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Analysis of Ground Potential Distribution under Lightning Current Condition

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ABSTRACT

The grounding system of a lightning protection scheme is designed basically to avoid arcing and dangerous step potentials. The grounding impedance of the system varies depending on soil structure and frequency. This paper describes the effect of harmonic impedance (also called frequency dependence of soil) on potential distribution under lightning strike to a metal tower with single grounding path, for different soil types. The results show that the peak value of ground potential rise (GPR) and step voltage (SP) may reach extremely hazardous values even at distances in the order of 90 m from the tower footing, especially when soil resistivity is high. Hence, we emphasise that, in contrast to power grounding, when designing of grounding systems that are meant to handle transient or high frequency currents as well, the frequency dependent soil parameters should be considered to avoid hazardous situations, especially at locations with a high probability of lightning strikes such as metal towers.

Keywords: Lightning, frequency dependence of soil, grounding, transient impedance, GPR, SP

INTRODUCTION

Many empirical and experimental studies have shown that electrical behaviour of soil under transient conditions such as lightning, is quite different from the behaviour of the same at d.c. or low frequencies (Pedrosa et al., 2010). In power systems, measurements of grounding impedance are usually performed at low frequencies as the systems are designed to handle currents at nominal power frequency (50/60 Hz). Under power frequency conditions, grounding impedance is represented by only resistance of the electrode system and the masses of soil. At low frequencies, electrical conductivity and permittivity of soil could reasonably be

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assumed to have constant or frequency independent values where the in situ is measured by Wenner method (IEEE, 2012).

On the other hand, in order to conduct accurate analysis of the behaviour of grounding systems under high frequency or impulse conditions, there are several additional parameters needed to be considered such as system geometry and the frequency dependent variation of resistivity and permittivity of the soil. Hence, a grounding system designed without considering such variables may produce dangerous potential gradients and large potential rises even at quite long distances which may be hazardous to both living beings (humans and livestock) and conducting systems (electronics, oil & gas pipelines etc.). Therefore, high accuracy in the prediction of potential distribution for a given grounding system plays a vital role in designing an appropriate grounding scheme for a given environment.

Several equations have been developed to analyse the frequency dependence of soil. In this paper we consider six different models/expressions which have been proposed by (Cavka, Mora, & Rachidi, 2014) for the representation of soil electrical parameters, namely the model by Scott (S), Messier (M), Visacro and Portela (VP), Portela (P) , Visacro and Alipio (VA) and constant impedance (C). This study had investigated the dependence of soil parameters with the frequency and its effects on the response of the grounding system of a metallic tower when the structure or a conducting line connected to the structure (e.g. Power line or communication line) is struck by lightning. Negative lightning, most prevalent in tropical countries, has been considered for the analysis (both first and subsequent strokes). Heidler current model has been employed to calculate ground potential rise (GPR) and (SP) by using MATLAB code.

METHODOLOGY

Current waveforms of lightning

The lightning stroke waveform is described by the IEC-62305-1 standards (IEC62305, 2010) as shown in Equations 2-3 (Rameli, Abkadir, Izadi, Gomes, & Azis, 2014; V. A. Rakov and M. A. Uman, 2003).

$$i(t) = [\frac{i_o}{\eta}\frac{\left(\frac{t}{\tau_1}\right)^n}{1+\left(\frac{t}{\tau_1}\right)^n}\exp\left(\frac{-t}{\tau_2}\right)] \tag{2}$$

$$i(t) = [\frac{i_{o1}}{\eta 1}\frac{\left(\frac{t}{\tau_{11}}\right)^{n1}}{1+\left(\frac{t}{\tau_{11}}\right)^{n1}}\exp\left(\frac{-t}{\tau_{12}}\right) + \frac{i_{o2}}{\eta 2}\frac{\left(\frac{t}{\tau_{21}}\right)^{n2}}{1+\left(\frac{t}{\tau_{21}}\right)^{n2}}\exp\left(\frac{-t}{\tau_{22}}\right)] \tag{3}$$

Where:

t is the time step,

i_{o1}/i_{o2} is the amplitudes of the channel base current,

τ_{11}/τ_{12} is the first/second front time constant,

τ_{21}/τ_{24} is the first/second decay- time constant,

$\eta_1/\eta i_2$ is the first/second exponent (2~10),

$$\ldots\ldots \quad \eta_1 = \exp[-\left(\frac{\tau_{11}}{\tau_{12}}\right)(n\left(\frac{\tau_{12}}{\tau_{11}}\right))1/n_1],$$

$$\ldots\ldots \quad \eta_2 = \exp[-\left(\frac{\tau_{21}}{\tau_{22}}\right)(n\left(\frac{\tau_{22}}{\tau_{21}}\right))^{1/n_2}] \quad .$$

Parameters for the first stroke and the subsequent stroke Heidler waveforms are given in Table 1. The first return stroke current is characterised by a peak value of 30 kA, zero-to-peak time of about 8μs and a maximum steepness of 12 kA/μs ,whereas the subsequent return stroke current has a peak value of 12 kA, zero to-peak time of about 0.8 and a maximum steepness of 40 kA/ s (Rachidi & Janischewskyj, 2001). Figure-1 shows the first and subsequent waveforms simulated with the above parameters.

