Effective Design of Large Grounding Systems

Lorentzou M.I. ***Hatziargyriou N.D.***

National Technical University of Athens
Department of Electrical Engineering
9 Heroon Politechniou, Zografou Campus, Athens, Greece

Abstract : Grounding systems have to be effectively designed in order to prevent electrical installation from excessive overvoltages and potential gradients when lightning occurs or in case of short circuit. In general, extended grounding systems improve their behavior under short circuit currents and in case of lightning. However in the second case there is a limit in the dimensions that seriously contribute in lowering raised potentials and grounding resistance. Effective design of large grounding systems as in case of windfarms grounding is done in terms of combining good performance in high and in low frequencies.

1. INTRODUCTION

Grounding systems play an important role in every electrical installation since currents from short circuit or lightning strikes need to be dispersed into the ground and raised potentials have to be minimized.

Large grounding systems have lower grounding resistance and better behavior under low and high frequency excitation. In case a sinusoidal current source is applied at a point of a grounding conductor, maximum GPR (Ground Potential Rise) decreases continuously as its dimensions increase. However, when high frequency components are injected as in the case of lightning, there is an upper limit in the area of the system that substantially effects the maximum GPR value observed. This is called here 'effective area' of the grounding system.

In this paper, effective design of a large grounding system is investigated. The contribution of grounding system elements located far from the energization source is calculated in order to improve grounding system design.

Calculation results are obtained for large square grids and also for concentrated grounding systems interconnected by a long grounding conductor, forming a large system. The second case is typical for a windfarm grounding system where individual wind turbine grounds are connected to each other with the armor of the power cable and/or additional grounding conductors. This results in lowering the total low frequency resistance to 1-2 ohms. Additionally, it is very common for lightning to strike windfarms, as they are situated in places of high altitude, where the wind potential is high. A windfarm consisting of 12 windturbines is used as study case. The effect of interconnection electrodes in lowering max. transient GPR, and transferred overvoltages is investigated.

For the purposes of this paper, existing software packages as EMTP and CYMGRD are used. Particularly, CYMGRD is used for grounding resistance and touch and step voltages calculation when fault currents are injected into the system. EMTP is used for both fault conditions and lightning strikes response simulations. In literature EMTP-based methods are summarized in two categories:

1. Pi-circuits methods which involve division of the electrode in elementary segments and its analysis as ladder network with lumped parameters [2-3,4,5]
2. Methods based in modeling grounding electrodes as lossy transmission lines[6-10]. More particularly the J.Marti model for transmission lines calculations has been successfully applied[7-10].

In this paper the second methodology has been applied, as it is valid for a wide frequency range. Thus the method is suitable for calculations involving high frequencies as lightning.

A frequency domain analysis code has also been used. The problem of the response of grounding system is firstly solved in the frequency domain. Then an Inverse Fast Fourier Transformation (IFFT) is applied to translate results in time domain.

In the analysis done here, soil ionization phenomena are not taken into account. This results in calculation of higher GPR values in some cases, considering a more conservative upper bound of transient impedance of the system.

2. CALCULATION METHODOLOGY

2.a Current Sources

In the industrial frequency analysis that follows, a sinusoidal current source $I_0 \cdot sin(\omega t)$ has been considered. For transient conditions examination, an impulse current source as been considered, which is of a double exponential waveform of 8/20μs and a 31 kA peak current value. This approximates a typical lightning waveform[11] and it is described using the following relationship :

$$i(t) = I_0 \cdot \left(e^{at} - e^{\beta t}\right) \quad (1)$$

Where I_0 = 32kA, α = − 9091, β = − 727300

2.b Calculation Methodology using EMTP

The single grounding electrode is examined first because it is the basic component of any grounding system. EMTP has been used in order to calculate its impulse response. A pi-circuit ladder network with lumped R-L-C-elements can firstly represent grounding electrode. In fig.1 R_e and L_e are per unit length series resistance and inductance and G_e and C_e are per unit length shunt conductance and capacitance.

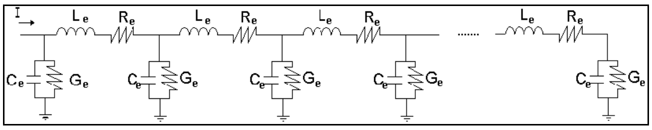


Figure 1: First grounding conductor representation

It has been proved that for infinite number of circuits the network model of the electrode is equivalent to an open-ended transmission line [12]. Following a single grounding electrode is handled as a transmission line. J.Marti's technique for transmission line calculations being suitable for analysis in a wide frequency range has been applied here.

