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Methods for Improving Transient Ground Impedance of Transmission Structures

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SUMMARY

This paper presents a comprehensive low frequency and high frequency approach for studying the ground resistance/transient ground impedance of transmission structures. The investigation compared a reference low frequency approach with two different high frequency models for the ground resistance/transient ground impedance of transmission structures. The high frequency response of typical structure foundation systems was thoroughly analyzed and the effectiveness of various ground improvement methods evaluated in a range of uniform soil resistivity values covering the most commonly encountered difficult soil conditions. The crossover from low-frequency to high-frequency impedance was described using an impulse coefficient, which was typically less than unity for compact electrodes and greater than unity for distributed electrodes, up to certain limits of length and resistivity. The two different high frequency models were in close agreement for some electrodes but tended to differ on the degree of reduction of high-frequency impedance for continuous counterpoise and deep-well electrodes. Best practices for improving the ground resistance/transient response include the use of four radial counterpoises. For the lattice structure case, the CDEGS HIFREQ and NEC-4 models did not agree on the relative ranking of loop electrodes, four radial counterpoise and continuous counterpoise, and this discrepancy should be addressed by field tests.

KEYWORDS

Grounding, transmission lines, transient impedance.

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INTRODUCTION

The transmission line structure foundations form an imperfect electrical connection to the earth that can be tested with a wide range of instruments and improved with the use of supplemental electrodes and materials. Recent improvements in testing and modeling have focused on the high-frequency response of transmission line structure footings, as this affects the lightning performance. Some of the testing equipment developed recently such as the EPRI Zed-Meter® [1] have relied on the NEC-4 software for analysis of test lead configurations [2]. The difference between high-frequency impedance Z and low-frequency resistance R_f of the structure footings has been recognized by several researchers [3, 4], who are evaluating effective length of buried wires in terms of the impulse coefficient Z/R_f.

Published experimental data [5] show that, in general, for compact electrodes (structure footings with no buried horizontal wires) the transient impedance of the structure base is significantly lower than the low frequency resistance ($Z < R_f$). This behavior is mainly due to the apparent resistivity value that, on average, is lower at 100 kHz than the apparent resistivity at 100 Hz. For the distributed electrodes (structures footings with horizontal extent of more than 40 m) the measured transient impedance of the structure base is significantly higher than the low frequency resistance ($Z > R_f$). This was explained through the concept of effective length. Z saturates once the length of the electrode reaches the effective length, while the low frequency resistance R_f keeps decreasing.

In this paper, the high frequency response of typical structure foundation systems is thoroughly analyzed and the effectiveness of various ground improvement methods evaluated in a range of uniform soil resistivity values covering the most commonly encountered difficult soil conditions.

A set of simulations are performed, including the most typical transmission structures such as: 1) single-pole structure (steel pole), 2) H-frame structure and 3) lattice structure on four legs. For each structure, the following methods for improving the ground resistance/transient impedance are considered: a) use of radial counterpoise, b) use of loop counterpoise, c) use of continuous counterpoise, and d) use of 152 mm dia. wells (6” wells).

Two different computer codes are used for modeling the response of ground electrodes: CDEGS [6], an industry-standard analysis package, and NEC-4 [7], a well-known and widely used computer code based on the Method of Moments for analyzing the electromagnetic response of antennas and scatterers.

MODELLING METHODOLOGY

The modeling methodology used for the evaluation of the transient impedance of transmission structures is the numerical equivalent of the EPRI ZedMeter® test method. It simulates a lightning-like impulse injection into the transmission structure base and measures the resulting potential rise relative to a remote ground. Figure 1 illustrates the typical setup used in this approach. A 200 V pulse is applied between the structure base and the current lead. The current pulse waveform has a pulse width of 1.4 μs (see Figure 2a).

The length of the current injection lead is 150 m and the remote potential lead is 100 m, simulating a realistic transient impedance test set-up. Both leads are positioned along the right-of-way and are terminated in ground rods. The leads are placed above the ground at a constant height of 10 cm. In addition, the adjacent structures are modeled as simple vertical stakes. The line span is 200 m and the groundwire is bonded to the structures.

