Grounding system design using EMTP

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Abstract

This paper addresses grounding systems analysis using EMTP. Grounding systems usually made of conductors embedded in or laid on the surface of the ground, can be modelled using two different methods that simulate the behavior of their components under fast and low frequency excitation. These methods are briefly described in the paper and results obtained from simulations of various grounding arrangements are compared. Comparison with other software packages or experimental data found in literature, are also presented.

Introduction

An electrical installation, must be grounded for the following reasons:

- To provide a low impedance connection between the electrical equipment and the general mass of the ground.
- To provide a reference potential for electrical equipment and,
- To prevent excessive overvoltages and potential gradients that may cause damage to equipment or threaten human life.

Any fault current, will flow via the general mass of earth through the earth electrode system which has an impedance to the current flow. There will therefore be a rise in the potential of the earth electrode system and of the earth in the vicinity of the grounded system, relative to the potential of the general mass of earth. If the voltage rise is excessive, then voltage differences might be created across the site that represent risk of damage to equipment and danger to human and livestock in the vicinity of the grounded system.

Several algorithms and methodologies have been derived to determine the criteria for safe design of a grounding system. By extending EMTP's capabilities, the response of a grounding system to transient or other phenomena, can be computed using transmission line models [1],[7].Two models can be used a)by dividing the system in a number of segments, each represented by a lumped parameter π-model with high shunt conductance or b) by using a frequency dependent distributed parameter transmisson line model. The mutual coupling between grounding system components is accounted for by treating them as differenr phases of a transmission line.

Grounding electrode's models

The lumped pi-circuit model

Grounding electrodes are characterized by a series resistance R, capacitance C, a series inductance L and a series conductance G.Therefore they can be modelled as series a of equivalent pi-circuits (fig.2), with lumped R-L-C elements, where each pi-equivalent circuit corresponds to a small conductor segment. A pi equivalent circuit is shown in the figure 1.

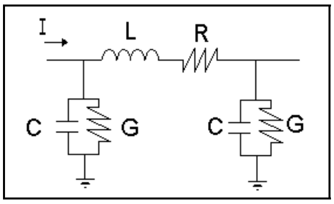

Figure 1 Pi-equivalent circuit

The R-L-C parameters of the pi-equivalent circuits are derived from the formulas below [2], based on the well known Sunde's expressions [3]

$$R=ñ_c\cdot\frac{4\cdot dl}{ð\cdot D^2},\qquad L=\frac{ì\cdot dl}{2ð}\left[ln\left(\frac{2l_c}{D}\right)+ln\left(\frac{l_c}{2h}\right)\right],$$

$$G=\frac{2ð\cdot dl}{ñ_g}\cdot\left[ln\left(\frac{2l_c}{D}\right)+ln\left(\frac{l_c}{2h}\right)\right]^{-1}\quad \text{and}\quad C=2ð\cdot å\cdot dl\Big/\left[ln\left(\frac{2l_c}{D}\right)+ln\left(\frac{l}{2h}\right)\right]$$

This circuit model, is as accurate, as the length of elementary segments decrease, so the effect of segmentation of conductors is quite important.

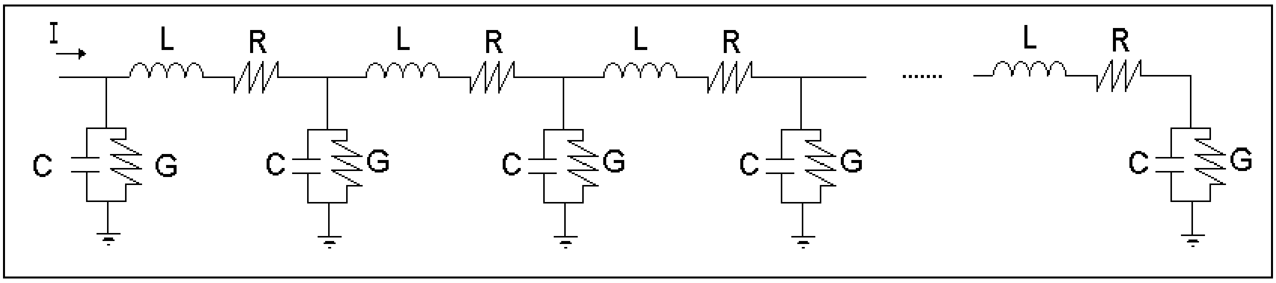

Figure 2 : Representation of a grounding electrode using the pi-equivalent circuits model

It is advisable to use a segment length smaller than two or three times the wavelength in the soil.

