Department of Electronic and Electrical Engineering

Grounding grid design for high voltage substations: An assessment of effectiveness for lightning currents

by

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Declaration

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Abstract

An electrical grounding system is an important element to ascertain a safe environment for both humans and equipment during fault or transient conditions. The performance of grounding systems under lightning current is quite different from the conventional frequency based power. In order to understand the grounding grid behaviour under lightning current, researchers typically carry out experiments on actual grounding systems or on laboratory scaled models. Although experiments can provide insights of the actual grounding operation, the shortcoming is that a large area of lab space is required which reflects into high costs. As an alternative, computer simulation has been introduced, and can be categorised into three different approaches, namely circuit approach, transmission line approach or electromagnetic approach.

In this work, the simulations are performed based on the electromagnetic approach under three dimensions (3D) mode due to its accurate results. For further understanding, a comparison between circuit and electromagnetic approaches is also carried out, where the resulting outcome shows that the circuit approach underestimates the impulse impedance at injection point compared with simulations by the electromagnetic approach. When the electromagnetic approach is applied, a finite element method is used to solve the partial differential electromagnetic equations in the time domain. Thereafter, the simulations results are validated with the existing published results covering the electromagnetic simulations by using the method of moment (MOM), and as well as actual field experiments. In addition, simulations are performed to understand the effect of different parameters, including lightning current, soil parameters, grounding design, and location of injection point of lightning current.

Moreover, a comparison study is carried out for potential rise between power frequency and impulse current at different grid sizes. The study shows the potential

generated at injection point for both current and saturation point when the grid size reaches a certain point. It's important to consider both types of current to get better grounding grid design. Besides that, empirical equations are used out to calculate the effective area under lightning conditions, where the effect of the down-conductor is taken into consideration as part of the grounding model. The effective area is an important parameter for the optimization of the grounding grid design when increasing grounding size does not improve the impulse impedance.

Transient ground potential rise (TGPR) above the ground is another interesting parameter to analyse. In this work, a good correlation is shown between the effective area and the impulse impedance at the injection point with rising transient ground potential. It is found that the TGPR is larger when it is closer to the injection point, but only lasts for a few microseconds. Step voltage evaluations are performed for different standing positions of the human above the grid, including the distance of the step voltage location from the injection point, and the effect of grid size to step voltage value.

List of Publications

I. F.Hanaffi, W. H. Siew and I. V. Timoshkin "Effective Size of Grounding Grid under Lightning Impulse", Universities High Voltage Network (UHVnet) Colloquium, Jan 18th – 19th, 2012, Leicester, United Kingdom.

II. F.Hanaffi, W. H. Siew and I. V. Timoshkin "Grounding transient analysis using Finite Element Method (FEM)", Universities High Voltage Network (UHVnet) Colloquium, Jan 16th – 17th, 2013, Glasgow, United Kingdom.

III. F.Hanaffi, W. H. Siew ,I. V. Timoshkin ,Bo Tan, , Xishan Wen and Lei Lan "Boundary Analysis on Transient Grounding Modelling using FEM", 8th Asia-Pacific International Conference on Lightning, Jun. 26-28, 2013, Seoul, Korea

IV. Bo Tan, , Xishan Wen and Lei Lan , F.Hanaffi, W. H. Siew ,I. V. Timoshkin "Calculation of Conductive Coupling of Substation Grounding Grid with Secondary Cable Under Lightning Stroke", 8th Asia-Pacific International Conference on Lightning, Jun. 26-28, 2013, Seoul, Korea

V. F.Hanaffi, W. H. Siew, I. V. Timoshkin "Grounding Grid Safety Evaluation under Lightning Current", Progress In Electromagnetics Research Symposium, August 12th – 15th, 2013, Stockholm,Sweden.

VI. F.Hanaffi, W. H. Siew ,I. V. Timoshkin "Transient Grounding Modelling using FEM: Infinite Boundary Condition", International Colloquium on Lightning and Power System , May 12-14, 2014, Lyon, France

VII. F.Hanaffi, W. H. Siew ,I. V. Timoshkin, Hailiang LU, Yu Wang , Xishan Wen , Lei Lan "Evaluation of Grounding Grid's Effective Area'', International Conference on Lightning Protection (ICLP), Oct 13 - 17 , 2014, Shanghai, China.

VIII. Chaoying Fang , Lei Lan, Yu Wang, Xishan Wen and F.Hanaffi, W. H. Siew ,I. V. Timoshkin, Jutian Li , Zeng Zhang "Feasibility Study on Using Jacket Structure as Natural Grounding Electrode of Offshore Wind Turbines'', International Conference on Lightning Protection (ICLP), Oct 13 - 17 , 2014 Shanghai, China.