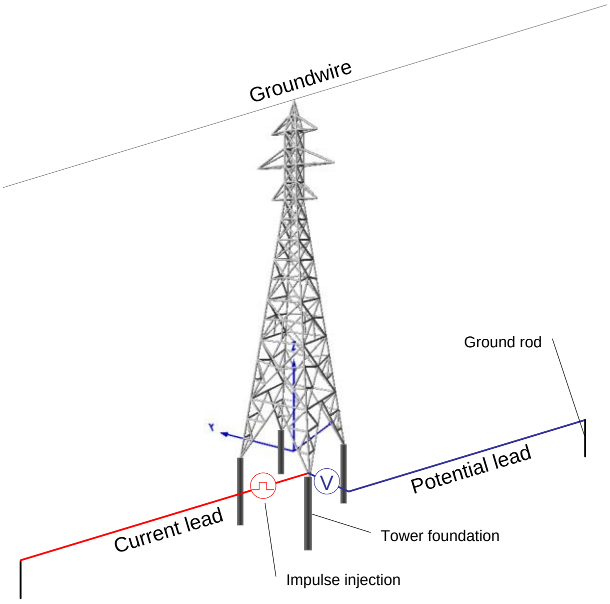


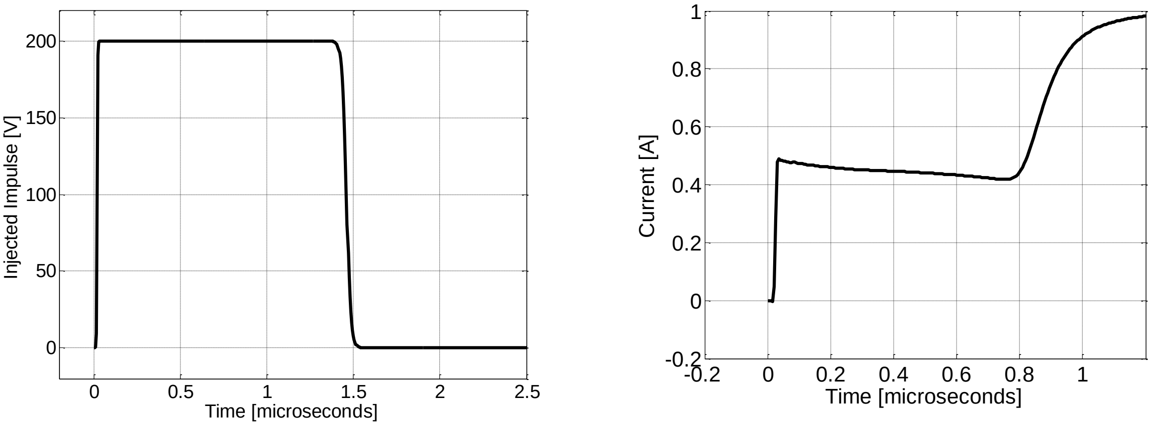
Figure 1 Transient impedance calculation: typical setup.

The NEC-4 computations have been carried out in the frequency range of 97.6 kHz to 100 MHz with the increment step of 97.6 kHz covering the frequency spectrum of the current pulse waveform used in this study. The results were converted into the time domain using Fourier transform.

A typical example of the current injected into the structure is given in Figure 2b when the pulse shown in Figure 2a is applied to the structure configuration presented in Figure 1, and where the structure height is 36 m, the foundation depth is 4.6 m, and the soil resistivity is 50 Ωm. Furthermore, the structure base voltage is showed in Figure 2c. In this case, the calculated structure transient impedance, after initial oscillations associated with transients propagating up and down the structure, settles to a constant value of 5 Ω, and remains fairly constant until the reflections coming from the lead ends arrive (see Figure 2d).

