Analysis of the performance of grounding grids buried in heterogeneous soil under impulse current

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ABSTRACT

The article presents the analysis of the transient behaviour of grounding grids subjected to impulse lightning current. The TLM including mutual coupling between conductors will be applied. The transient behaviour will be assessed into complete time domain solution by entombing under homogeneous and stratified soil. Different simulations carried out altering, the influence of the grid dimension, the kind of the ground and the current injection point on the grid voltage and impedance will be presented. Simulation results will be shown for two extreme cases. The current is going to be injected twice. Firstly, in the center of the grid. Secondly, in one corner of the two configuration. Consequently, the lowest transient potential displays in the grid 1x1 when the injection point is in the lower resistivity. Whereas the better behaviour is shown in the grid 2x2 when the current is injected at center point. It is obvious that the suggested simulations are in a good agreement, with corresponding results of other researchers.

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1. INTRODUCTION

Optimization is to improve the grounding systems a so as to protect surroundings people in the grounded installations with low cost [1]. The performance of grounding system under power frequency current is not well understood [1]. The act of this system is changed under impulse current [2]. This makes the behaviour of grounding systems an objective for different investigations, and which have been improved by several simulations and practical tests cited as follow: Ramlee et al. [3] have studied the use of multiple grounding points on the lightning phenomenon. Azmi et al. [4] have improved the grounding system impedance by adding enhancement materials in the surrounding of the studied electrode. Parise et al. [5] have studied the efficiency of grounding system safety by studying the step/touch voltages in the studied system. The first method is known by Antenna theory which tends to solve Maxwell’s electromagnetic field equations either by method of moments or by finite difference time domain [6-8]. Its main shortcoming consists in the long calculation time. Visacro [9] has applied another approach namely hybrid electromagnetic method. Transient potential and the variation of grounding system impedance in function of frequency. The second method consists in solving Maxwell equations using finite element methods as made by Nekhoul et al. [10-11], by Qamar et al. [12-13] and by Akbari et al. [14]. This method requires a long time of calculation with a powerful process calculation [15]. Hasni et al. [16] have used COMSOL to study the effect of concrete orientation in grounding system by FEM. As main result, the full concrete is the best orientation of concrete design to be employed at the grounding systems since it generates a low electric field compared to the other concrete orientation. The third approach, the simplest in the calculation method for the grounding grids
systems is based in transmission line approach of grounding grid and could be treated as well as circuit models [17]. Seixas and Kurokawa [18] have proposed electrical grounding systems model which could be simulated directly in the time domain using conventional software such as the alternative transient program (ATP).

The grounding grids hasn’t been studied with the TLM. Several parameters have been proposed for the characterization of grounding system transient behaviour. In lightning protection, many terms are used as like “impulse resistance”, “impulse impedance”... The transient analysis of grounding systems may contains the transient impedance, \( v(t)/i(t) \) peak voltage to peak current \( V_p/I_p \), and \( V(t_p)/I_p \) [19].

In the present investigation, we use the TLM method to transient analysis of a grounding grid buried in homogeneous and stratified soil subjected to lightning impulse current. We continue the study of the transient behavior that we have already begin with our recent paper [20], in which we have studied the economic optimization of copper conductor to obtain the best transient response. As main results of the precedent paper, we have obtained that the increasing of conductor paths leads to improve the transient response. In order to validate the behaviour of grounding systems the knowledge of their performance over a wide range of frequencies is required. The new version of this investigation is based on the study of transient behavior of two simple configurations etomd under homogeneous and heterogeneous soil, in order to evaluate simultaneously the impact of increasing of conductor paths and heterogeneity of the soil on the transient behavior. For each studied configuration; the transient potential and impedance obtained were displayed, with considering a different point of injection for such case. Certain parameters of the impulse of the grounding grids were studied to detect the lower potential transient.

Our article presents the transient study of grounding grids according to the next organization: In the second section we have presented our used transmission line model, with introducing the principal changes which have been added to include mutual coupling phenomena, and we present the impedances relation which have been determined for each studied configuration. The third section is composed of several parts: in the first one we have validated our grounding grids simulation for homogeneous soil by comparing with other studies and we present the transient impedance, after that we have simulated the transient response of grounding grids buried in stratified soil. In the last part, many injection points have been considered and the transient impedance has been determined. The fourth section summanizes most findings and essencail comments.

