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Evaluation of Grounding Grid's Effective Area

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***Abstract*—Grounding grid performance when subject to lightning current are different when compared to power frequency environment. Various computer models have been developed to understand transient grounding performance. The models led to the introduction of an "effective area" concept. It is an important concept as the parameter is used to optimize grounding-grid design. Several approaches and numerical equations are proposed by previous researchers to estimate the effective area. Each equation defines the grounding impedance at the injection point. In this paper, transient ground potential rise (TGPR) alongside the grounding grid is used to evaluate the empirical equations proposed by previous researchers. Simulations are based on the electromagnetic approach and the governing equations are solved using the Finite element method (FEM). Different soil resistivity and impulse front times were considered in the simulations.**

Keywords-Transients Grounding modelling; Finite Element Method (FEM)

I. INTRODUCTION

Main purpose of grounding is to provide a safe environment for human and equipment from any potential rise from fault or transient current. Besides that, grounding is common reference for all the connected electronic equipment. Grounding behavior under transient lightning current may increase the value of step and touch voltage of the grounding grid and may create electromagnetic incompatibility (EMC). Therefore it is important to evaluate the performance of any grounding topology under lightning current flow

In order to simulate and analyse the response of a ground-grid under lightning current, many researchers have developed their own models. Those models were based on circuit approach [1, 2], transmission line approach [3, 4] or electromagnetic theory approach [5, 6]. Circuit analysis is the most simple and easily observable method, but it cannot predict surge propagation delay. On the other hand, the disadvantage of the transmission line method is that it is limited to a certain frequency thus making it less accurate to evaluate injected current with fast rise-times [7]. The electromagnetic theory approach makes fewer assumptions by solving Maxwell's equations but requires more computational time for a complex structure. In this study, the Finite Element Method (FEM) is used to model and analyse the ground-grid's behavior under lightning current. COMSOL Multiphysics is an application package that is proven and tested by many researchers and it was also used by the authors.

Effective area of the grounding grid is an important parameter to design an optimum grounding system. Effective area is achieved when an increase in grid size does not give a significant improvement of the grounding impedance at injected point. Different approaches and numerical equations are introduced to calculate the effective area. As mentioned in [8], effective area is not directly related to the area of conductor that is effective to discharge the impulsive current. It's more on controlling grounding impedance by increasing the size of the grid.

Therefore, purpose of this paper is to understand ground potential rise on any grid conductor when the grid has satisfied the condition for effective area. Maximum Ground Potential rises alongside of conductors are evaluated for every 1m distance. Results are compared with effective area numerical values calculated from previous authors. Simulations were done for different soil resistivity, grid sizes and front times of an impulse current.

II. FINITE ELEMENT METHOD (FEM) MODELLING

Electromagnetic modeling approach is used to simulate performance of grounding grid under transient condition. The partial differential equations were solved using Finite Element Method. Governing equation for the model was derived from Maxwell's equation as shown in equation 1

$$\nabla \times H = J + \frac{\partial D}{\partial t} \tag{1}$$

By introducing the vector magnetic potential A as

$$B = \nabla \times A \tag{2}$$

and introducing the scalar potential V as

$$E = -\nabla V - \frac{\partial A}{\partial t} \tag{3}$$

The governing equation for the model can be re-written as the following A-V formulation

$$\nabla \times \mu_r^{-1}(\nabla \times A) + \sigma\mu_0 \frac{\partial A}{\partial t} + \mu_0 \frac{\partial}{\partial t}(\varepsilon_0\varepsilon_r \frac{\partial A}{\partial t}) = 0 \tag{4}$$

Magnetic Vector potentials are solved for every node of the mesh element using Comsol Multhiphysic software.

The challenge in FEM simulation is to determine the boundary of the simulation space for an unbounded problem. Most software packages will suggest perfect match layer (PML) to avoid reflections from the boundary [9]. In COMSOL transient study PML can't be implemented due to complexity of the required solution-procedure. The other way to avoid the boundary problem is to increase the boundary size to achieve a current density near to zero at the boundary. Although that can be implemented in simulation, the computational time will be increased as the size increased. Boundary size used in this simulation and validation of the model are shown in [10].

III. EFFECTIVE AREA

Effective area is an important criterion to improve grounding grid design when considering lightning current. There are several definitions which led to different numerical equations to calculate the effective area for a transient current flow. Gupta-Thapar defines effective grounding area as illustrated in Figure 1. It is achieved when the grounding impedance at the injected point is within 3% departure from the final value of grounding impedance[11]. Final value is achieved when the grounding impedance remains constant with increment of grounding grid size.