Per unit length parameters R_e L_e G_e and C_e are calculated from formulae given by Sunde [13].

2.c High/Low frequency response calculation using a suitable code

A software program has been also developed and used. It is suitable for both high and low frequency analysis. The frequency behavior of grounding systems elements is calculated for frequencies up to 10MHz. The method of moments is then used for the solution of the retarded potential problems[14-17]. Inverse Fourier Transformation is applied to translate frequency domain to time domain results.

3. APPLICATION

The high and low frequency response of square grounding grids is calculated first. Then the effect of conductors located far from the energization point is examined. A large grounding system of interconnected windturbine grounds is also examined. The effect of interconnection grounding electrodes is investigated.

Square Grounding Grids

The response of square grounding grids of dimensions 4x4m^2 to 20x20m^2 under the typical lighting strike given in (1) has been calculated and compared to their low frequency grounding resistance. Impulse current has been assumed injected at the center of the grid. Soil resistivity is equal to 100Ωm. Grid conductors are separated in both directions by 2m distance. Results are presented in Table 1. It is observed that impulse V_{max}/I_{max} ratio reduces slowly as the system dimension increase, than the low frequency grounding resistance. It can be also observed that the area taken by the grounding system following an inverse square law mainly reduces grounding resistance

Table 1

Number of meshes	Eqiv. radius (m)	Impulse Coeff.	Low Frequency Resistance	Impulse V_{max}/I_{max} Ratio
4	2	1.02947	11.0778	12.27294
36	6	1.02973	3.69261	4.092025
64	8	1.02998	2.6946	2.986789
100	10	1.03011	2.52	2.793609

In figure 1, the ground potential rise for grounding grids of various dimensions are shown. It is observed that the raised potentials have the injected current wave-shape with a small shift even in 100x100 meshes grid that has the highest inductance.

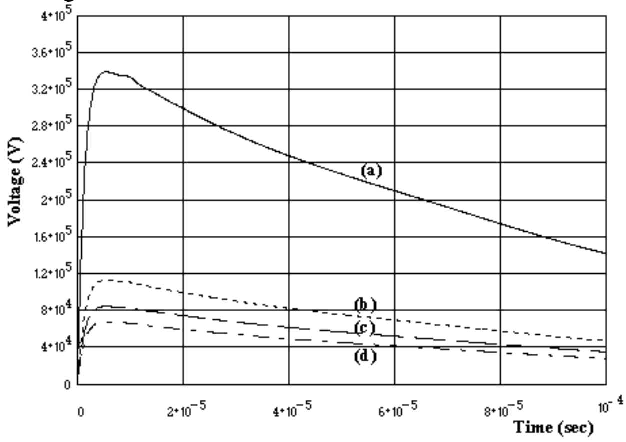


Figure 1: GPR under a typical lightning strike of a)4x4 meshes, b)36x36 meshes, c)64x64 meshes and d)100x100 meshes grid

Impulse coefficient is determined here as the ratio of impulseV_{max}/I_{max} to grounding resistance of the grid in low frequencies. It can be observed that it remains close to 1 because the reactance of the system is small. An increase of the impulse coefficient would be expected in systems with equivalent radius above 15m.

The equivalent radius of the grid is determined from: $r = (Area/\pi)^{0.5}$. The impulse V_{max}/I_{max} ratio vs. equivalent radius of grid has been plotted in figure 2. It can be seen that increase in dimensions above 7m does not introduce further increase in system impedance. This value of equivalent radius can determine an area called "effective area" of the grid. Consequently, the effective design of a large square-grounding grid involves determination of its effective area, and probably its dimensions should be within this area.

