

On Tower Impedances for Transient Analysis

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Abstract—The analysis of the dynamic behavior of power transmission line and telecommunication towers is of interest in protection and EMC studies related to lightning. Usually, time-domain surge impedance is used to characterize tower dynamic behavior. The main drawback in the definition of such surge impedance is that it is dependent on the excitation waveshape and there is no consensus on the current waveshape to be used. Also, there is no consensus on the unique definition of the involved voltage. This paper explores possibilities for a systematized approach to the analysis and uniquely defined quantities that characterize transient response of towers. Further, limitations associated with simplified approaches are emphasized by examining examples of direct comparison between computations based on transmission-line approach and antenna theory for a 100-m tall tower. It is pointed out that problems in the definition of voltages might occur above 100 kHz, especially near resonant frequencies, while differences in current distribution exist already at the lowest frequencies.

Index Terms—Electromagnetic analysis, impedance, lightning, power system lightning effects, power system transients, power transmission lines, power transmission protection, simulation, towers, transmission line theory.

I. INTRODUCTION

THE analysis of transient behavior of towers struck by lightning is an important problem when studying the lightning performance of transmission lines (e.g., [1]). The issue has gained more importance with the recent use of instrumented telecommunication towers to capture lightning return stroke currents. Indeed, lightning current waveforms recorded at the top of tall telecommunication towers in Germany, Switzerland, Russia, and Canada (see a recent review in [2]) clearly show the presence of reflections at the top and at the bottom of the tower on the measured lightning currents. The extraction of primary lightning return stroke currents from the measured records requires an accurate modeling of transient behavior of the tower [3].

Analysis of a lightning stroke to a tower (transmission line, communication, etc.) is an electromagnetic problem. Although the analysis often starts from a field point of view, it is usually cast in circuit terms. Most usually, differently defined impedances are used to characterize tower response to lightning.

In general, approaches to the problem may be categorized as:

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1) Theoretical

- a) in time domain [4]–[6];
- b) in frequency domain [7]–[9].

Based on:

- i) circuit and transmission-line theory [7], [10], [13], [15];
- ii) waveguide theory [11];
- iii) electromagnetic-field theory [5], [6], [8], [9].

2) Experimental

- a) on scaled models [12]–[14], [16];
- b) on actual towers [14].

Whatever the approach is, the aimed quantity usually is the so-called “surge impedance.” It is important to note that although surge impedance is a well-defined quantity in electromagnetic textbooks, the same denomination has been adopted to describe differently defined quantities in the literature dealing with transient analysis of towers.

For example, the following are some definitions of such “impedances”:

- *Transient surge impedance* is a time-domain function defined as [4]

$$z(t) = \frac{v(t)}{i(t)} \quad (1)$$

where $v(t)$ is the voltage at the top of the tower, and $i(t)$ is the current impulse injected at the top of the tower.

- Another time-domain definition of *surge impedance* is [9]

$$z(t) = \frac{v(t)}{\max[i(t)]}. \quad (2)$$

- Most usually *surge impedance*, as a constant value, is defined as [5] and [6]:¹

$$Z = \frac{\max[v(t)]}{I} \quad (3)$$

where I is the current value at the moment when $v(t)$ is maximal.

It is worth noting that in all of the above time-domain definitions, the resulting impedance is not only dependent upon the tower’s geometry and electrical parameters, but also on the injected current pulse [17].

Moreover, neither the currents nor the voltages in the above definitions of impedances are uniquely defined. Indeed, the current waveform may be:

- unit step pulse;
- ramp;
- double exponential;
- any.

¹Note that in some studies (e.g., [4] and [12]), an average voltage taken over two tower travel times was considered.

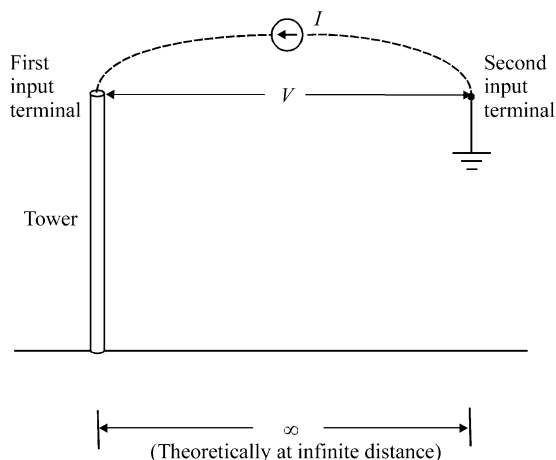


Fig. 1. Current and the voltage required for the definition of the impedance.