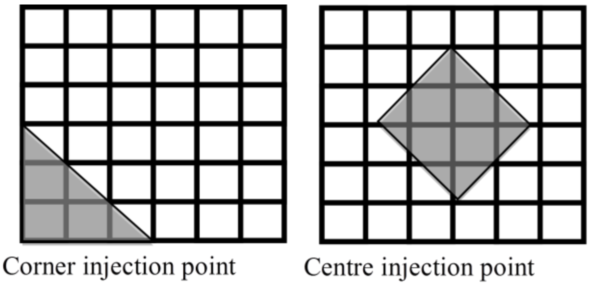

Corner injection point Centre injection point

Figure 1 Illustration of effective area proposed by Guptar and Thapar

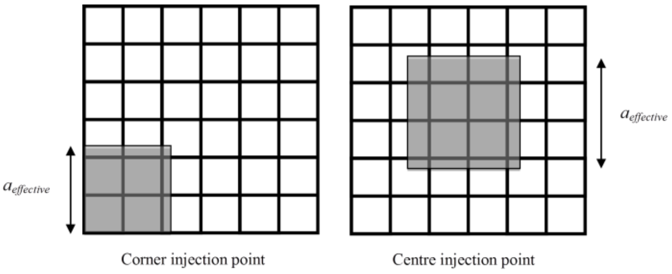
The effective area is represented by an equivalent circle with radius calculated using equation (5).

$$
\begin{aligned}
&r_{effective} = K(\rho T)^{0.5} \\
&K = (1.45 - 0.05S) \text{ for center fed grid} \\
&K = (0.6 - 0.025S) \text{ for corner fed grid}
\end{aligned}
\tag{5}
$$

Where ρ is soil resistivity in Ω.m, S is spacing between conductor of the grid in m and T is wave front time in microsecond. Another formulation as shown in equation (6) was introduced by Zeng et al[12]. It is similar to Gupta's definition but analysis is based on a circuit model with consideration of soil ionisation.

$$
\begin{aligned}
&r_{effective} = 0.21\rho^{0.42}T^{0.32} \text{ for corner fed grid} \\
&r_{effective} = 0.34\rho^{0.42}T^{0.32} \text{ for center fed grid}
\end{aligned}
\tag{6}
$$

Meantime L.Grcev [8] defined the effective area as the area of the grid which can reduce impulse impedance by applying more dense meshes within the area. L.Grcev illustrates the effective area as shown in Figure 2.



Corner injection point Centre injection point

Figure 2 Illustration of effective area proposed by L.Grcev

By determining the impulse coefficient, the effective area is achieved when the grounding impedance value is equal to the low frequency resistance. The side of a square effective area can be calculated by using equation (7).

$$
\begin{aligned}
&a_{effective} = K.\exp\left[0.84(\rho T_1)^{0.22}\right] \\
&K = 1 \text{ for center fed grid} \\
&K = 0.5 \text{ for corner fed grid}
\end{aligned}
\tag{7}
$$

All the above formulations are based on grounding impedance (at the injected point) which reduces by increasing the size of the grounding grid. In this paper the peak transient ground potential rise through the conductors are calculated to get a better understanding of the current distribution through the soil when effective area is achieved.

IV. COMPUTATION SET UP

Five grounding grid configurations as shown in Figure 3 are adopted for simulation. Size of the grid was varied from 5m×5m to 40m×40m with 5m×5m inner mesh size. The grids are buried 0.5m below the earth surface and a 10KA impulse current is injected at a corner of the structure.

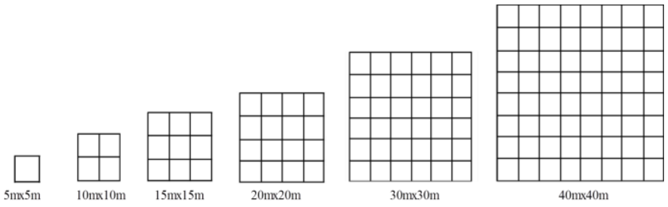


Figure 3 Grounding grid configuration

V. RESULTS

Peak transient ground potential rises (TGPR) were evaluated every 1m alongside of the grid conductor. Different soil resistivity and front time were considered in the simulation. Numerical formulation from Gupta and Zeng is adapted to calculate effective side length ($a_{effective}$) of square effective area as shown in Figure 2. Table 1 shows effective side length for different numerical equation and different soil resistivity, while Table 2 shows for different front time.