Frequency Dependent Transmission Line model

This technique, uses the Bergeron' s travelling wave technique. According to this approach, the inherent frequency dependence of the transmission line characteristic impedance Zc(ω) and the corresponding propagation constant A(ω), due to the existence of resistive elements, is taken into account. The functions Zc(ω) and A(ω), the values of which depend on the line configuration, are calculated using the supporting calculation subroutine LINE CONSTANTS. These are expressed in the frequency domain, by rational functions of the form [4]:

$$Q\frac{\prod_{i=1}^{n}(s+z_i)}{\prod_{j=1}^{m}(s+p_j)}=k_0+\sum_{j=1}^{m}\frac{k_j}{s+p_j}$$

where the zeros, poles and residues are denoted by z_i, p_j and k_j respectively. This approach is known as JMARTI approach [6]. The advantage of this approximation is that the left hand side of the above equation is transformed in the time domain as quickly damped exponential functions. This facilitates and accelerates the simulation calculations involving convolutions of Zc and A.

The impedance Z’ and the susceptance Y’ per unit length of an horizontally buried or a vertical bare electrode are obtained by:

$$Z' = Z_i' + Z_e' \qquad Y'^{-1} = Y_i'^{-1} + Y_e'^{-1}$$

where the internal impedance and susceptance of a cylindrical electrode are given by Sunde :

$$Z_i' = \frac{jwì_c I_0(ã_c a)}{2ðaã_c I_1(ã_c a)} \qquad \text{with} \qquad ã_c = \sqrt{jwì_c(ó_c + jwå_c)}$$

$$Y'^{-1}_i = 0$$

since there is no insulation coating, as in the cases examined here.
In the case of a horizontal electrode buried at h m depth in the ground

$$Z'_e = \frac{jwì_ï}{2ð}\log\frac{1.85}{\sqrt{ã^2+Ã^2}\sqrt{2ah}} \quad , \quad Y'^{-1}_e = \frac{1}{ð(ó_Å + jwå_0å_{r,E})}\log\frac{1.12}{ã\sqrt{2ah}}$$

with

$$Ã = \sqrt{jwì_ï(ó_Å + jwå_0å_{r,E})} \qquad \text{and} \qquad ã = \sqrt{Z'(ã)Y'(ã)}$$

while in the case of a vertical electrode [10]

$$Z'_e = \frac{jwì_ï}{2ð}\log\frac{1.12}{\sqrt{ã^2+Ã^2}a} \quad , \quad Y'^{-1}_e = \frac{1}{2ð(ó_Å + jwå_0å_{r,E})}\log\frac{a\sqrt{ã^2+Ã^2}}{3.56}$$

EMTP Implementation

Comparison of the results of the two models

In order to compare the results obtained from the application of the two simulation methods, an impulse test current (53kA, 8/20μs) has been injected at the end of a 1m long grounding electrode which is buried horizontally (fig.3) or vertically (fig.4)

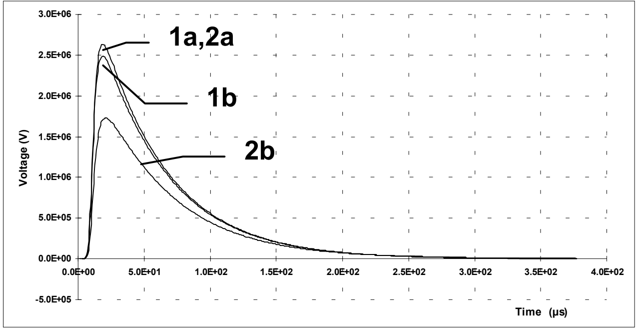

Figure 3 Voltages at start (1) and end (2) points of the grounding conductor, using (a) the lumped pi-equivalent and (b) the frequency dependent line model