Voltage is defined as:

- line integral of electric field from the ground surface to the tower top [5];
- difference of potentials between the top and the bottom [9];
- measured along a given path from the top of the tower to a “distant” point at the ground surface [18].

The aim of this paper is to explore possibilities for a systematized approach to the analysis and uniquely defined quantities that characterize the transient response of towers. Further, limitations associated with simplified approaches will be emphasized.

II. VOLTAGE AND CURRENT FOR THE DEFINITION OF IMPEDANCE

The notion of impedance is so basic to the work of the electrical engineers that sometimes they are inclined to forget its limitations (e.g., that it is defined for sinusoidal time variations, and, strictly speaking, applies only between points separated by electrically short distances) [19].

Fig. 1 illustrates the considered situation of a tower. In the simple cylindrical model of the tower, the return conductor may be considered at infinity. When the tower is struck by lightning, the excitation of the tower can be represented with a current source with one terminal connected to the tower and the other at infinity. The influence of the current source connecting leads is ignored. Voltage between the terminals is required for the definition of the impedance.

This approach is directly taken from the static analysis where the voltage in Fig. 1 is uniquely defined. This is a classical circuit approach to this field problem. The classical circuit point of view is that the given system consists of components whose individual behavior and mutual interactions can be completely specified in terms of their terminal voltages and currents [20]. Important questions are:

- How are terminal voltages and currents related to the electromagnetic field?
- Under what conditions are the assumptions inherent to the circuit approach justifiable?

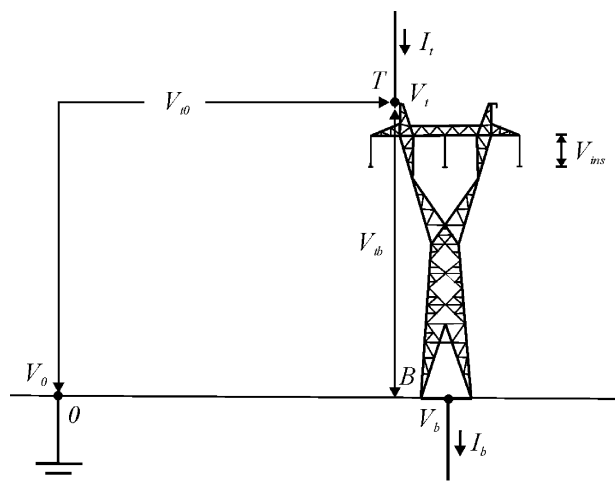


Fig. 2. Physical view on the voltages and the currents used in transient analysis of towers. V_{tb} —voltage between the top and bottom points of the tower, V_{t0} —voltage between the top point of the tower and the reference point, V_{ins} —voltage along the insulator string, V_t and I_t —potential and current at terminal T at the top of the tower, V_b and I_b —potential and current at terminal B at the bottom of the tower.

III. POSSIBLE PROBLEMS RELATED TO THE DEFINITION OF THE VOLTAGE BETWEEN DISTANT TERMINALS

The first problem is the definition of the voltage at high frequencies between (theoretically infinitely) distant terminals along unspecified paths.

In general, voltage is defined as a line integral of the electric-field vector between two points along a given path. In the quasi-static regime, the voltage between two points is uniquely defined. At higher frequencies, however, the voltage between two points may become path dependent and, therefore, loses its significance. In transmission-line theory, the voltage can be uniquely defined in the plane transverse to the line conductors. Indeed, the TEM line response assures that no magnetic-field component will be present along the conductors and, therefore, the voltage between two conductors can be obtained by integrating the electric field along any path entirely contained in the transverse plane.

Fig. 2 illustrates different paths used for the definition of the voltage at the top of the tower. In [18], the voltage was determined considering a path consisting of a horizontal part from the tower top away to a given distance and a vertical part down to the ground. Other different paths from the tower top to a distant point on the ground were also considered in [21]. Voltages calculated by integrating the electric field along those different paths should be different if there is any time-varying magnetic flux through the area bounded by these paths [22].

In Section VII, we examine the quantitative implications of the path dependence of such defined voltages.

It is worth noting that there are fewer problems in the definition of voltages at higher frequencies between two closely spaced terminals, compared to terminals that are separated by an electrically large distance. It is clear that there should be no such problems for the definition of the voltage along the insulator string, where the terminals are much closer and the path of integration is clearly determined.