Table 1 $a_{effective}$ for different soil resistivity

Front time	Soil Resistivity (Ω.m)	effective side length (m)		
		Gupta	Grcev	Zeng
1.2μs	10	2.92	2.14	1.038
	300	16	10.74	4.33
	1000	29.16	27.208	7.18

Table 2 $a_{effective}$ for different front time

Soil Resistivity	Front time (μs)	effective side length (m)		
		Gupta	Grcev	Zeng
100Ω.m	1.2	9.22	5.56	2.73
	2.6	13.58	8.68	3.5
	10	26.62	23.25	5.38

A. *Different soil resistivity*

Impulse current with 1.2μs front time is injected at corner of every grid. Three soil resistivities, 10Ω.m, 300Ω.m and 1000Ω.m were used to represent low, medium and high resistivity soil. Figure 5 Figure 6 show the relationship between peak TGPR alongside the grid conductor and different soil resistivity for the grid arrangement as described in section IV. It showed that the peak TGPR will start to reduce along the grid when effective area is achieved. An example of this is shown in Figure 5 for results from a grid buried in 300 Ωm soil. It shows that the peak TGPR starts to reduce when the grid size is 10mx10m. Besides that, peak TGPR at the injection point was not significantly improved when the grid size considered was 15mx15m. This observation agrees with the effective area empirical equation that was proposed by Grcev and Gupta but not with Zeng's formulation. The calculated effective areas are 10.74m x 10.74m from Grcev, 16m x 16m from Gupta and 4.33m x 4.33m from Zeng as shown in Table 1. The difference between the results obtained using Gupta's and Grcev's equations are due to the boundary used to define the limit of effective area. Zeng's formulation assumed soil ionization will occur in every case and that may lead to the error observed. Same trend and observation can be seen for low and high resistivity soil in Figure 5 and 6. Also, reduction gradient of peak TGPR value over distance is influenced by soil resistivity. It can be seen the gradient of reduction is higher for low resistivity soil.