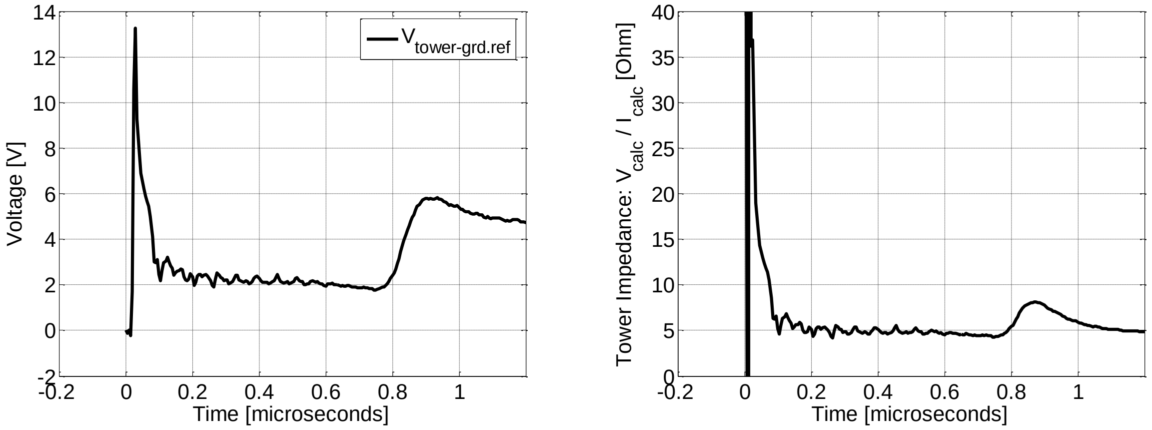
The structure transient impedance is calculated in this paper, for all the configurations analyzed, as the median value between 450 ns and 650 ns. The presence of adjacent structures and the ground rod terminations at lead ends are not influencing the calculated or measured structure impedance, as its median value is read out or measured before the arrival of the reflections. Therefore, a detailed model of the adjacent structures is not necessary. Moreover, it is worth noting that in both software packages, the computational time increases exponentially with the number of wire segments used in the model. Thus, it is important to choose carefully the level of complexity used in the models to obtain accurate results and still maintain reasonable computation times.

This model and methodology for the calculation of transient impedance of transmission structure footings was similarly simulated using CDEGS HIFREQ module.



a) Pulse waveform used in this study.

b) Injected currents into the structure base.



c) Structure base voltage to remote ground (potential lead)

d) The calculated structure transient impedance

Figure 2 Typical results obtained using NEC-4 model for a ground resistivity of 50 Ωm

CONFIGURATIONS MODELLED

The structure footing impedance in the areas of high soil resistivity can be improved with the use of additional buried electrodes. The active transient injection method presented in the previous section was applied in this study to the most common structure configurations and treatment options for the validation of treatment effectiveness. The cases analyzed are given in Table 1.

Table 1 Structure configurations and treatment options analyzed

Method for improving ground resistance		**Structure Type**		
		Single-Pole structure (Steel Pole)	**H-Frame structure with and without guys**	**Lattice structure on four legs**
1	No treatment	Var soil resistivities	Var soil resistivities	Var soil resistivities
2	Radial counterpoise	Var soil resistivities	Var soil resistivities	Var soil resistivities
3	Loop counterpoise	Var soil resistivities	Var soil resistivities	Var soil resistivities
4	Continuous counterpoise	Var soil resistivities	Var soil resistivities	Var soil resistivities
5	Vertical well	Var soil resistivities	Var soil resistivities	Var soil resistivities

The following simulations were performed for each structure configuration modeled: 1) the low frequency resistance of the structure footing was computed with CDEGS MALZ module, and 2) the high-frequency (transient) impedance of the structure footing was computed with NEC-4 and CDEGS HIFREQ.

For each configuration, the low-frequency resistance and transient impedance were calculated, for four soil resistivity values: 300, 1000, 2000, and 5000 Ωm. In these simulations, a value of 10 was assumed for the relative permittivity of the soil.