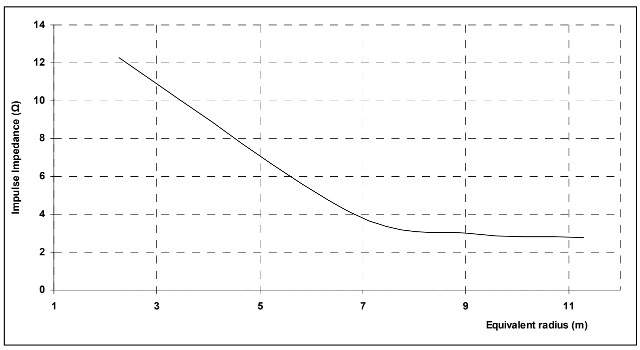
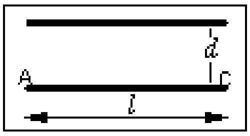


Figure 2: Impulse V_{max}/I_{max} ratio vs. grid equivalent radius

Effect of Conductors located far from the energization point

The effect of components of the grounding system located far from the energization point is examined. Two horizontal conductors have been placed in parallel as shown below.



d=1 to 50 m
l=1 to 3 m
Conductor radius=.005m
Burial Depth=.5 m
Soil Resistivity =500 Ωm

Mutual conductance is calculated according to [18]. Mutual inductance is given by Grover's formula [19]

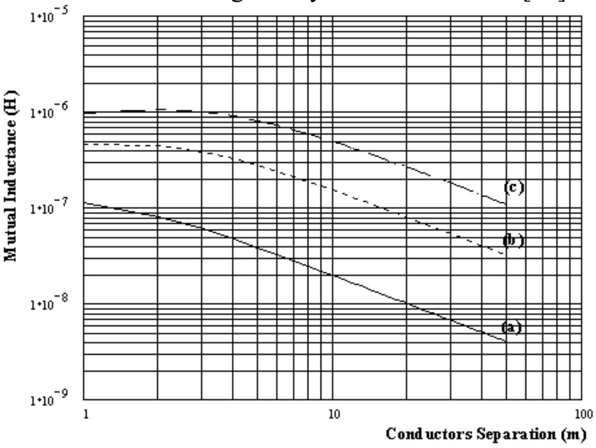


Figure 3: Mutual Inductance vs. conductor separation for Conductors length a)1m, b)2m, c)3m

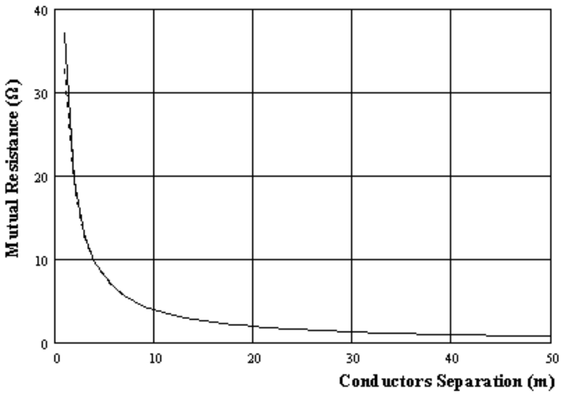
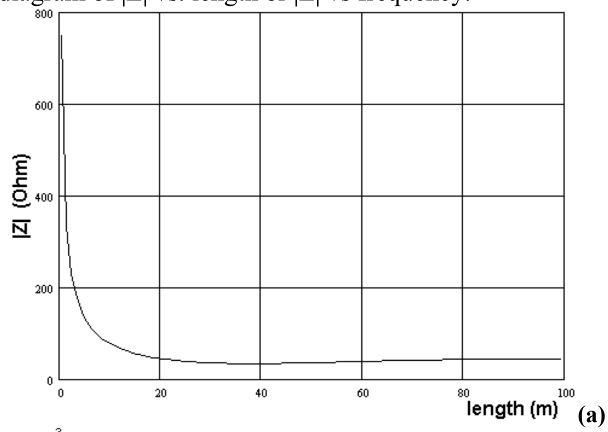


Figure 4: Mutual Resistance vs. conductor separation for Conductors length a) 1m, b) 2m

Mutual inductance is not dependent on soil resistivity. It depends on the length of conductors and their separation distance. It can be observed in figure 3 that mutual inductance values decrease considerably when electrode separation exceeds 10m. Mutual conductance is dependent on soil characteristics and conductors separation. In figure 4 it can be observed that only the electrodes placed in a distance <15m from energization seriously contribute to the grounding resistance decrease. A similar conclusion can be drawn in case of non-parallel grounding segments.

Interconnected grounding systems

The case of interconnected grounding systems is examined next with particular reference to windfarms. Firstly the effect of interconnection electrodes is examined. Effective design of large grounding systems usually involves calculation of the effective length of horizontal grounding electrodes. Effective length is the length above which, no considerable reduction of the high frequency impedance of the electrode is observed. It depends on the frequency and can be determined using a diagram of |Z| vs. length or |Z| vs frequency.



