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Step Voltages in a ground-grid arising from lightning current

F. Hanaffi, W.H .Siew and I.Timoshkin

Abstract—**Behavior of a grounding grid when subjected to power-frequency fault currents is well studied and probably well understood. However, the behavior of the ground-grid when subjected to transient or lightning currents is different when compared to power frequency currents. The objective of this paper is to provide a better understanding of the behavior of a ground-grid when excited by transient voltages and currents. The Finite Element Method (FEM) is used to solve Maxwell's equations when modeling the grounding behavior under lightning current. In this study, step voltages above the ground are evaluated for different scenario. Effect of soil resistivity and grid size were analysed. Comparison with the safety limit, as proposed by previous researchers, is shown in the results.**

Keywords — **Grounding modeling; Finite Element Method (FEM). Step Voltage**

I. INTRODUCTION

Electrical current flow through a human body is an important element to consider when considering safety of an electrical system. Duration, magnitude, and frequency components of current; and body weight influence the amount of current that can safely flow through a human body. The current flow through a human body may cause respiratory problem, ventricular fibrillation, and cardiac fibrillation, muscular contraction and burn [1]. In lightning injuries study, the accident can happen through direct strike or indirect strike such as side flash and step voltage. As reported in [2, 3], over 50% of lightning injuries in developed countries is caused by step voltage.

Behaviors of grounding under 50Hz/60Hz application is well understood [4] . However, under transient lightning currents, the ground reactance and the high frequency components of the lightning current may increase the value of step and touch voltage of the grounding grid. No Standards give detailed guidelines to design a grounding grid to consider transient and lightning current although standards exist for faults at power system frequencies [5]

Therefore efficiency of grounding systems is an important element in lightning protection system to provide the lowest impedance path for high magnitude lightning current to discharge through the soil. Potential difference on the top of the soil can cause dangerous shock current flow through human or electrical equipment.

In this paper, the electromagnetic approach was used to model grounding grid behavior under lightning current. The partial differential equations were solved using the finite element method (FEM). FEM was chosen because of its flexibility to model the geometry in 3D and to run time-domain simulations. COMSOL Multhiphysics is an application package that is proven and tested by many researchers and it was also used by the authors. Step voltages were evaluated inside and outside the grid to know where the maximum step voltage may occur in a typical grounding grid design. The step voltages were evaluated for different locations and the locations chosen depend on their distance from the injection point. In order to consider the effect of grid size, five grids from 5mx5m to 40mx40m were used to compare the variation of maximum step voltage with increase in grid-size. The results of this paper may be used to predict potential safe areas of a ground-grid when lightning current flows to the ground through a ground-grid.

II. ELECTRICAL SAFETY

Currently, there is very limited knowledge on the safety limit for impulse current on a human body[6]. Based on electrocution experiments on animal using power frequency current, Dalziel [7] concluded that an impulse current with energy of 50 watt-seconds is the safe-limit.. A Bio-electromagnetic group suggested that when energy in the range from 10 to 50 Joules is absorbed by a human body, ventricular fibrillation can occur [8]. The safe limit of energy that could be absorbed by a human due to impulse currents is still not determined due to lack of research and much restriction on experimentation.

Based on electrocution experiment on animal using power frequency current, Dalziel [7] concluded that an impulse current with energy of 50J is a safe limit. Bio-electromagnetic groups suggest that the absorption of 10 to 50 joules by a human body is the range of values that can cause ventricular fibrillation [8]. Energy that flows through a body is calculated using equation (1) with an assumed voltage applied directly from foot to foot with no other insulation.

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$$Energy(J) = \frac{1}{R_b}\sum_{1}^{n}[\mathrm{V}_n(\mathrm{t})]^2\Delta t \qquad (1)$$

Where R_b is body resistance which is assumed to be 1000Ω, n is the total number of voltage transients, V_n is voltage between the two feet and Δt is sample period

III. FINITE ELEMENT MODELING (FEM)

Electromagnetic modeling approach is used to simulate performance of grounding grid under transient condition. The partial differential equations were solved using Finite Element Method. The governing equation for the model can be re-written as the following A-V formulation

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

Magnetic Vector potentials are solved for every node of the mesh element using Comsol Multiphysic 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 cannot 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 given in [10]. The step voltage is calculated by the integral of the electric field between two points (with 1m separation at the top of the soil).