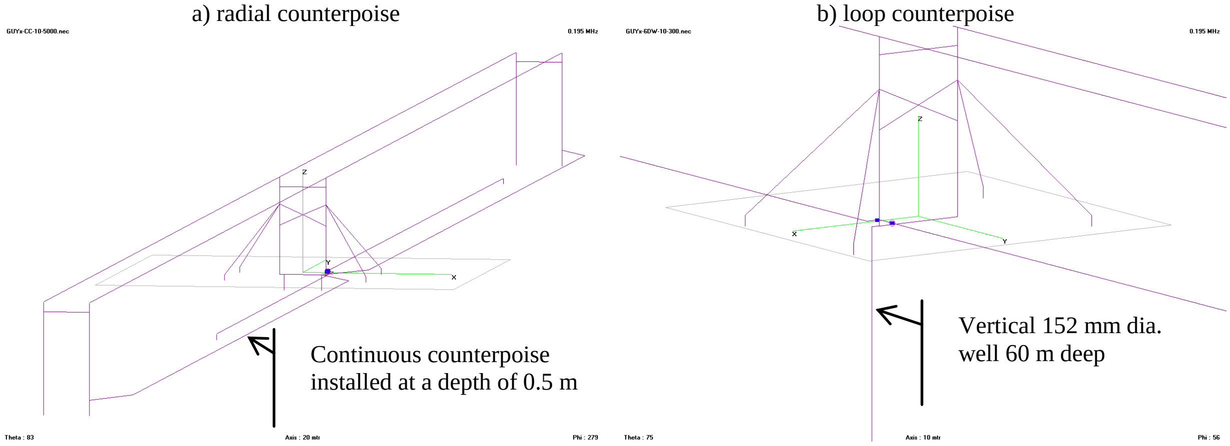
As an illustration of the configurations analyzed the 3d models of the H-frame guyed structure and the lattice structure, with the treatment options considered, are given in Figure 3 and Figure 4.

4 x radial counterpoise, each 30 m long, installed at a depth of 0.5 m

Loop counterpoise total length 30.7 m, installed at a depth of 0.5 m

a) radial counterpoise

b) loop counterpoise



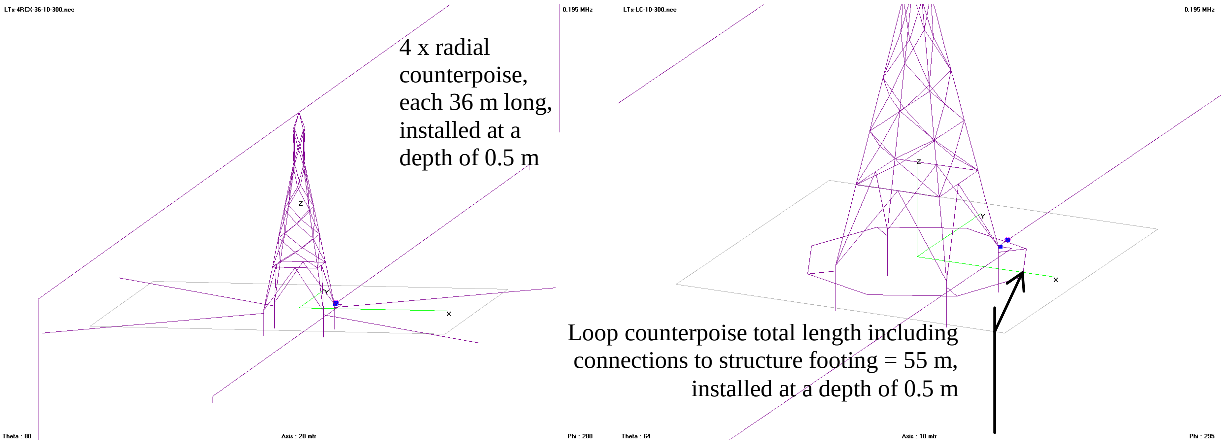
Continuous counterpoise installed at a depth of 0.5 m