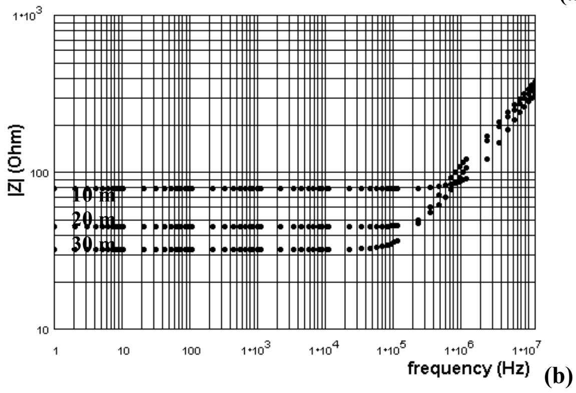


Figure 5: Impedance of horizontal conductor in 500 Ωm soil a)vs. conductor length , b)vs. frequency

Effective length of an electrode in 500 Ohm-m soil in 100kHz is 20m, as it can be seen in figure 5a. In figure 5b, |Z| of 10, 20 and 30m long electrodes vs. frequency have been plotted. For the 20m long it remains to a low value until 100kHz where it begins to increase. Plot of |Z| of a longer electrode would show the expected increase at a lower frequency value, as it would be more reactive. However the effective length of any longer electrode above a certain high frequency f is almost equal.

The ratio of peak voltage to peak current has been plotted when a fast 1/4μs (Fig.6) and a slow 8/20μs (Fig.7) impulse current has been injected to show the influence of effective length.

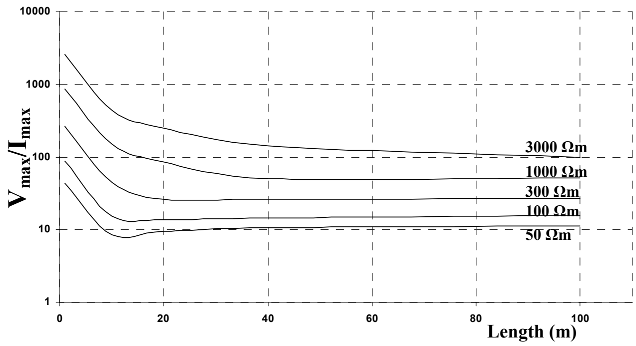


Figure 6: V_{max}/I_{max} of horizontal conductor under fast impulse

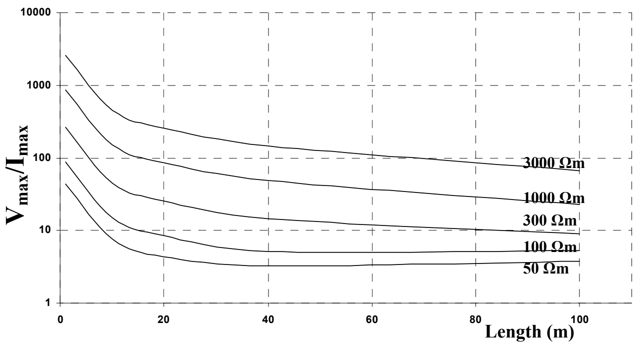


Figure 7: V_{max}/I_{max} of horizontal conductor under slow impulse

The faster the injection current rises to its maximum value, the shorter the effective length value is. It can be generally observed that lengths which can be used to notably reduce raised potentials in all cases do not exceed 25-30m.

Effective length of horizontal electrodes should be calculated when the effect of adding long conductors to an existing arrangement is investigated. It is also useful in estimation of the impulse impedance «seen» from an impulse injection current in case of windfarms with interconnected windturbine grounds.

A practical windfarm consisting of 12 windturbines is examined next. Windturbines are connected in series with horizontal electrodes. Single windturbine arrangement has a grounding resistance of 12Ω, in 500Ωm soil. Plots of the impedance that the current sees in case of injection in the middle or at last windturbine, are shown in figures 8 and 9

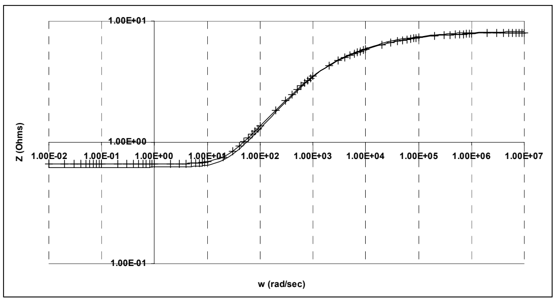


Figure 8: (--) Impedance magnitude seen from WT1 (++) Impedance approximation for EMTP input