IV. SIMULATION RESULTS

A. Maximum location

Maximum step voltages for different locations above the grid were calculated. Fig 1 shows a 20m x 20m grid with 5m x 5m mesh and buried 0.5m deep in 1000Ω-m soil. An impulse current with 10kA peak and 1.2/50µs waveshape is injected through a corner of the grid.

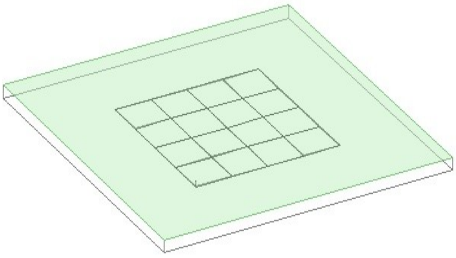

Fig 1 Grounding model

Six different locations near the injection point were chosen to evaluate the maximum step voltage as shown in Fig 2 . Location a, b, c is chosen to represent situations when a human is standing with both feet inside the grid while locations d, e, and f represents situations when one of the feet is located outside the grid. The locations chosen should cover all step-voltages possible with the injection point as reference.

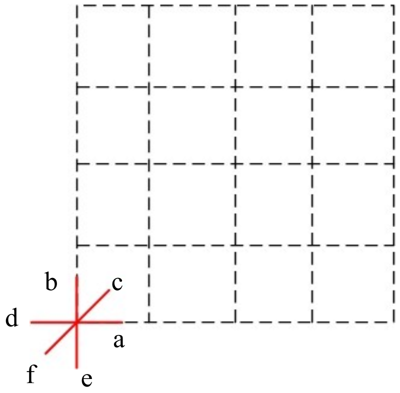

Fig 2 location at injection point

Fig 3 shows that the step voltages inside the grid is around 30%-40% less when compared to cases when one of the feet is located outside the grid. Step voltages calculated inside or outside the grid are not influenced by the positions of the human standing above the grid.

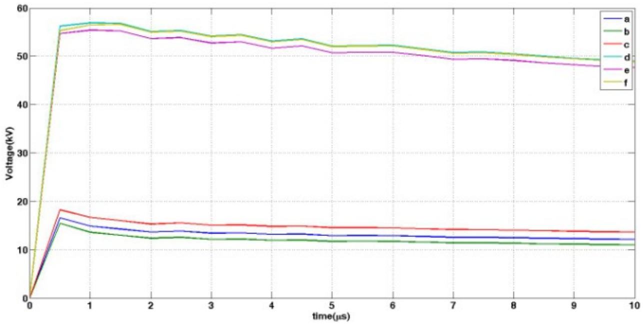

Fig 3 Step Voltages for different locations

In order to enhance knowledge about step voltages when lightning current flow through the ground-grid, step voltages further from the injection point were calculated as shown in Fig 4. Four directions are chosen further inside and outside the grid. Step voltages were calculated for every 2.5m from the injection point.

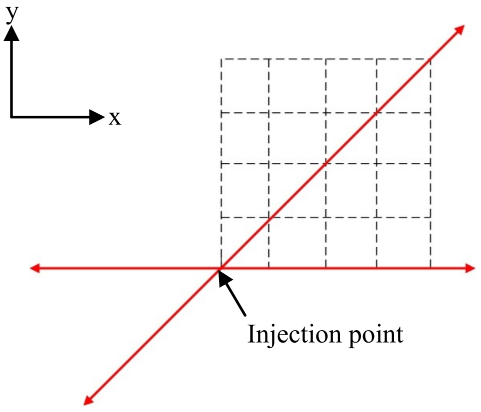

Fig 4 Locations where step voltages further from the injection point were calculated

Fig 5 and Fig 6 shows peak values of step voltages calculated for x direction and xy direction. XY direction is the direction along the diagonal of the grid from the injection point. It can be seen that the step voltage decreases with distance away from the injection point and inside the grid. The step voltage inside the grid does not change much when the location is far away from the injection point. However, high step voltage values are observed when one of the legs is on the edge of grid and the other one is outside the grid.