Vertical 152 mm dia. well 60 m deep

c) continuous counterpoise

d) vertical well 60 m deep

Figure 3 Model of the H-frame guyed structure with various treatment options

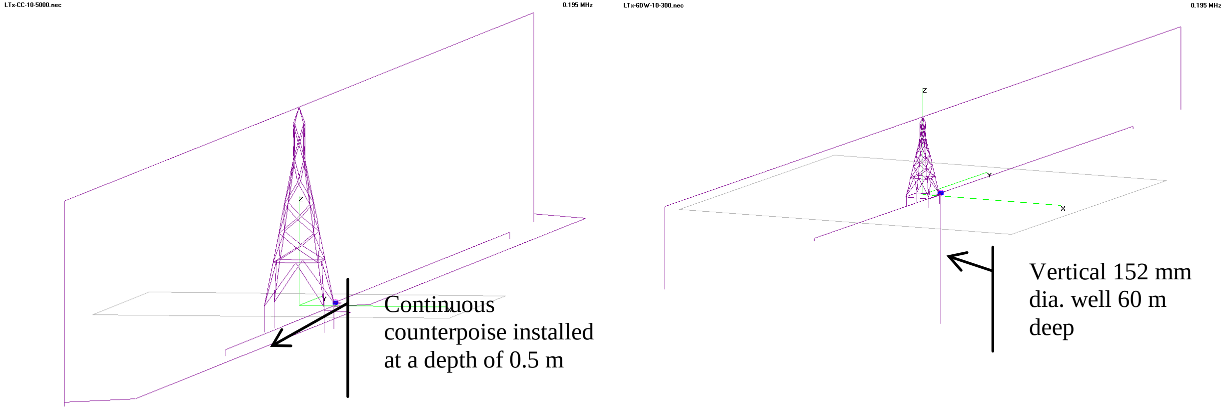


4 x radial counterpoise, each 36 m long, installed at a depth of 0.5 m

Loop counterpoise total length including connections to structure footing = 55 m, installed at a depth of 0.5 m

a) radial counterpoise

b) loop counterpoise



Continuous counterpoise installed at a depth of 0.5 m

Vertical 152 mm dia. well 60 m deep

c) continuous counterpoise

d) vertical well 60 m deep

Figure 4 Model of the lattice structure with various treatment options

SIMULATION RESULTS

A total of more than 200 simulations cases were performed. A representative set of results obtained in this study is presented in this section. The low frequency resistance R_f and transient impedance Z variation with the soil resistivity, grouped by the method of treatment, is shown in Figure 5 for the H-frame guyed structure case and in Figure 6 for the lattice structure case.

In the analysis of the simulation results, we used the impulse coefficient I_C concept given by the ratio of the transient impedance Z and the low-frequency resistance R_f. As noted in [8], the impulse coefficient is a useful and important parameter for lightning protection applications as the common practice consists simply in measuring the low-frequency resistance. Therefore, the knowledge of the ratio Z/R_f permits the estimation of the lightning response based on the measured or calculated low-frequency resistance.

The results obtained show that the impulse coefficient is typically less than unity for compact electrodes and greater than unity for distributed electrodes, up to certain limits of length and resistivity, in fair agreement with the published experimental data.

One of the main outputs of this study was the comparison between the NEC-4 and CDEGS HIFREQ results in uniform soil conditions for the same grounding electrodes. A good agreement between these results was expected. However, the summary of the results obtained in uniform soil shows a different picture. While for some structure configurations the simulation results agree closely, in other cases the discrepancy is significant. The most notable disagreement was found for the continuous counterpoise case, in which the Z estimated by CDEGS was much lower than NEC-4 result.