2. RESEARCH METHOD

Each grounding conductor is divided in several sections presented in Figure 1 for modeling the transmission line of grounding systems the wavelength of this current \( \lambda \) is able to be determined by:

\[
\lambda = \frac{1}{f \sqrt{\frac{\mu \pi \varepsilon_m}{\sqrt{1 + \frac{\rho \pi \varepsilon_m}{2 \rho_m \varepsilon_m^2}}}}}
\]  

(1)

To validate our TLM use to study the transient behaviour, every segment length much be smaller than one tenth of wavelength \( (\Delta l \ll \lambda /10) \). The following formulas represent parameters for each segment of the grounding systems [21]:

\[
R = \rho_s \frac{4 \Delta l}{\pi D^2}
\]

(2)

Figure 1. Transmission Line Model [13]
\[ L = \frac{n\Delta l}{2\pi \left( \ln \left( \frac{2l}{\sqrt{\pi}R} \right) - 1 \right)} \]  
(3)

\[ C = 2\pi (\varepsilon_0 \varepsilon_r - \frac{\Delta l}{\ln(\frac{2\pi}{\Delta l}) - 1}) \]  
(4)

\[ G = \frac{2\pi}{\rho_s \left( \ln(\frac{2\pi}{\Delta l}) - 1 \right)} \]  
(5)

In our simulation, we have treated the transmission line method in time domain. For injected current \( I_e \) in transmission line between points \( i \) and \( j \) of grounding conductor, the differential equations of potentials \( (U_i) \) and currents \( (I_{ij}) \) (which presenting the potentials and currents along the electrode) as presented in (6)-(8):

\[ \frac{du_i}{dt} = \frac{2}{c} I_e - \frac{\rho_s}{c} U_i - \frac{2}{c} I_{ij} \]  
(6)

\[ \frac{dI_{ij}}{dt} = \frac{1}{c} U_i - \frac{R}{L} I_{ij} - \frac{1}{L} U_j \]  
(7)

\[ \frac{dU_j}{dt} = \frac{2}{c} I_{ij} - \frac{\rho_s}{c} U_j \]  
(8)

these equations and the other ones of grounding electrode are solved by using iterative methods according to the next algorithm as shown in Figure 2.

Grounding grids contains several interconnected copper conductors. These two conductors are said to be inductively and capacitively coupled, in addition a mutual conductance exists Figure 3. The parameters of mutual coupling, mutual capacitance \( C_m \), mutual conductance \( G_m \), and mutual inductance \( L_m \) are defined as next [22-23]:

\[ C_m = \frac{2\pi \varepsilon_0 \varepsilon_r}{\ln(1/D)} \]  
(9)

\[ G_m = \frac{C_m}{\rho_s \varepsilon} \]  
(10)

\[ L_m = \frac{\mu}{2\pi} \ln(\frac{1}{D}) \]  
(11)

different indices are used to estimate grounding systems impulse performance [24-25]. These parameters generally relate the potential of an electrode to the injected current. The transient injected current, potential and input impedance for a grounding system are presented in Figure 5. The “impulse impedance” is the most commonly used parameter for lightning protection system, defined by the ratio of potential maximum \( V_p \) to the current maximum \( I_p \).

\[ Z_1(t) = \frac{V_p}{I_p} \]  
(12)

The impedance of the impulse is used to evaluate the potential of the impulse current grounding system. The second parameter consists in the ratio of potential obtained at the moment when the current reach the peak value \( v(t_{1p}) \), to the current peak value \( I_p \). Such parameter shows the predominance of resistive effects on the transient behaviour of grounding system [26-28]. The last parameter is the ratio of potential peak \( V_p \) to the current value when the potential gets it highest value \( i(t_{1p}) \). This parameter may estimate the maximum potential since it has higher value than the above impedances [29].

\[ Z_2 = \frac{v(t_{1p})}{I_p} \]  
(13)

\[ Z_3 = \frac{V_p}{i(t_{1p})} \]  
(14)
3. RESULTS AND DISCUSSION

3.1. Simulation validation

Two configurations were simulated using our TLM model shown in Figure 4 to validate our TLM simulation. The radius of the conductor is 7 mm, both grounding grids have been buried at a depth 0.5 m in uniform soil of $\rho_s = 1000 \, \Omega \cdot m$ and $\varepsilon_r = 9$ [2]. The injected current is $i(t) = 1(e^{-27000t} - e^{-5600000t})$ shown in Figure 4. The obtained results by [2] using ATP-EMTP for these configurations are shown in Figure 5.

