EVALUATING THE TRANSIENT IMPEDANCE OF TRANSMISSION LINE TOWERS

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Abstract – The low-frequency methods used by most utilities nowadays for measuring the resistance of transmission line ground electrodes are inaccurate or cannot be applied when overhead groundwires are connected to the towers. Moreover, many of them are costly and time consuming. This paper proposes and compares two new methods for evaluating the transient impedance of transmission line towers. Both methods simulate the lightning-like impulse injection into the transmission tower base and measure the resulting potential rise relative to a remote ground.

1 INTRODUCTION

A recent published study [1] introduced the active transient injection at tower based technique for testing the transmission line ground electrodes. This method was first applied on 345 kV transmission line towers with a wide range of treatment options, and used highly portable, low-power instrumentation including a pulse generator and a digital oscilloscope, to inject a 440 ns transient pulse current into distributed or lumped tower footings and measure their transient response.

In this initial study the pulse was applied between the tower base and the sheath of a 50 Ω coaxial cable, oriented at right angles to the right-of-way. The reference potential lead ran along the line. Both 60 m length leads were terminated at the remote ends in ground rods. The length was selected to ensure that reflections did not distort the measurements during the 440 ns pulse application. By centering the test equipment at tower base, problems with high-frequency attenuation and lethal test signals associated with other proposed impulse test methods [2] are eliminated.

The results of transient tower base injection have been compared with the footing resistance estimate from Airborne Electromagnetic data and with values obtained using three-terminal fall-of-potential measurement methods on isolated towers. The active transient injection technique proved to give a good indication of the effectiveness of tower electrode modifications under lightning impulse conditions.

This paper presents two new improved methods for evaluating the transient impedance of transmission line towers using transient injection at tower base.

2 METHODS OF ANALYSIS

The first method is numerical and uses the Numerical Electromagnetics Code NEC-4 [3], a well-known and widely used computer code based on the Method of Moments for analyzing the electromagnetic response of antennas and scatterers. Compared to previous NEC versions, such as NEC-2 used by Baba and Ishii [4, 5], NEC-4 is numerically more efficient and can also model wires buried in the ground or penetrating from air into ground [3].

The second method proposed is experimental. Its origins are based on initial developments presented in [1] and, together with the numerical technique constitute a closed-loop approach that gives greater confidence in the results.
Figure 1 illustrates the typical setup used in both approaches.

These methods simulate the lightning-like impulse injection into the transmission tower base and measure the resulting potential rise relative to a remote ground. The 200 V pulse applied between the tower base and the current lead is given in Figure 2 and has a pulse width of 1.4 µs.

The NEC-4 computations have been carried out in the frequency range of 195.3 kHz to 100 MHz with the increment step of 195.3 kHz covering the spectrum of interest. The results were converted in time domain using Fourier transform.

3 DIPOLE OVER LOSSY GROUND

The successes of these approaches are based on the behavior of the horizontal wire antenna placed near lossy ground, described originally as the Beverage antenna [6]. Theoretical and experimental studies [7, 8] indicate that the phase velocity would be slow for a surge injected into antennas located near the earth, and losses along the way would reduce the magnitude of the surge. This gives us a practical way to excite a large transmission tower, with its overhead groundwires, using a signal that gives practical ground impedance measurements with low-voltage pulses.

The transient surge impedance of an insulated wire, laid on the surface of the earth to make a Beverage antenna, can be measured by applying a step wave to the middle of the wire. The computed or observed ratio of the step voltage to the currents in each leg of this dipole establishes the transient surge impedance.

3.1 Dipole over ground: numerical results

Figure 3 shows the transient impedance of a 200 m dipole over lossy ground, as computed with NEC-4. The simulation has been performed for a ground resistivity of 50 Ωm and a relative permittivity of 10. The wire is placed above the ground at a constant height of 5.4 mm and has radius of 1.8 mm. The wire insulation is a pure dielectric with relative permittivity of 3 and radius of 2.5 mm. The dipole is terminated at both ends with ground rods buried 0.1 m in the ground. The injected pulse is described in Figure 2. Figure 3b shows the slow propagation speed of the current wave along the insulated wire at different distances from the source.

Figure 3 - Dipole over lossy ground; 50 Ωm soil resistivity.
(a) Dipole geometry. (b) Current propagation along the wire. (c) Calculated transient impedance.
The transient impedance in Figure 3c is obtained by dividing the source voltage in Figure 2 by the NEC-4 computed current in Figure 3b. This impedance settles fairly rapidly to a constant value of 370 Ω, and remains nearly constant until the reflections coming from the ground rods arrive at the source at 1.3 µs.