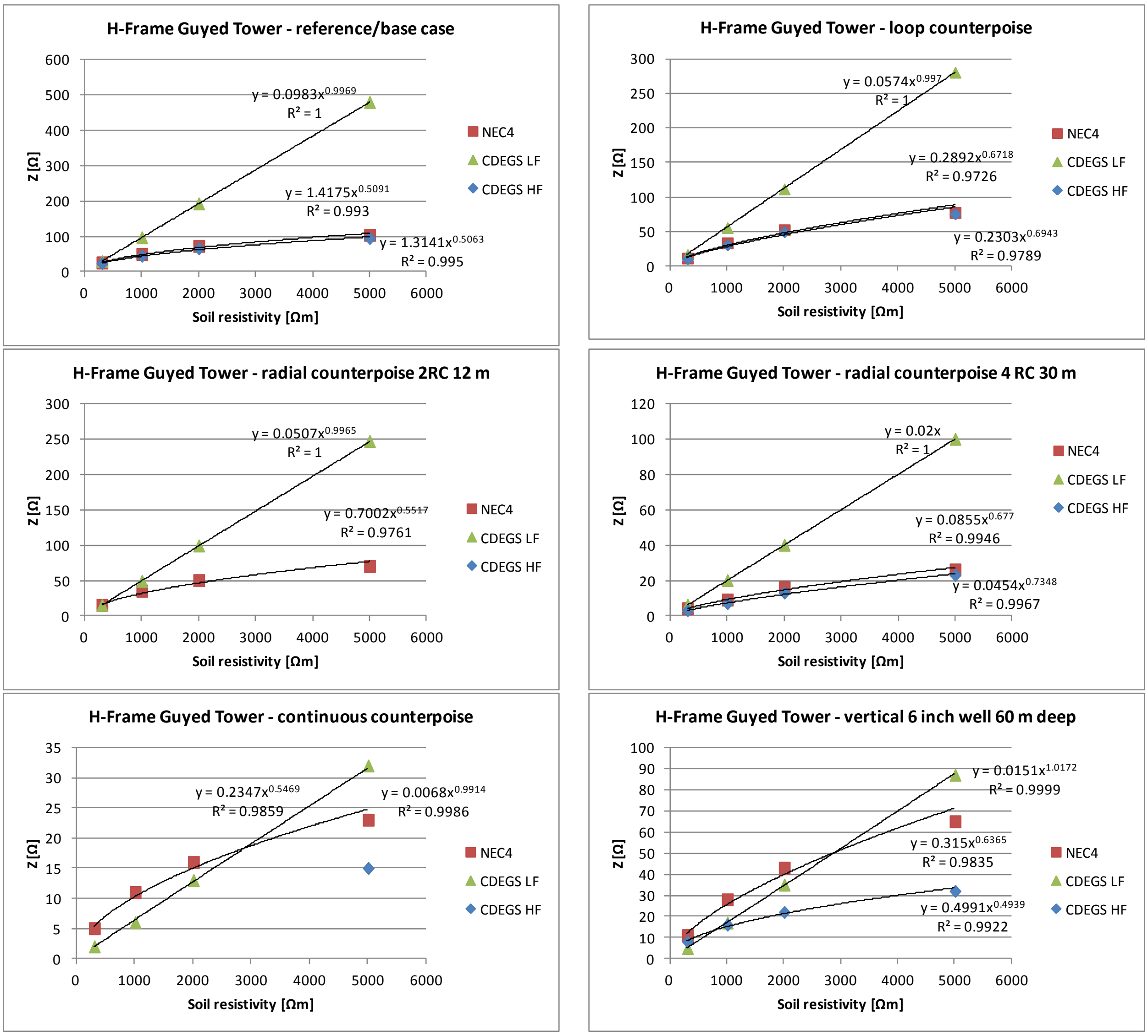


Figure 5 H-frame guyed structure results in uniform soil grouped by treatment option