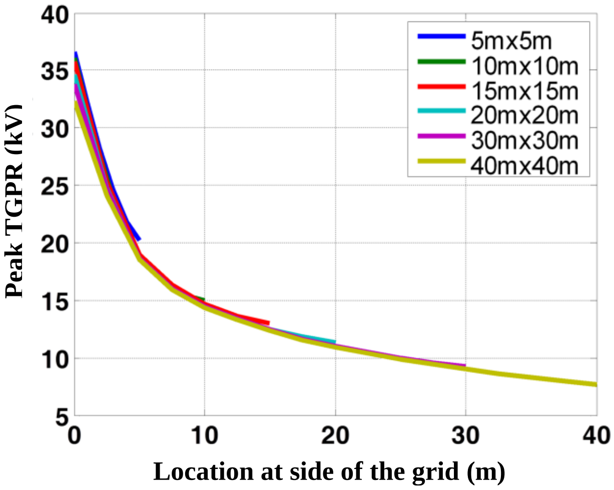


Figure 4 10Ω.m soil resistivity

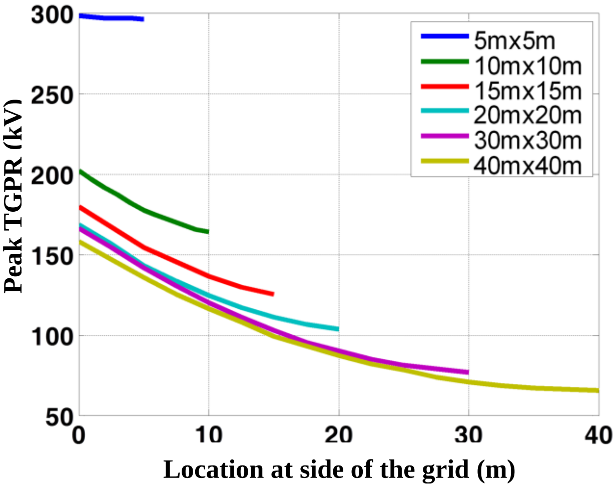


Figure 5 300Ω.m soil resistivity

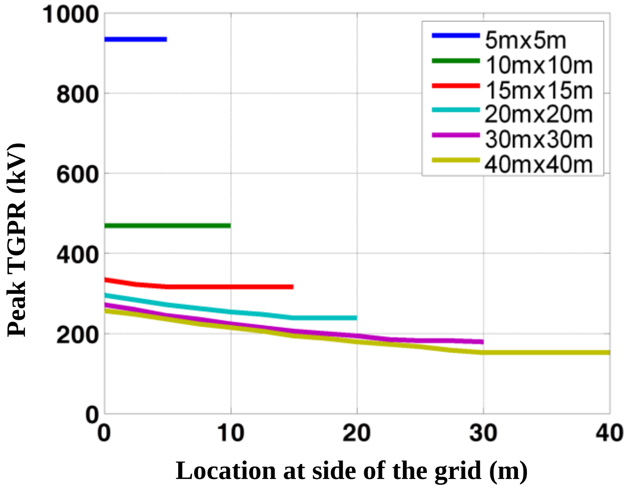


Figure 6 1000Ω.m soil resistivity

B. *Different front time*

Impulse current was injected at the corner of each grounding grid configuration. Three different impulse currents with 1.2µs, 2.6µs and 10µs front time are used in the simulation. Figure 7, 8 and 9 shows the relationship between peak TGPR alongside the grid and different front time of injected impulse current. It can be observed for all cases, the peak TGPR will start to reduce when the grid size satisfied the condition for effective area. It agrees with that the formulation proposed by Gupta and Grcev as shown in Table 2. Peak TGPR is also influenced by the rise time, fast rise time will generate larger ground potential and faster to achieve effective area.