IX. F.Hanaffi, W. H. Siew ,I. V. Timoshkin "Step Voltages in a ground-grid arising from lightning current", Asia-Pacific International Conference on Lightning (APL), Jun. 23-26, 2015, Nagoya, Japan

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List of Acronyms

AC	Alternating Current
BEM	Boundary Element Method
EMC	Electromagnetic Compatibility
FDTD	Finite Different Time Domain
FEM	Finite Element Method
FFT	Fast Fourier Transform
HV	High Voltage
MOM	Method of Moment
PML	Perfect Match Layer
TGPR	Transient Ground Potential Rise
2D	Two Dimensional
3D	Three Dimensional

Chapter 1

Introduction

1.1 Background

Grounding systems play an important role in protecting life or facilities from any fault or transient in power systems. The main purpose of a grounding system is to provide the lowest impedance path for unwanted current during faults or transient conditions, such as lightning and switching. Relatively, the level of safety of a protection system is influenced by the efficiency of the grounding system, where the grounding conductors can range from a horizontal rod, vertical rod, ring rod, and grounding grid depending upon the application. In a substation grounding design, the grounding grid is buried below entire installed equipment to maintain the potential rise above the ground within the safety limit during the discharging process of a fault or lightning current. Parameters that influence the potential above the ground are soil resistivity, conductor configuration and level of fault current, where soil resistivity depends on geography, water content, chemical compound and type of soil. In practice, lower soil resistivity is advantageous for grounding system. Apart from that, the grounding grid configuration also depends on the size of the grounding grid and the mesh size within the grounding grid.

For the practical scenario, it is necessary that a grounding system is designed with a low magnitude of earth resistance, so the protection device can divert the high fault current to the earth effectively. In the British Standard [1], the value of earth resistance was proposed to be below than 20Ω for the independent earth electrodes that are associated with the local grounding of the star point of generating plant, and below 1Ω for a substation grid. In the grounding grid design, touch and step voltage are the main components that required to be guaranteed to operate below the safety limit. Step voltage is generally defined as the voltage difference between the earth surface potential experienced by an operator bridging at 1m distance and without any contact with the earthed structure. For the case of the touch voltage, it is the voltage difference between the earth potential rise at the metal and the surface potential where a person is standing at (1m) from the earthed structure. Step and touch voltage limits depend on the tolerable current flow through human body and accidental circuit. Tolerable current depends on the critical limit that human can withstand before the ventricular fibrillation happens. These values depend on the duration of shock and magnitude of the current, while the British standard defined tolerable current as dependent of current path, duration and magnitude and the American standard defined the tolerable current as the limit that depends on weight, duration and magnitude of current.

Grounding design and procedure under power frequency is well described in many standards. However, grounding will perform differently when a lightning current discharge through the system, due to the inductive and capacitive effects. A large lightning current with a fast rise time will flow to the grounding grid, which will behave like an antenna, and induces large transient potentials in the system. The resulting potential can create a huge potential rise and electromagnetic coupling, which will lead to system malfunctions and errors, or even damage the valuable and sensitive electronic equipment.

Therefore, a study of grounding systems under lightning condition is vital to improve the performance and design. The study can be performed in three categories, namely laboratory tests, site tests and analytical modelling. The analytical modelling method can be further divided into circuit, transmission line and electromagnetic approaches. In the proposed research herein, an analytical modelling based on the electromagnetic approach is adopted to investigate the impact of lightning current towards the grounding grid design. Simulations are carried out in three-dimensional (3D) geometry modelling, while a Finite Element Method (FEM) is used to solve the partial differential equations. The electromagnetic approach is chosen due to its accuracy of results that it computes based on Maxwell's equations.

On the other hand, the performance of the grounding grid under lightning current can be improved by reducing the soil resistivity, increasing the grounding grid size and mesh density. However, the grid is limited to a finite size, which is known as the effective area, and this can be achieved when there is no significant improvement in the grounding impedance with increasing grounding grid size. Besides, it is useful to enhance more conductors near the injection point and within the effective area to improve the impulse impedances .The impulse impedance is a value used to evaluate the grounding performance under lightning current, in other word, it is a ratio between peak potential rise at injection point and peak injected current. It is very important to understand the relationship between transient ground potential rise (TGPR) and impulse impedance, which will provide insights into how lightning current is dissipated through the grid. Furthermore, the grounding grid evaluation depends on the value of ground potential rise above the ground. Since the simulations are performed in 3D, post processing can be carried out to evaluate the transient ground potential rise (TGPR).

1.2 Objective of Research

Grounding is a main element in the lightning protection system that provides low impedance path for unwanted current through the soil. In substation grounding design, it is very important to maintain low step and touch voltages, which increases the level of safety. Although the grounding response and safety limits are quite different under lightning conditions, most of the standards are still based on power frequency safety hazards without any specific guidelines that consider fast transient response within the grounding design framework. It is challenging to achieve the best protection concurrently for both humans and equipment under lightning conditions.