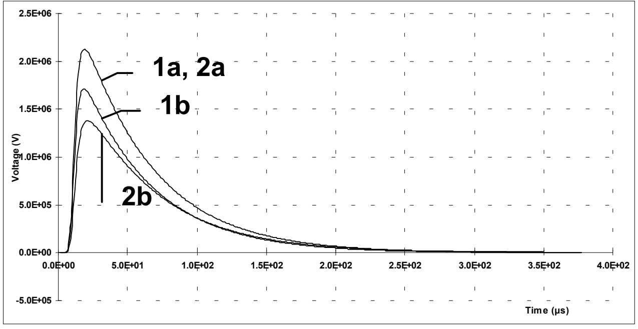

Figure 4Voltages at start (1) and end (2)points of the grounding rod, using (a) the lumped pi-equivalent and (b) the frequency dependent line model.

There can be observed a slight difference in the results ,more noticeable in figure 3, due to an error introduced in the analysis from the pi-circuits model, when the excitation includes high frequency components.

Limitations of each method

When the pi equivalent circuit model is used, there is an upper limit in the maximum number of segments the grounding system is divided into, relative to the max. number of lumped elements that can be handled by EMTP. Therefore the division of a grounding system into 0.01m or smaller segments is practically impossible. Using the lumped pi-circuits model, a computationally efficient division of a grounding electrode, introducing an error within acceptable limits in the range up to 100 kHz, is division into 1m segments. Application into various cases, has shown, that when dividing the electrode into .01 m segments, the results are accurate, even in the MHz frequency range.

When the frequency dependent transmission line model is used, and long grounding electrodes (above 100m) are examined, difficulties arise when trying to approximate propagation constant A(ω) with zeros and residues. These are numerical difficulties caused, by the big slope of A(ω) to the negative values, in the high frequency range, requiring a large amount of poles. By division of the grounding electrode into smaller segments, this problem can be overcome.

Frequency dependent transmission line model, has the advantage of being suitable, for a wide range of frequencies examined, so it can be accurate enough in the case of examining the effects of very fast transient conditions, as lightning.

Validation of EMTP results

AC excitation current-Comparison with CYMGRD and hand calculation formulae

EMTP results have been compared with CYMGRD[9] results, and simple hand calculation formulae. CYMGRD is a software package which uses the finite elements method for electromagnetic fields calculations, in the area surrounding a grounding arrangement. It is possible to calculate touch, maximum touch, step and maximum step voltages, surface potentials, total grounding resistace, GPR, and current distribution at each segment of a grounding system for every soil type, homogeneous or not, which is modelled using the Wenner method by a two layer soil. Hand calculation formulae are provided by ANSI/IEEE Std. 80-1986 Standards.

The grounding resistance of various arrangements, has been calculated, and it is equal to the max Voltage divided by the max. current value. The calculation data and the results are as following:

Horizontal electrode

Calculation data

	Cond. Length (m)	**Cond.diameter (m)**	**Burial Depth (m)**	**Soil Resistivity (Ωm)**
Case a :	10	.008	.75	50
Case b :	10	.008	.75	3000
Case c :	100	1.50	1.0	50
Case d :	100	1.50	1.0	3000

Results

	EMTP pi-circuits	**EMTP JMarti model**	**CYMGRD**	**Hand formula**

Case a	11.834	12.032	12.6855	12.731
Case b	756.601	757.201	756.6744	759.298
Case c	0.993	1.0084	1.0139	1.02
Case d	59.772	60.007	60.8333	61.193

Vertical electrode

Calculation data

	Cond. Length (m)	**Cond.diameter (m)**	**Burial Depth (m)**	**Soil Resistivity (Ωm)**
Case a :	1.5	.008	top in the surface	50
Case b :	1.5	.008	top in the surface	3000
Case c :	30	.017	top in the surface	50
Case d :	30	.017	top in the surface	3000

Results

	EMTP pi-circuits	**EMTP JMarti model**	**CYMGRD**	**Hand formula**
Case a	32.4550	33.201	33.4182	33.493
Case b	2007.231	2008.564	2009.9847	2010.0
Case c	1.998	2.004	2.2620	2.269
Case d	135.214	135.555	135.7186	136.16