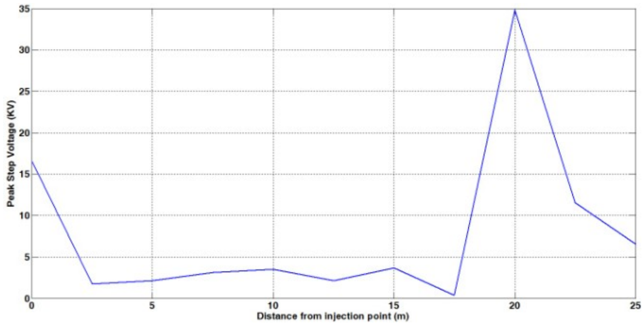

Fig 5 Peak Step Voltage x direction

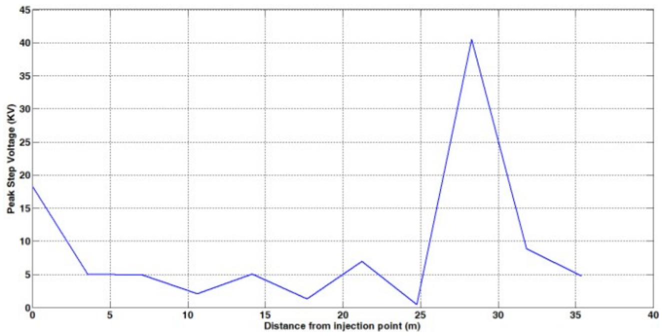

Fig 6 Peak Step Voltage xy direction

Fig 7 and Fig 8 shows when step voltages are calculated away from the injection point but outside the grid. It shows that the step voltage decreases non-linearly with distance from the injection point. The step voltage reduces to almost 20% of the maximum value when a human being is standing 2.5m from the grid. The step voltage is nearly constant and low when a certain distance from the injection point is reached.

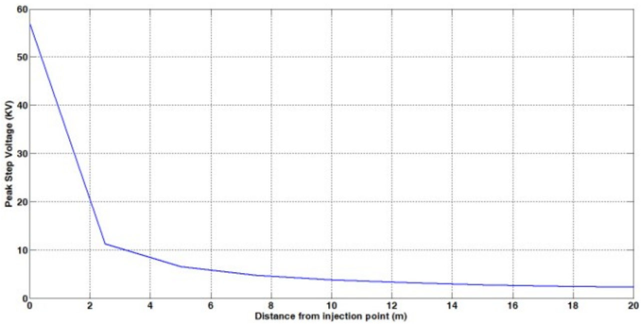

Fig 7 Peak Step Voltage -x direction

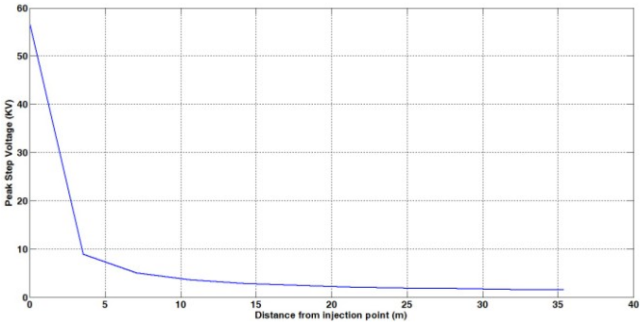

Fig 8 Peak Step Voltage -xy direction

B. *Effect of Size*

Five grounding grid configurations as shown in Fig 9 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 with 1.2µs front time was injected at a corner of the structure. Three soil resistivity 100Ω.m, 300Ω.m and 1000Ω.m are used to compare the effect of different soil resistivity.