This demonstrates that a careful selection of a pulse width and dipole length might enable us to obtain a time window large enough for a robust transient impedance measurement. Moreover, the ground rod terminations at remote ends are not influencing the calculated or measured impedance, as its median value is read out or measured before the arrival of the reflections.

The transient impedance varies mainly with effective wire height over ground and with earth resistivity. Figure 4 illustrates the strong influence of the dipole height on the calculated value of the transient impedance and on the propagation speed. The simulations have been performed using the dipole geometry described in Figure 3a for a soil resistivity of 50 Ωm and for two different heights above the ground: 1 m and 0.01 m respectively.

3.2 Dipole over ground: experimental results

Experimental results were obtained using a 200 m coaxial cable over ground and a similar setup as in Figure 3a. The pulse was injected into the cable sheath and the current propagating in both directions away from the source was measured using wideband current transformers. The soil resistivity was determined to be 49 Ωm with Wenner measurements. The experimentally observed transient impedance is given in Figure 5.

A comparison between the transient impedance determined experimentally (see Figure 5), and those predicted by the NEC-4 simulation (see Figure 3c) shows that the simulation results are in very good agreement with experimental data.

Figure 5 - Dipole over ground: experimentally observed transient impedance using 200 V pulse [9].

4 TRANSIENT IMPEDANCE OF TRANSMISSION LINE TOWERS

The basic geometry and test methods used in the dipole study can be easily adapted for the case of the transmission towers described in Figure 1. The length of the current injection and remote potential leads is 100 m. Both leads are positioned along the right-of-way, and are terminated in ground rods. The double circuit suspension tower is 36 m tall. Its foundation was modeled in NEC-4 as having a depth of 4.6 m. The adjacent towers were also modeled as simple vertical stakes. The line span is 200 m and the groundwire is bonded to the towers. In the numerical model the leads were placed above the ground at a constant height of 10 cm.

4.1 Numerical results

Figure 6 shows the waveshape of the current injected into the tower when the pulse given in Figure 2 is applied to the configuration described above, and the soil resistivity is 50 Ωm. The tower base voltage is showed in Figure 7. The calculated tower transient impedance, after initial oscillations associated with transients propagating up and down the tower, settles to a constant value of 5 Ω, and remains fairly constant until the reflections coming from the lead ends arrive (see Figure 8).

The major impact of the ground resistivity on the computed/measured values of the tower transient impedance is shown in Figure 9, where the calculations have been performed using a soil resistivity of 1000 Ωm. The value obtained in this case is 46 Ω.

Similar to the dipole case, it can be noted that the presence of adjacent towers and the ground rod terminations at lead ends are not influencing the
calculated or measured tower impedance, as its median value is read out or measured before the arrival of the reflections. For the cases in which the initial oscillations are more extensive, the accuracy of the measurement can be kept by increasing the length of the test leads and the duration of the pulse applied.

The tower footing impedance in the areas of high soil resistivity can be improved with the use of additional buried electrodes. The active transient injection methods proposed here can also be successfully applied to treated towers for the validation of treatment effectiveness.

The calculated transient impedance for the treated tower described above is given in Figure 11. The use of additional buried electrodes improved significantly the transient impedance, in this case reducing it from 46 \( \Omega \) (see Figure 9, untreated tower) to 19 \( \Omega \). The four radial counterpoise wires are remarkably effective even at 200 ns after the impulse.
4.2 Experimental results

Extensive measurements have been conducted for various tower configurations and leads arrangements in different soil conditions [9]. The experimentally observed transient tower impedance, for a soil resistivity of 49 $\Omega$m determined with Wenner measurements, is given in Figure 12. The experimental setup is identical to the one illustrated in Figure 1.

We can see excellent overall agreement between the experimental data in Figure 12 and the simulations in Figure 8. The only important discrepancy is that the simulations predict a faster return time and stronger magnitude of reflection from the ground rod, at 800 ns, while in the experiments, the reflections are weaker and occur at later time. This effect can be reproduced by adjusting the effective height of the leads above ground to distances closer than 10 cm.

5 CONCLUSION

We showed that the new improved methods using transient injection at tower base are an excellent tool for the evaluation of the transient impedance of transmission line towers, and can be applied without the need of insulating the tower to be tested [1].

The closed-loop approach proposed in this paper has proved to be rapid and effective, insensitive to noise, tower or lead configurations, for most of the practical cases.

6 REFERENCES