Grounding system- Grid

Calculation data

	Dimensions (m^2)	**Burial Depth (m)**	**Cond.diameter (m)**	**Soil Resistivity (Ωm)**
Case a	10x10	.5	0.008	50
Case b	10x10	.5	0.008	1000

Results

	EMTP pi-circuits	**EMTP JMarti model**	**CYMGRD**	**Hand Calculations**
Case a	1.9932	2.001	2.0740	2.443
Case b	110.5130		124.4379	48.857

Grounding system-Four point Star

Calculation data

	Dimensions (m^2)	**Burial Depth (m)**	**Cond.diameter (m)**	**Soil Resistivity (Ωm)**
Case c	30 m radius	1	0.017	50
Case d	30 m radius	1	0.017	1000

Results

	EMTP pi-circuits	**EMTP JMarti model**	**CYMGRD**	**Hand Calculations**

Case a	17.938	18.008	18.4848	18.4
Case b	365.452	367.067	369.6955	367.996
Case c	.99932	1.0000	1.0018	1.002
Case d	18.678	18.975	20.0358	20.036

Impulse waveform excitation current

Horizontal electrode

Long horizontal electrodes behavior under impulse strike, can be analysed using EMTP, as it is shown in fig.5 and 6, where voltage values are plotted along a 100m electrode.

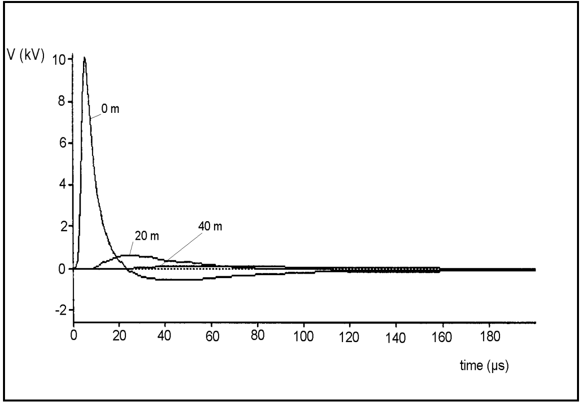

Figure 5 :Voltage of conductor points vs. Time (0-40 m)

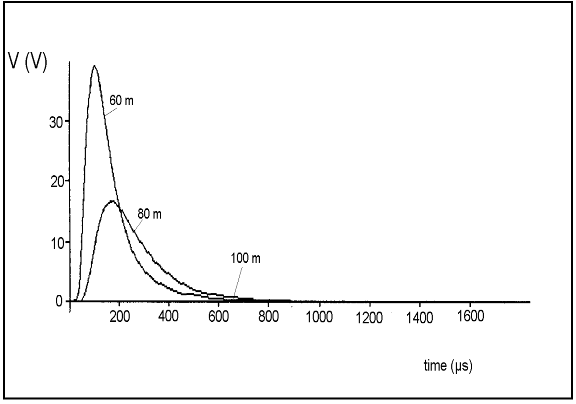

Figure 6: Voltage of conductor points vs. Time (60-100m)

Validation of EMTP results can be done by comparison with measurements data or other software packages simulation results (fig.7).

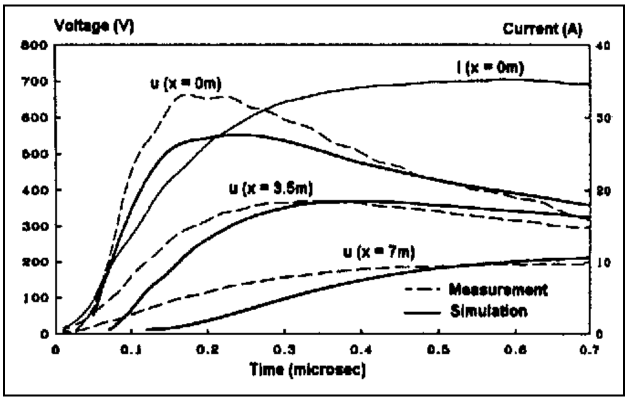

Figure 7 : EDF Voltage measurements along a 15m horizontal wire, buried in .6m depth in 70Ωm soil, compared with simulations [8]