IV. QUEST FOR IMPEDANCE INDEPENDENT OF THE EXCITATION WAVESHAP

One of the problems in the definition of the time-domain surge impedance in (1) to (3) is that it is dependent on the wave-shape of the excitation.

The frequency-domain alternative to the surge impedance is the harmonic impedance [13]. It does not depend on the excitation and it depends solely on geometry and electromagnetic characteristics of the tower and the medium. A basic requirement for a frequency-domain analysis being that the system is linear, makes this method not suitable for modeling of nonlinear phenomena. On the other hand, it is well suited for modeling frequency-dependent characteristics such as soil characteristics.

As it is well known, the system functions, such as the harmonic impedance, are Fourier transforms of the impulse response [23]. Since the impulse function has a constant spectrum, the harmonic impedance may be evaluated simply by determining the voltage $V_h(\omega)$ as a response to a steady-state time harmonic current excitation $I_h(\omega) = 1$ A in a frequency range up to the highest frequency of interest for the transient study

$$Z(\omega) = \frac{V_h(\omega)}{I_h(\omega)}. \quad (4)$$

Now the voltage $u(t)$, as a response to an excitation $i(t)$ that may be measured or simulated lightning current impulse, is given by

$$u(t) = \mathbf{F}^{-1}\{I(\omega) \cdot Z(\omega)\} \quad (5)$$

where $I(\omega) = \mathbf{F}\{i(t)\}$. Here, \mathbf{F} and \mathbf{F}^{-1} denote Fourier and inverse Fourier transforms, respectively.

If the response to a unit step function, that is, the surge impedance is needed, it can be determined from the harmonic impedance [9]. If we write

$$Z(\omega) = R(\omega) + jX(\omega) \quad (6)$$

then, the response to a unit step function (surge impedance) is [23]

$$z(t) = R(0) + \frac{2}{\pi} \int_0^\infty \frac{X(\omega)}{\omega} \cos \omega t d\omega. \quad (7)$$

However, it should be emphasized that whether time functions and spectra of the currents and voltages are available in discrete or continuous form, for usual digital computations, the discrete versions of both are required.

As it is well known, Fourier transform is one possibility for frequency-domain analysis. Discrete Laplace [14] and Modified Fourier [32] transforms are two alternatives for implementing practical frequency (or Laplace) domain analysis. These two alternatives usually employ the fast Fourier transform algorithm. As another alternative, the harmonic impedance might be used in the time-domain transients programs, such as EMTP using rational approximation techniques described in [33].

However, one should be aware that the mentioned discrete transform techniques should be applied carefully with a thorough understanding of their limitations and errors introduced by sampling, numerical integration, and truncation of functions in time and frequency domains.

V. ANTENNA THEORY ALTERNATIVE

An antenna theory approach is well suited to the frequency-domain analysis discussed in the previous section. It is very important to emphasize that antenna theory, contrary to transmission-line theory, does not need voltages in the formulation. Excitation of the antenna is usually defined by a voltage source, but it may also be defined by a current source between two terminals on the antenna [24], which is favorable in the lightning studies. After the excitation by a current source is defined, the current distribution in the conductors may be determined. Consequently, the electromagnetic field at any point and voltage as a line integral of the electric-field vector between any two points along a given path may be determined.

For example, if the voltage across the insulator string is of primary interest, then transfer impedance should be defined as

$$Z_{\text{ins}}(\omega) = \frac{V_{\text{ins}}(\omega)}{I_h(\omega)} \quad (8)$$

where $V_{\text{ins}}(\omega)$ is the voltage along the insulator string as a response to a harmonic 1-A current injected in the tower.

VI. COMPARISON BETWEEN TRANSMISSION-LINE AND ANTENNA APPROACHES

To illustrate some of the previous points, a simple example is used. We consider a 100-m-tall thin cylindrical tower with 1-m diameter on a perfectly conducting earth (see Fig. 3).

To examine the limitations and points of special concern, we compare modeling based on transmission-line approximation and antenna theory. It should be noted that since the scope of this paper is fundamental considerations mostly concerning the unique definition of impedance and limitations of circuit concepts, we compare the simplest models of transmission-line and antenna approaches. Analysis of the influence of parameters and comparison with other more advanced models in both approaches is out of the scope of this paper.

If the tower is represented as an ideal transmission line, the following formula [19] may be used for the characteristic impedance:

$$Z_o = 60 \ln \frac{2H}{a} - 60 \quad (9)$$

where H and a are the height and the radius of the tower, respectively. Z_o in (9) is the average characteristic impedance assuming the ground-based antenna as an opened-out transmission line. Equation (9) is not exactly equal to usual formulas used for towers [13]; however, since it is derived by an antenna/transmission line analogy [19], it is suitable for comparison between antenna and transmission-line theory approaches.