Table 1
Parameters (Rachidi & Janischewskyj, 2001)

	i_{o1}(kA)	$\tau_{11}(\mu s)$	$\tau_{21}(\mu s)$	η_1	i_{o2}(kA)	$\tau_{12}(\mu s)$	$\tau_{22}(\mu s)$	η_2
First stroke	28	1.8	95	2				
Subsequent stroke	10.7	0.25	2.5	2	6.5	2	230	2

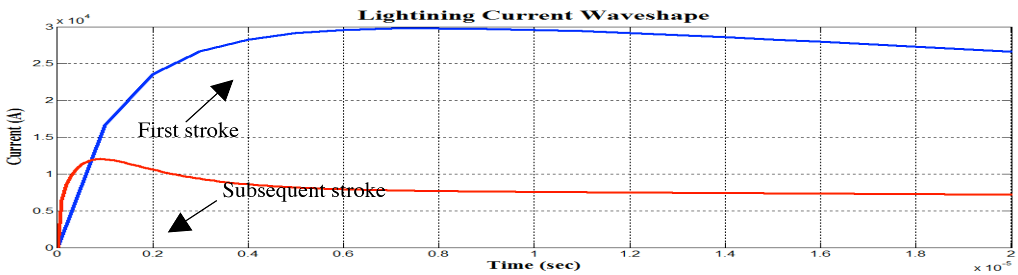

Figure 1. First and Subsequent return stroke current wave shapes

Tower grounding system

Figure 2 shows the model of the tower grounding system. The buried grounding electrode, made of steel with the radius of 6 mm, resistivity of 1.66 × 10-7 Ωm, relatively magnetic permeability of 636 and a depth of 3m have been considered (Lu, Liu, Qi, & Yuan, 2012). We considered three values of soil conductivity (σ =0.01, σ =0.001 and σ =0.0001 S/m) that represent most of the soil types that are found in Malaysia. The computations have been repeated for several distances.

Grounding system analysis

Practically-equivalent approaches to excitation-independent ground impedance have been widely used for computation of ground protection distribution. The first is the time-domain ground surge impedance *Z(t)*, which is the ratio of the voltage response to a unit step current excitation. The second is the frequency-domain alternative to the surge impedance: ground

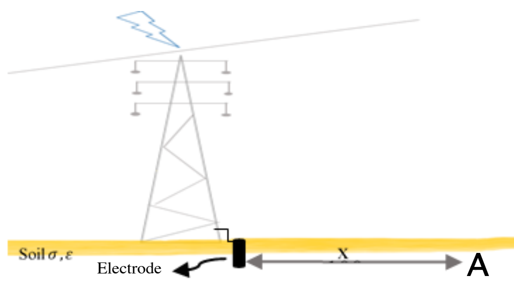

Figure 2. The geometry of problem

harmonic impedance $Z(\omega)$ (Cooray, 2010). The harmonic impedance in the frequency domain is defined as:

$$Z(\omega) = V(\omega)/I(\omega) \tag{4}$$

Where $V(\omega)$ and $I(\omega)$ are phasors of the steady state harmonic electric potential at the feed point with reference to the remote neutral ground and the injected current respectively, in a frequency range from 0 Hz up to the highest frequency of interest in transient studies. The harmonic impedance depends only on the geometry and electromagnetic properties of the electrodes and the medium. As it is well known, $Z(\omega)$ enables evaluation of the time functions of the transient potential $v(t)$ as a response to an arbitrary current pulse $i(t)$ by:

$$V(t) = F^{-1}\{F[i(t)] * Z(\omega)\} \tag{5}$$

In equation (6) F and F^{-1} denote Fourier and inverse Fourier transforms respectively (Pedrosa et al., 2010). The admittance is given by

$$Y(\omega) = \left(\frac{1}{Z(\omega)}\right) = \frac{1}{R + JX} = G + j\omega C \tag{6}$$

Where σ is electric conductivity, ω is angular frequency and ε is the electric permittivity. To calculate $Y(\omega)$ we used six empirical equations (Alipio & Visacro, 2013; Messier, 1985; C. Portela, Eng, & Grillo, 1999; S. V. and C. Portela, 1987; Scott, 1966). To determine the value of $\rho_{(f)}$ and $\varepsilon_{(f)}$ we used Liew-Darveize equation (Liew & Darveniza, 1974) model:

$$R = 1/G = \frac{\rho}{2\pi h}\ln\left(\frac{x}{r_o}\right) \tag{7}$$

$$\mathrm{x}\omega C = \frac{\omega\varepsilon_0\varepsilon_r}{2\pi h}\ln\left(\frac{r_o}{x}\right) \tag{8}$$

Step potential (SP) at the distance for a 0.5 m gap was calculated by the following equation:

$$SP = (v_x - v_{x+0.5m}) \tag{9}$$

Where x =10m, 50m, 90m.