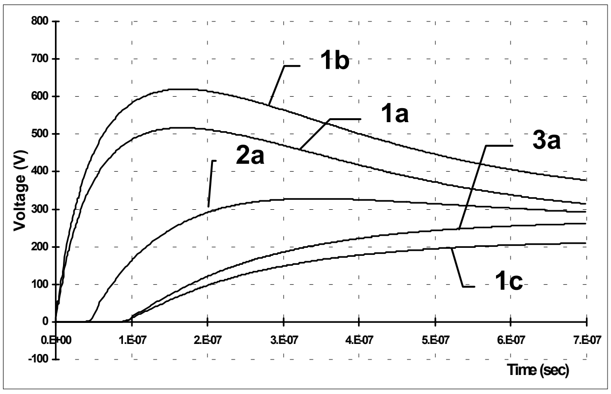

Figure 8 : Voltage at (1) the start, (2) 3.5 from the start and (3) 7m from the start of the wire using the (a) pi-circuits model, and (b) freq. dependent transmission line model

Vertical electrode

Results can be found in literature[7], such as following figure 9, comparing EMTP's performance (frequency dependent transmission line model) when simulating grounding rods, to measurements, under an impulse current excitation. Lumped pi-circuits model has also been applied (fig.10). Differences in the results, when time passes 1µs are caused by the double exponential waveform used to approximate the excitation current.

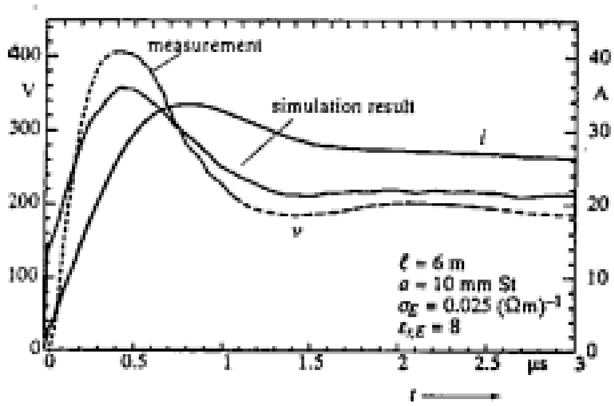

Figure 9 : Results of EMTP simulation of a vertical rod, using frequency dependent transmission line model, compared with EDF measurements

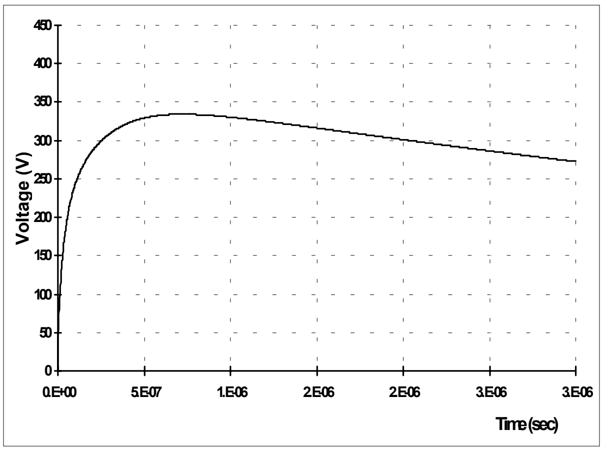

Figure 10 : Results of EMTP simulation of a vertical rod, as in fig. 9 using lumped pi-circuits model.

Conclusions

Grounding system analysis using EMTP can follow any of the methods described in this paper. Frequency dependent transmission line models are theoretically more accurate when fast transient phenomena are examined as the response under a lightning strike. Both methodologies are in good agreement when the response under AC/50Hz current is calculated.

EMTP is computationally efficient and fast when compared to other commercial software packages. It provides voltages and currents vs. time in every point on the earthing system, but not in the surrounding soil and in the surface of the earth. Safe design of grounding systems however can follow calculation of the unknown current or voltage values in the grounding system conductors, under any excitation. Post processing calculations of the field values in the vicinity of the examined grounding system, [5] according to Standards can be used to check if step and touch voltages are below the acceptable limits.

References

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