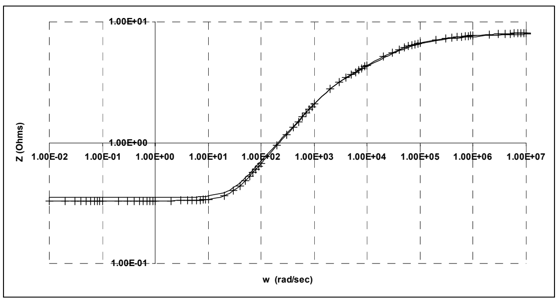


Figure 9: (--) Impedance magnitude seen in WT9 (++)Impedance approximation for EMTP input

It can be observed that impedance “seen” in windturbine 9 is lower than impedance in WT 1 but increases rapidly in high frequencies. The effective length of interconnection electrodes results in slightly lower high frequency values of the impedance seen from WT 1.

In fig. 10 the voltages at WT1, WT2 and WT3are plotted. Lightning is supposed to strike WT1. Transferred potentials to wind turbines situated at a distance greater than 500 m from WT1, are less than 5% of the max GPR (Ground Potential Rise)

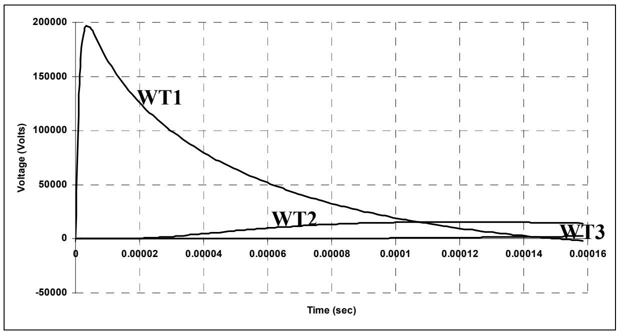


Figure 10: Potential at WT1 and transferred potentials to WT2 and WT3 when lightning hits WT1

In fig. 11 the voltages at WT9, WT10 and WT11 are plotted. Lightning strikes WT9. Transferred potentials to other wind turbines except from WT10 and WT8 are negligible. It is generally observed that:

- Interconnection electrodes reduce the max GPR values compared to a single WT arrangement. It is also lower in case the WT arrangement is connected from both sizes to other WTs
- Percentage of Transferred GPRs to neighboring WTs is lower when lightning hits WT9 rather than if it hits WT1.
- Transient impedance is maximum when lightning hits the first or last WT. It can be observed that it reduces in case lightning strikes a middle WT.

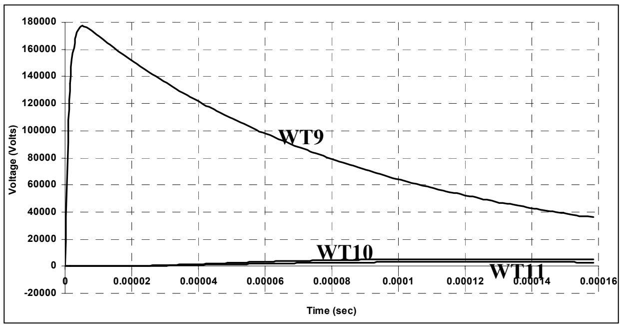


Figure 11: Potential at WT9 and transferred potentials to WT10 and WT11 when lightning hits WT9

4. CONCLUSIONS

Grounding systems serve the purpose of effectively dispersing fault or lightning currents into the ground. Dimensioning of grounding systems for lightning protection involves calculation of their transient response.

In this paper, impulse response of large grounding systems is calculated and the results are commented. The impulse impedance of a large grounding system is higher than their low frequency grounding resistance resulting in higher values of raised potentials. The following examples of large grounding systems have been analyzed:

- Square grounding grids
- Interconnected grounding arrangements resulting in a large grounding system with particular reference to windfarms.

Effective length values are given for most practical cases of grounding electrodes, while effective area of grounding grids is limited to few square meters around the energization point.

In case of a windfarm, interconnection electrodes, lower low frequency grounding resistance but result in transferred potentials to the neighboring windturbines. In addition only partially the length of interconnections contributes to the reduction of transient potential rise.

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