RESULT AND DISCUSSION

Figure 3 shows the variation of voltage distribution for the first and subsequent strokes at several distances for σ =0.01 S/m. At this rather low soil resistivity value 100 Ωm, at 10 m distance from the grounding electrode, for first stroke the peak voltage is 3.6 kV and for subsequent stroke is 1.5kV at 10 m.

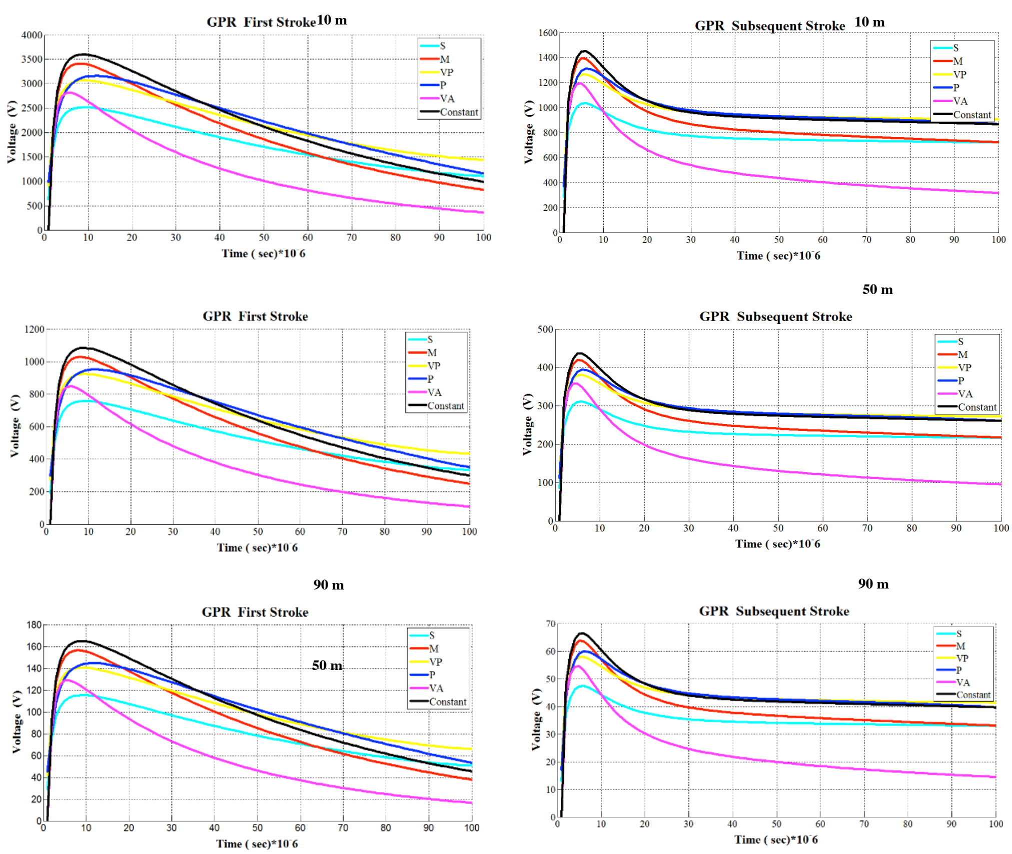

Figure 3. GPR for first and subsequent stroke at different empirical equations and σ =0.01 S/m

Table 2-3 shows the correlation between the distance and peak voltage GPR for the different empirical equations and different soil conductivity. As it is depicted in these tables, as the soil resistivity increases the peak potential increases rapidly and at 10 m for σ =0.0001 S/m (resistivity of 10,000 Ωm) the value may exceed 100 kV. Such values, may heavily damage equipment in a TT wiring system that have been grounded near the tower and connected with power neutral that has been grounded at a distant point (at the substation). Even at 50 m, the potentials may be harmful to most of the equipment that have impulse withstanding voltage of few kilo Volts. Hence equipotential sizing power and communication systems in the vicinity of towers with properly coordinated system of SPDs is essential for the safety of such equipment. In addition, such potential rises may also drive considerable transient currents in the skin of underground oil and gas pipelines in the vicinity enhancing metal corrosion. Therefore, isolation of pipelines that run close to the transmission and communication towers with suitable high resistive material is a need for their corrosion avoidance. Further studies should be done in this regard to find the most appropriate solution for a given pipeline arrangement, soil resistivity and electrode system. It should also be noted that the potential rise in the case of subsequent strokes is also significant. As a majority of negative flashes in most parts of the world may reach multiplicities above 5, the equipment in the nearby systems and metal pipelines may be