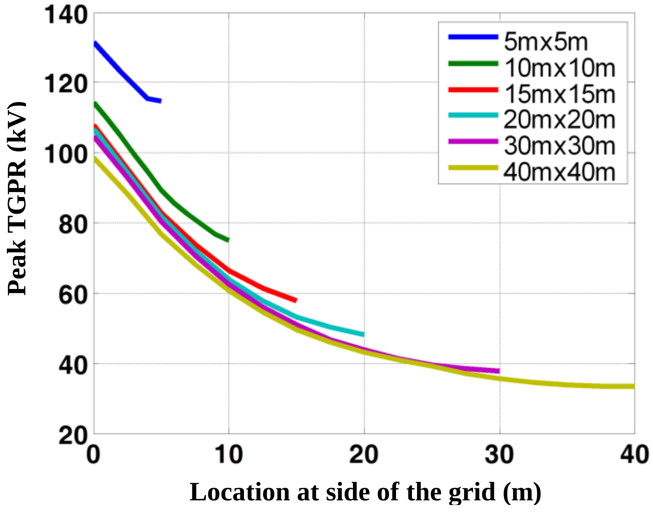


Figure 7 1.2µs front time

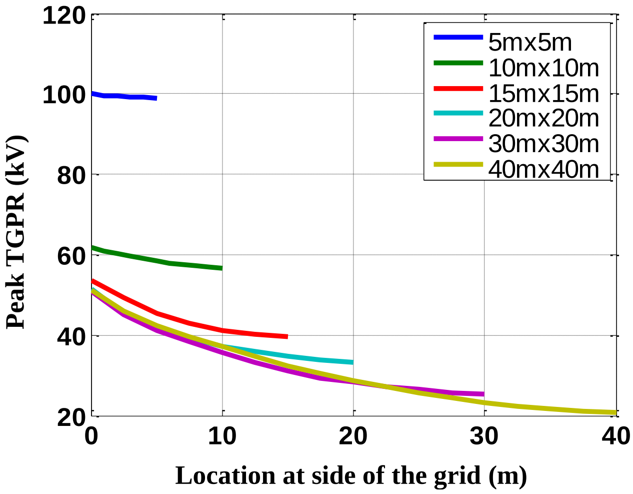


Figure 8 2.6µs front time

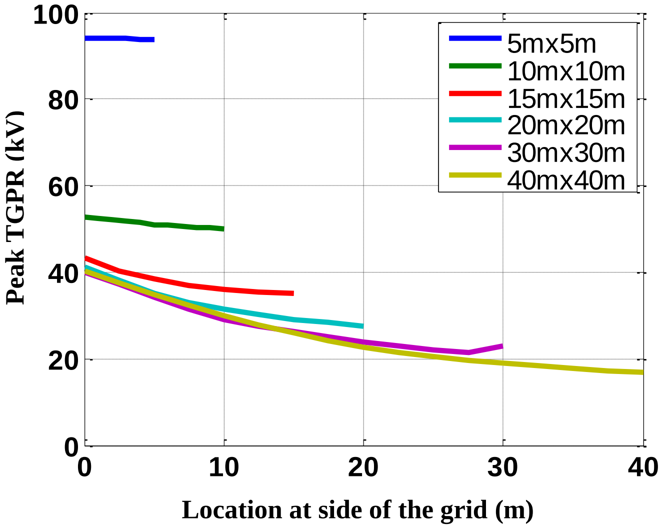


Figure 9 10µs front time

VI. CONCLUSION

Electromagnetic approach is used to model grounding system under lightning condition. Partial differential equation is solved using finite element method (FEM). Several formulations and definitions of effective area are proposed by Gupta, Grcev and Zeng which are based on grounding impedance at injected point. In this paper, relation between numerical formulation and peak transient ground potential rise (TGPR) alongside grid conductor are evaluated. Reduction of peak TGPR is quite significant when the size of grid satisfies the condition for effective area as proposed by Grcev and Gupta. The formulation proposed by Zeng gave a slightly different result and that may be due to the assumption that soil ionisation will happen for all conditions. The value according to proposal of Grcev is slightly lower than Gupta's and this may be due to the different approach used to determine the effective area. Good agreement shows that grounding impedance evaluation can be used to represent effectiveness of the grid to dissipate lightning current to the soil. It's very important to achieve effective area in grounding grid design in order to avoid high potential rise on the ground for human and equipment safety.

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REFERENCES

[1] M. A. F. Mattos, "Grounding grids transient simulation," *IEEE Transactions on Power Delivery,* vol. 20, pp. 1370-1378, 2005.

[2] A. P. Meliopoulos and M. G. Moharam, "Transient Analysis of Grounding Systems," *Power Apparatus and Systems, IEEE Transactions on,* vol. PAS-102, pp. 389-399, 1983.

[3] R. Velazquez and D. Mukhedkar, "Analytical Modelling of Grounding Electrodes Transient Behavior," *Power Apparatus and Systems, IEEE Transactions on,* vol. PAS-103, pp. 1314-1322, 1984.

[4] L. Yaqing, N. Theethayi, and R. Thottappillil, "An engineering model for transient analysis of grounding system under lightning strikes: nonuniform transmission-line approach," *IEEE Transactions on Power Delivery,* vol. 20, pp. 722-730, 2005.

[5] L. D. Grcev and M. Heimbach, "Frequency dependent and transient characteristics of substation grounding systems," *IEEE Transactions on Power Delivery,* vol. 12, pp. 172-178, 1997.

[6] W. Xiong and F. P. Dawalibi, "Transient performance of substation grounding systems subjected to lightning and similar surge currents," *IEEE Transactions on Power Delivery,* vol. 9, pp. 1412-1420, 1994.

[7] L. Grcev, "Time- and Frequency-Dependent Lightning Surge Characteristics of Grounding Electrodes," *IEEE Transactions on Power Delivery,* vol. 24, pp. 2186-2196, 2009.

[8] L. Grcev, "Lightning Surge Efficiency of Grounding Grids," *IEEE Transactions on Power Delivery,* vol. 26, pp. 1692-1699, 2011.

[9] H. D. Bruns, C. Schuster, and H. Singer, "Numerical Electromagnetic Field Analysis for EMC Problems," *IEEE Transactions on Electromagnetic Compatibility,* vol. 49, pp. 253-262, 2007.

[10] F.Hanaffi, W. H. Siew, I. Timoshkin, B. Tan, X. Wen, and L. Lan, "Boundary Analysis on Transient Grounding Modelling using FEM " in *Asia-Pacific International Conference on Lightning*, Seoul, Korea, 2013.

[11] B. R. Gupta and B. Thapar, "Impulse Impedance of Grounding Grids," *Power Apparatus and Systems, IEEE Transactions on,* vol. PAS-99, pp. 2357-2362, 1980.

[12] Z. Rong, G. Xuehai, H. Jinliang, Z. Bo, and G. Yanqing, "Lightning Impulse Performances of Grounding Grids for Substations Considering Soil Ionization," *Power Delivery, IEEE Transactions on,* vol. 23, pp. 667-675, 2008.