In order to solve these shortcomings, this research aims to achieve the following objectives:

i. Study and review the effect of lightning current in a grounding grid, and understand human safety limits under power frequency and impulse currents.
ii. Perform a 3D grounding grid system modelling by using the electromagnetic approach with FEM
iii. Analyse the effect of down-conductor through the simulation of impulse impedance and effective area
iv. Consider and assess the improvements of grounding methodologies and topologies for lightning currents by introducing effective area empirical equations as an engineering guide.
v. Investigate transient grounding potential rise throughout the conductor and above the ground

1.3 Summary of Contribution

The main contributions and achievements of this research can be summarised as follows:

I. Modelling using Maxwell’s equations in Electromagnetic domain, which considers the displacement current effect. The FEM is applied to solve the equations. Open boundary problems are solved by evaluating the current density between regions of interest relative to the perfect conductor boundary. Computer simulations are performed in time domain based 3D mode. Thereafter, the validations are performed by comparing with the simulation results from MoM and actual experiments.

II. The effects of various parameters of soil, lightning and grounding grid are used for a parameter analysis. In addition, the effect of the down-conductor is investigated to obtain better results for the effective area evaluation.

III. A new empirical equation for effective area is proposed, which is developed based on electromagnetic modelling. The equation takes into consideration the effect of the down-conductor during simulation.

IV. A transient ground potential rise is analysed to understand the relationship between the grounding impedance and the effective area.

Recently, computational modelling and evaluation can be carried out in accurate methods, due to the advancement in the ability of computer simulation. The modelling of the grounding grid by using the electromagnetic approach and FEM is an effective methodology to improve the understanding of electrical systems for different conditions and designs.

1.4 Thesis Organisation

This thesis is organized into 7 chapters, as described below:

Chapter2 provides a review of grounding grid design that are adopted from different standards. The chapter also discusses the effect of lightning current on the grounding systems based on both experimental and simulation results.

Chapter3 presents a review of the analytical modelling approach that is used to model the grounding grid under lightning conditions, where circuit, transmission line and electromagnetic approaches are discussed. In addition, a comparison between circuit approach and electromagnetic approach is given in this chapter.

Chapter4 proposes a grounding grid model based on Ampere's law from Maxwell's equation. The governing equation is solved by using the FEM, where the geometry modelling is performed in 3D with a solution produced in the time domain. More specifically, the simulations are performed for different values of soil resistivity, lightning current front time, location of injection, and grounding grid design using COMSOL Multiphysics commercial simulation package. The challenges and problems related to mesh geometry and open boundary will be discussed in this chapter.

Chapter5 presents a comparison of potential at injection point between power frequency and lightning injection current for the investigation on the effective area. The effects of the down-conductor are analysed for different depths. A new empirical equation is formulated for effective area calculation under the assumption of lightning current being injected at the corner and at the centre of the grid. The proposed equation also considers the effects of the down-conductor in the simulation framework. Subsequently, the equations are compared with the published empirical equations.

Chapter6 evaluates the transient ground potential rise throughout the grid. This evaluation demonstrates the relationship between grounding impedance and effective area. Step voltages are evaluated for different locations and distances from the injection point.

Chapter7 presents a conclusion based on the results and analysis drawn from this study, and recommendations are formed for future work within this chapter.

Chapter 2

A Review of Electrical Grounding under the Condition of Lightning Current

2.1 Introduction

The demand on electrical supplies is continuously increasing, hence making it more challenging to provide a high-efficiency system that ensures a constant power delivery to customers. Consequently, there is a steep rise in the development of new substation technologies and designs, which requires an improved safe grounding design. The following objectives need to be achieved to successfully design a safe grounding for a substation:

I. A low-impedance path to earth under normal conditions should be provided for circuit or signal reference, under fault conditions, and even at high frequencies (lightning currents).

II. A safe condition for human and equipment from ground potential rise (GPR) should be facilitated under any condition, and the radiation and conduction of electromagnetic emission either between or within the systems should be reduced.

Therefore, this chapter will present a review on the grounding grid design according to the standards and human electrocution limit that are proposed for impulse current. Thereafter, a review of the experimental and simulation results will be presented to aid the understanding of grounding behaviour under lightning current. Apart from that, the TGPR are also discussed to gain a better understanding of step voltage and electromagnetic coupling under lightning current.

2.2 Tolerable Voltage for grounding grid design

The main objective of designing the grounding system is to provide a safe potential rise above the ground for both human and equipment. In order to design a safe substation, the values for limit of transfer, step and touch voltages are adopted from different standards. The limit is influenced by the definition of the step and touch voltages, allowable permissible current flow through human body and accidental circuit.

2.2.1 Tolerable voltage definition

The limits of step, touch and transfer voltages are a reference for grounding grid design. However, the definitions of each type of the voltages are different among the international standards. Touch, step and transfer potentials' definition can vary in various standards, as discussed in the followings:

According to **IEEE80[2]:**

- Touch voltage is the potential difference between the GPR and the surface potential in a situation where a person is standing and concurrently in contact with a grounded structure.
- Step voltage is the difference in surface potential experienced by a person that is bridging a distance of 1m with the feet, but without contacting any other grounded object.