Table 2
Peak voltage GPR first stroke for six empirical equations

Conductivity	Models						
	Distance (m)	S (V)	M (V)	VP (V)	P (V)	VA (V)	Constant (V)
α =0.01 S/m	10 m	2518	3416	3071	3162	2816	3603
	50 m	758.3	1028.5	924.5	952	848	1085
	90 m	115.2	156.3	140.5	144.7	128.88	164.87
α =0.001 S/m	10 m	15566	30930	30710	27535	16440	36000
	50 m	4686	9310	9245	8288	4949	10850
	90 m	712	1415	1405	1260	750	1650
α =0.0001 S/m	10 m	83000	243780	307110	215850	57400	360000
	50 m	25000	73400	92450	65000	17280	108400
	90 m	3800	11155	14050	9875	2626	16500

Table 3
Peak voltage GPR subsequent stroke for six empirical equations

	Models						
Conductivity	Distance (m)	S (V)	M (V)	VP (V)	P (V)	VA (V)	Constant (V)
α =0.01 S/m	10 m	1034.5	1393	1265.8	1310	1191.5	1451.2
	50 m	311.4	419.3	381	394.5	358.7	436.8
	90 m	47.3	63.75	57.9	60	54.5	66.4
α =0.001 S/m	10 m	6477.5	12857	12685	11386	7366.7	14512
	50 m	1950	3870	3810	3425	2218	4368.5
	90 m	297	589	579.5	520	337	664
α =0.0001 S/m	10 m	35000	104000	126600	92000	29500	145000
	50 m	10500	31300	38100	27700	8885	43685
	90 m	1600	4760	5792	4210	1350	6640

subject to repeated high potential rises during a single flash. The protective systems should be developed by considering this factor as well.

Figure 4 shows the relation between the distance and step voltage for 0.5 m in the cases of first and subsequent strokes for different empirical equations at soil conductivity of 0.001 S/m (resistivity of 1000 Ωm). The step voltage for constant impedance is higher than that calculated by other models. At 10 m, for first stroke, the value of step voltage for different model vary between 3.8 kV to 1.0 kV and for subsequent stroke the same parameter ranges between 1.5 kV and 0.7 kV. At 50 m and 90 m the step potentials are 0.8 kV-0.15 kV and 0.3 kV-0.15 kV for first stroke. For subsequent strokes, the values are 0.4 kV-0.7 kV and 0.17 kV-0.03 kV. The results show that at a moderate soil resistivity, dangerous step potentials may be reached at close vicinity to the grounding system which may knock-off workers or visitors that walk/stand around. The SP may take much higher figures as the soil resistivity is increased to large values. These factors should be taken into account by the grounding system designers to ensure safety of the people at a tower site.

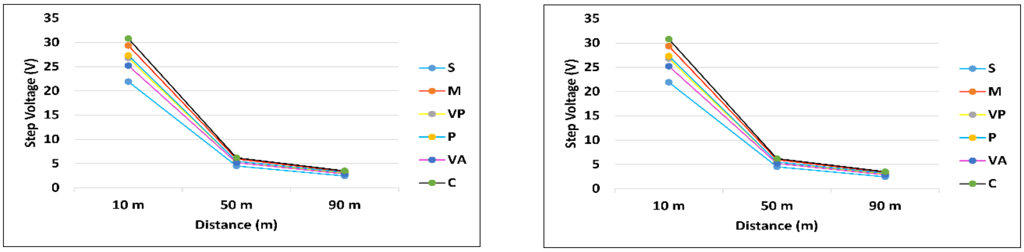

Figure 4. SP for first and subsequent stroke at different distance

CONCLUSION

This experiment has shown that lightning strikes to a metal tower or service line connected to that may drive impulse current into the soil may cause dangerous GPR and SP in the vicinity. The peak values and time variation of the GPR and SP depend on soil resistivity and the type of lightning current. They should also be a function of the grounding system arrangement as well but in this study, we have considered only a single grounding electrode connected to one footing of the tower. The engineering designers should take these parameters into account in developing the grounding system for a tower to ensure the safety of workers and visitors and the protection of equipment connected to the nearby grounded power and communication systems. The corrosion enhancement of nearby oil and gas pipelines is also a concern with respect to GPR. Further studies should be conducted in this regard with respect to various electrode arrangements, non-uniform soil resistivity profiles and positive lightning as well, to understand the frequency dependent electrical behaviour of soil in the vicinity of the grounding system.

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