Our obtained results are presented in Figure 6 the transient potential is presented on the Figure 6(a) and the transient impedance is presented on the Figure 6(b). We note that we have present the transient potentials and impedances in the time range [0,5] to show the important variations in the transient period of the studied grounding system. When comparing the transient potentials in the Figure 6(a) with those presented in the Figure 5, we observe a good accordance between our TLM results with those obtained by [2] using ATP-EMTP. Because of the calculation procedure a brief difference has been appeared. We notice that the transient potential of the 2x2 grid has lower peak, but the impulse form is greater than that of the 1x1 grid. From Figure 6(b); the transient impedance before 1μs dramatically increases until the oscillations in grid transient impedance 2x2 are higher than those of grid 1x1 hitting the maximum value (80Ω) then decrease. From 1μs, the impedance given a constant value (54.1Ω for 1x1 grid and 17.3Ω for grid2x2) which corresponds to low frequency resistance. Table 1 present the impulse parameters $Z_1$, $Z_2$ and $Z_3$ calculated according to (12, 13 and 14) from the obtained results appearing in Figure 6.
The results show that for homogeneous soil, no difference between the impedances $Z_1$, $Z_2$ and $Z_3$ for the grid 1x1. For the grid 2x2, the difference between these three parameters is clear. So, the behaviour for the grid 1x1 converges to the resistive behaviour. For the grid 2x2, the inductive behaviour appears since the variations of the transient impedance are accentuated but an observable decrease has been obtained for $Z_1$ and $Z_2$.

![Figure 4. The different configurations [2]](image)

![Figure 5. The transient potential obtained using ATP-EMTP by [2]](image)

(a) Transient potential  
(b) Transient impedance

![Figure 6. The obtained results for configurations presented in Figure 4](image)

| Table 1. The impulse parameters for grids 1x1 and 2x2 |
|-----------------|-----------------|-----------------|
|                 | $Z_1$ ($\Omega$) | $Z_2$ ($\Omega$) | $Z_3$ ($\Omega$) |
| Grid 1x1        | 53.59           | 52.92           | 56.41           |
| Grid 2x2        | 38.56           | 18.27           | 55.08           |

### 3.2. Heterogeneous soil

Following validation of our TLM grid simulation, we propose to assess the transient potential of grids buried in vertically stratified soil as presented in Figure 7. The 1x1 grid configuration has been buried as seen in Figure 7 in heterogeneous soil. The first soil is defined by the following soils: $\rho_s = 1000 \ \Omega m$ and $\varepsilon_r = 9$, and $\rho_s = 200 \ \Omega m$ and $\varepsilon_r = 40$. Two points A and B of the grounding device present in Figure 8 indicate the same pulse present.

![Figure 8. The obtained results for configurations presented in Figure 7](image)

The findings in Figure 8(a) suggest that the lowest peak value of transient potential is reached by injecting the lower resistivity side, which is why injecting in the lower resistivity side of the corner provides the desired potential. As the lower resistivity side injection gives the lowest potential, the transient impedance is lower. Otherly we say that injection at the choose of corner in existing in lower resistivity side is a solution to obtain a reduced transient impedance. The parameters $Z_1$, $Z_2$ and $Z_3$ for the three studied configurations (homogeneous and heterogeneous soil) are present in Table 2.
Table 2. Impulse parameters for grids 1x1 evaluated in Figure 8

|        | $Z_1$(Ω) | $Z_2$(Ω) | $Z_3$(Ω) |
|--------|----------|----------|----------|
| Homogeneous soil | 53.59    | 52.92    | 56.41    |
| Injection point B | 17.47    | 17.50    | 18.01    |

(a) Transient potential

(b) Transient impedance

Figure 8. Results obtained for 1x1 grid buried in uniform and heterogeneous soils

For injection point A; an observable difference between the parameters $Z_1$, $Z_2$ and $Z_3$ because of the impulse form of transient potential. For the injection point B; the parameters $Z_1$, $Z_2$ and $Z_3$ are around the same level, which shows the resistive behaviour for this configuration. The results shown in Table 2 prove that the injection at the low soil resistivity side gives the lowest impulse parameters values.