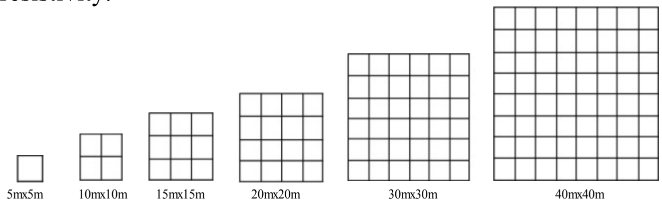

Fig 9 Grounding Grid Size

Peak step voltages were evaluated for situations where one of the legs is positioned outside the grid. Fig **10** shows peak step voltages for different soil resistivity and size of grids. It can be seen that the higher the soil resistivity, the higher the value of step voltage. It is also evident that by increasing the size of grid, the step voltage can be reduced until the grid reaches the effective size. Effective size is achieved when the change in ground potential rise (GPR) is not significant when increasing the size of grid.

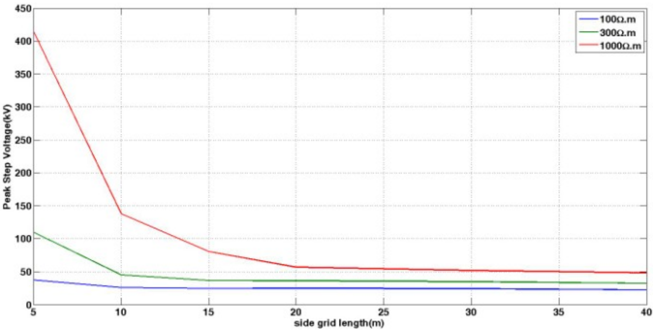

Fig 10 Peak Step Voltage for different size and soil resistivity

C. *Safety*

In order to compare with safety limit, equation 1 is used to calculate the potential energy absorbed by the human body. In this analysis, internal impedance of human body considered was 1000Ω; duration of the pulse was 10μs and the Thevenin impedance of the step voltage is neglected. Fig **11** shows the energy that flows into the body compared with the 50J limit proposed by Dalziel. It shows that soil resistivity and size of grid can be major factors in influencing safety afforded by the grounding grid under impulse current.

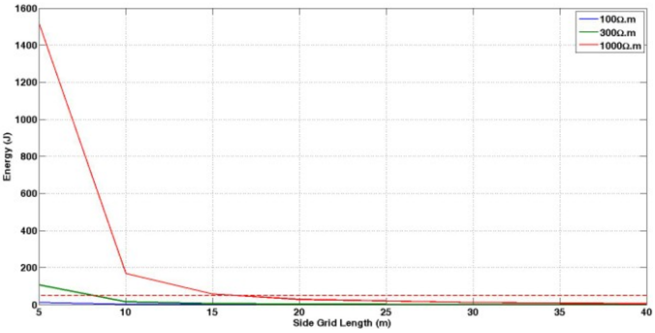

Fig 11 Energy

V. CONCLUSIONS

The electromagnetic approach is used to model a grounding system under lightning condition. The partial differential equations were solved by using the finite element method (FEM). In this paper, step voltages at the top of soil were evaluated. Maximum step voltages can be observed when a human is standing with one of the legs outside the grid. Step voltage is reduced when location of the step is far away from the grid. The results indicate that it is very important to locate the fence of a substation at a safe distance from the edge of a grounding grid to avoid hazard from ground potential rise. Low resistivity soil gives better performance of grounding grid to reduce the step voltage. Increasing the size of grid will reduce the peak step voltage value but the reduction becomes insignificant once the grid size exceeds the dimensions given by the effective area. Knowledge about human limit to impulse current is very limited; in this study 50J is used based on experiment on animal in the 50's. Comparison for 10us duration shows lightning current can be fatal due to ground potential rise for small grid size and high resistivity soil. It is very important to consider transient or lightning behavior in grounding grid design in order to avoid high potential rise on the ground for human and equipment safety and this study shows that achieving satisfactory impulse impedance may not be sufficient to achieve a safe working area in terms of potential step voltages.

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