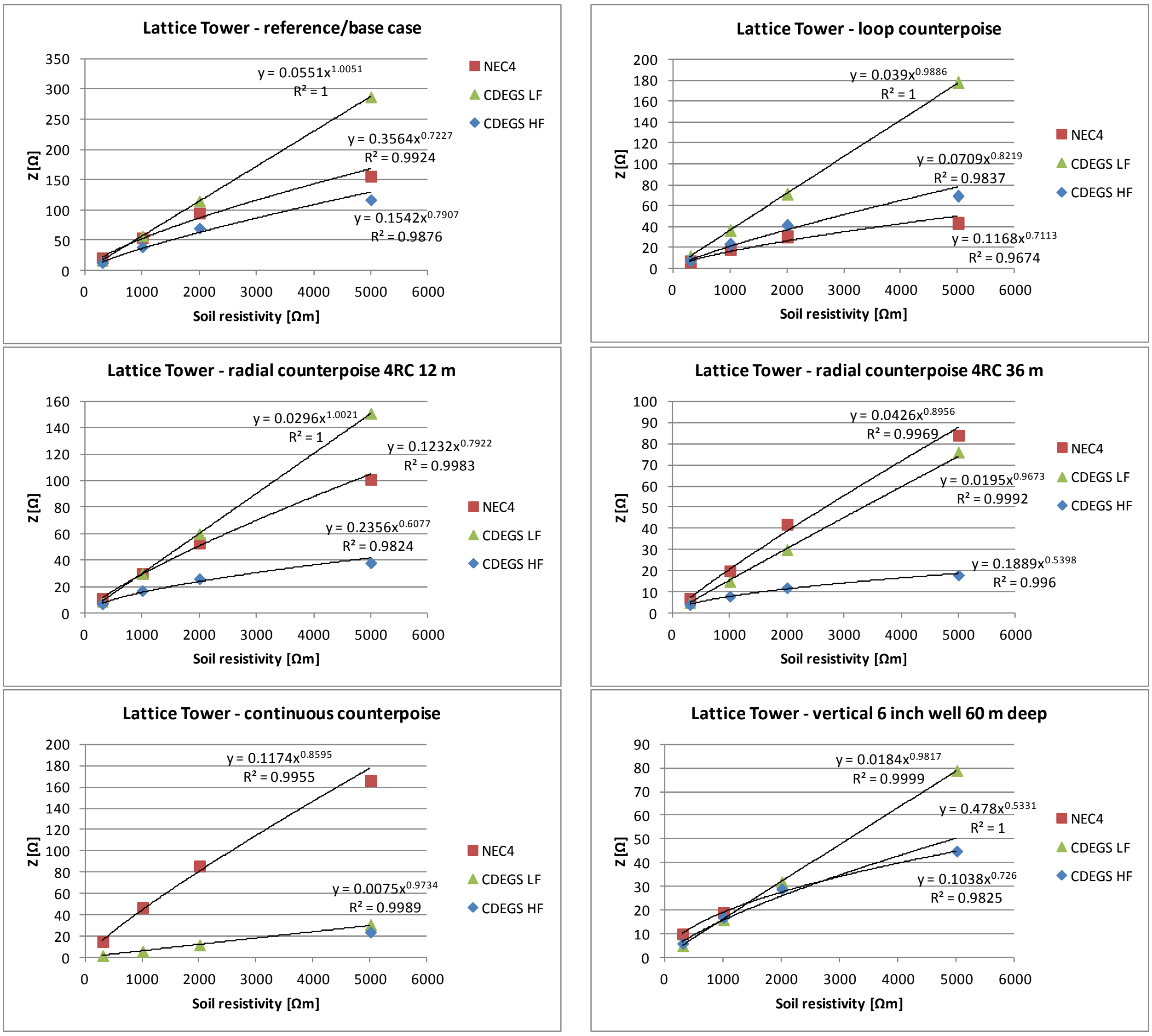


Figure 6 Lattice structure results in uniform soil grouped by treatment option

CONCLUSIONS

The simulations results show that the transient impedance Z has a non-linear variation with the soil resistivity. In other words, the degree of improvement offered by the various methods of treatment, judged from the transient impedance point of view, varies with the soil resistivity.

The crossover from low-frequency to high-frequency impedance was described using an impulse coefficient, that was typically less than unity for compact electrodes and greater than unity for distributed electrodes, up to certain limits of length and resistivity. In most of the cases, the results obtained with both programs are showing a decrease of calculated impulse coefficient with the increase of soil resistivity. This indicates that the electrode is becoming more efficient in dissipating the lightning currents with the increase of the soil resistivity compared to what the low-resistance may suggest.

The two different high frequency models were in close agreement for some electrodes but tended to differ on the degree of reduction of high-frequency impedance for continuous counterpoise and deep-well electrodes.

Best practices for improving the ground resistance/transient response include the use of four radial counterpoise. For the lattice structure case the CDEGS HIFREQ and NEC-4 models did not agree on the relative ranking of loop electrodes, four radial counterpoise and continuous counterpoise, and this discrepancy should be addressed by field tests.

A number of areas of interest for future research work include the investigation of the ground electrical parameters, their frequency-dependence, and the impact on the calculated transient response of the transmission line structures, and a comprehensive testing program that will establish experimental values of impulse coefficient for transmission line structures and wind turbines.

ACKNOWLEDGEMENTS

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