When the same impulse current is presented, the grid 2x2, presented in Figure 7 was evaluated. Soil 1 features are: $\rho_s=1000$ and $\epsilon_r=9$, and for soil 2 features: $\rho_s=200$ and $\epsilon_r=40$. Three separate points A, B, and C were inserted into the impulse current. The results obtained at injection point are can be seen in Figure 9; Figures 9(a) shows the transient potential and Figure 9(b) shows transient impedance.

For all of the cases, an oscillation of transient potential is observed, the results obtained in Figure 9(a). The most signification is the potential achieved by injecting point A, and the potential achieved by injecting point B. The lowest values for transient potential results were obtained when injected under C. All the potential is stabilized after these oscillations and gives the same response. The injection in the middle of the grid therefore gives the lowest transient maximum value.

The results of Figure 9(a) show that when injecting in A, maximum transient impedance was achieved when the grids buried into uniform soil reached the peak value. The injection in point B gives a lower value for a transient impedance. During the injection at the middle of the grounding grid, the least impedance values were obtained. The parameters $Z_1$, $Z_2$ and $Z_3$ for the three studied configurations for 2x2 grid (uniform and heterogeneous soil) are shown in Table 3.

For the injection point A; an observable difference between all of the parameters $Z_1$, $Z_2$ and $Z_3$, note that the values of $Z_1$ and $Z_3$ are close to those obtained for uniform soil. For the injection point B; a decrease in the value of $Z_1$ and $Z_3$ has been observed, but the difference $Z_1$ and $Z_2$ and $Z_3$ between still significant. For the injection point C; a slight decrease in the value of $Z_1$ and $Z_2$ has been noted, but it gives low values.
for all of the parameters Z1, Z2 and Z3. The results shown in Table 3 prove that lowest impulse parameters values are given by a 2x2 grid injection in the middle. All of the data linked to the potential are presented in the Table 4.

Figure 9. Results obtained for 2x2 grid buried in uniform and heterogeneous soils

### Table 3. Impulse parameters for grids 2x2 evaluated in Figur 9

|                | Z1(Ω) | Z2(Ω) | Z3(Ω) |
|----------------|-------|-------|-------|
| Homogeneous soil | 38.56 | 18.27 | 55.08 |
| Injection point A | 38.48 | 8.10  | 56.58 |
| Injection point B | 19.61 | 8.10  | 23.62 |
| Injection point C | 18    | 7.90  | 25.71 |

### Table 4. Data linked with potential graphs. Transient potential [V]

| Time [μs] | 1x1 grid [V] | 2x2 grid [V] | 1x1 grid [V] | 2x2 grid [V] | 2x2 grid [V] |
|-----------|--------------|--------------|--------------|--------------|--------------|
|           | homogeneous soil | homogeneous soil | Injection point A | Injection point B | Injection point A | Injection point B | Injection point C |
| 1         | 53           | 18           | 17           | 17           | 10           | 10           | 10           |
| 2         | 50           | 17           | 16           | 16           | 9.3          | 9.3          | 9.3          |
| 3         | 49           | 16           | 15           | 15           | 8.4          | 8.4          | 8.4          |
| 4         | 48           | 15           | 14           | 14           | 7.4          | 7.4          | 7.4          |
| 5         | 45           | 14           | 13           | 13           | 6.5          | 6.5          | 6.5          |

### 4. CONCLUSION

In this paper we presented evaluated the transient potential and impedance of simple grounding systems. The TLM has been used with incorporate mutual interconnection between grounding conductors. Many parameters have been changed in the simulations namely: heterogeneity of soil, the grounding grid configuration, the current injection point. The potential and transient impedance have been calculated for each simulation. The obtained results showed that when the injection point is placed on the lower resistivity side of the 1x1 grid, the lowest transient potential is obtained. When injecting in the center point of the 2x2 grid, the lowest transient potential values are obtained. The validity of our TML results was tested by comparing the behavior of grounding grids subjected to impulse current in simulation on simple buried structures with some other calculations done with the ATP-EMTP software package, and our results have showed a good satisfactory. The present paper has been limited to the study of the simple grounding grids as an effective solution to replace grounding electrodes when the space proposed for the grounding is limited, and this has been already proved in our previous work. The transient responses obtained present that stratified soil have an important impact on the transient behavior, which is more important when comparing to the injection point impact. The next paper will be devoted to developing these studied configurations to study the behavior of wind turbine grounding systems which some similarities with the configurations have studied in this work.
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