\text{cm} )</th>
<th>( z = 15\text{cm} )</th>
<th>( z = 30\text{cm} )</th>
<th>( z = 70\text{cm} )</th>
</tr>
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<tbody>
<tr>
<td>50</td>
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<td>15.624</td>
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<td>11.941</td>
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### Tabel 2. Grounding Impedance for 4 Rods Paralel

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<th>( z = 5\text{cm} )</th>
<th>( z = 15\text{cm} )</th>
<th>( z = 30\text{cm} )</th>
<th>( z = 70\text{cm} )</th>
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### Tabel 3. Grounding Impedance for Rectangular Grid

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<th>( f(\text{Hz}) )</th>
<th>( z = 5\text{cm} )</th>
<th>( z = 15\text{cm} )</th>
<th>( z = 30\text{cm} )</th>
<th>( z = 70\text{cm} )</th>
</tr>
</thead>
<tbody>
<tr>
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<td>9.631</td>
<td>7.843</td>
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### Tabel 4. Grounding Impedance for Combination of Rectangular Grid and Rods

<table>
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<tr>
<th>( f(\text{Hz}) )</th>
<th>( z = 5\text{cm} )</th>
<th>( z = 15\text{cm} )</th>
<th>( z = 30\text{cm} )</th>
<th>( z = 70\text{cm} )</th>
</tr>
</thead>
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<td>5.438</td>
<td>4.674</td>
<td>3.630</td>
<td>0.401</td>
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<tr>
<td>10000</td>
<td>5.144</td>
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<td>3.427</td>
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<td>50000</td>
<td>4.128</td>
<td>3.513</td>
<td>2.714</td>
<td>0.298</td>
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<td>100000</td>
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<td>3.366</td>
<td>2.563</td>
<td>0.279</td>
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<tr>
<td>200000</td>
<td>3.849</td>
<td>3.237</td>
<td>2.461</td>
<td>0.267</td>
</tr>
</tbody>
</table>
$Z = 5 \text{ cm}$

$Z = 15 \text{ cm}$

$Z = 30 \text{ cm}$

$Z = 70 \text{ cm}$

**Figure 12.** Grounding Impedance Vs Frequency
Figure 13. Phase Angle Vs Frequency for 2 Horizontal Parallel Rods

Figure 14. Phase Angle Vs Frequency for 4 Horizontal Parallel Rods

Figure 15. Phase Angle Vs Frequency for Rectangular Grid.
Figure 16. Phase Angle Vs Frequency for Combination of Rectangular Grid and Rods

Figure 17. Electric Field Pattern for 2 Horizontal Parallel Rods at 5 cm depth

Figure 18. Electric Field Pattern for Grid Configuration for many depth (z) at frequency f = 1 KHz
From Table 1 and Table 2 above can be mentioned that the value of grounding impedance will decrease if used 4 parallel rods than 2 parallel rods, that it means that more electrodes will make more effective grounding systems. Actually we must also consider the distance between the 2 rods. For high frequency the grounding impedance will decrease too, and the measurement data like this maybe the inductance of grounding systems not yet influences of impedance. The depth Z also make the experiment data of grounding impedance will decrease, from this phenomena can be indicated that the electrode prob for measuring the voltage not allowed too long, because can make the confuse indication. This measurement with the long prob for the measuring voltage is for calculating the distribution of under ground voltage and to calculate the electric field in the ground. By knowing the distribution of under ground voltage and electric field can be perdicted the condition of grounding systems, and at the later can make the procedure how to reduce the impedance of grounding systems.

From Table 3 and Table 4 special for Grid and combination of Grid and Rods configuration can be seen that the grounding impedance are vary to the frequency and to the depth of measuring prob. For high frequency, the grounding impedance will decrease and impedance of the grid configuration is higher than the combination of grid and rods, at the same frequency and the same depth of measuring prob. The detail pattern of these data can be seen at Figure 12.

**Phase angle of grounding systems**

According to the basic of experiments that the injected current is sinussoidal frequency variable, and the range of this frequency is from 50 Hz until 200 KHz so the result of this experiment indicate that at the low frequency the grounding impedance is capacitive and at the high frequency trend to inductive. The curve of this data for all type of configuration can be seen at Figure 13; 14; 15 and 16 below. The frequency changes of the impedance about 5 KHz - 10 KHz.

**Electric field and equipotential pattern in the ground surface**

The pattern of electric field and equipotential in the ground surface specially for the 2 horizontal parallel rods and grid configuration of grounding systems for many frequency at 5 cm depth and for many depth at 1 KHz can be seen at Figure 17-19 below.

**CONCLUSIONS**

According to experiment data so can be concluded that the characteristics of grounding impedance for horizontal and grid configuration are:

1. The measurement of grounding impedance with the sinusoidal injected current to indicate that the frequency of current is very influence to the grounding impedance.
2. The grounding impedance for 2 horizontal parallel rods is higher than the 4 horizontal parallel rods. This phenomena also occur for the grounding impedance for grid is higher than the grounding impedance for combination of grid – rods.
3. The volume and surface area of grounding conductors is very importance for grounding impedance, for the configuration that have the higher volume or surface area will make the grounding impedance will be amller than the configuration that have the small / little volume or surface area.

4. The grounding impedance for grid configuration is higher than the grounding impedance of combination gird – rod configuration, and the grid configuration is smaller than the horizontal configuration, so the grounding impedance also depends on the configuration.

5. The characteristics of grounding impedance at low frequency trend to higher than if the grounding impedance is injected by the high frequency.

6. According bto experiment data that the grounding impedance at frequency f = 50Hz-5KHz trends to inductive and at frequency f = 5KH-10KHz the grounding impedance trends to capacitive.

7. The pattern of equipotential and electric field in the grounding surface can be used for analyzing the characteristics of current that make the low or high of grounding impedance.

REFERENCES