The propagation constant is

$$\gamma = j\beta = j\omega\sqrt{LC} = j\omega\frac{10^{-8}}{3} \quad (10)$$

where L and C are the inductance and the capacitance per-unit length of the tower, respectively.

To compare this model with general antenna theory, a time harmonic 1-A current source is connected to the base of the tower. In this case, the transmission line may be considered as open-circuited at the top (see Fig. 3). The input impedance Z_i

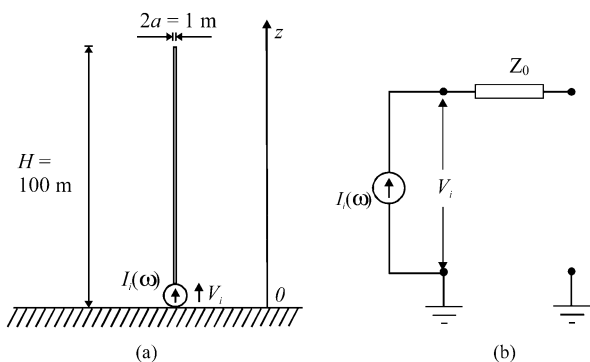


Fig. 3. (a) Antenna and (b) transmission-line representations of the tower.

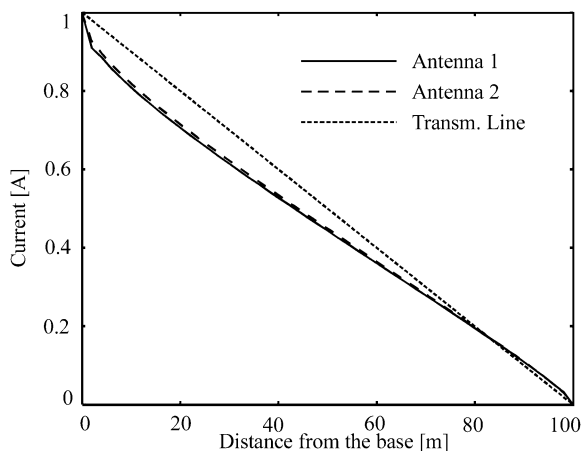


Fig. 4. Current distribution along the tower at 10 kHz.

seen by the source and the current distribution along the tower in the frequency domain are, respectively, given by [22]

$$Z_i = -jZ_0 \cot(\beta H) \tag{11}$$

$$I_z(\omega) = I_i \cos \beta z - j \frac{Z_i}{Z_0} \sin \beta z. \tag{12}$$

In the case of the antenna representation, the impedance is simply

$$Z_i(\omega) = \frac{V_i(\omega)}{I_i(\omega)} \tag{13}$$

where $V_i(\omega)$ is the voltage between the terminals of the current generator, connected between the base of the tower and the earth.

For the antenna theory analysis, we use two well-known computer codes ([25] and [26]) based on different mathematical models and different numerical techniques. Details on the modifications of these codes for the earth effects, the current source modeling, and treatment of low frequencies are presented in [27]. Validation of this approach applied to the grounding systems analysis by comparison with field measurements is presented in [28]. These modified antenna codes are validated for use at as low frequencies as 50 Hz by comparison with static methods.

Fig. 4 shows the current distribution² along the tower at 10 kHz. It should be noted that low frequencies are of interest in lightning studies, since the frequency spectrum associated with

²All results are root mean square (rms) values.

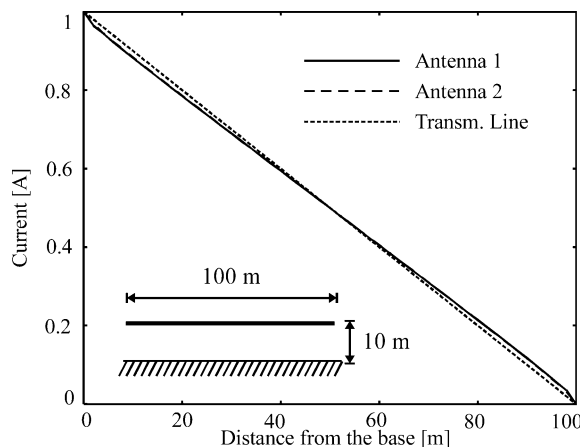


Fig. 5. Current distribution along the horizontal “tower” at 10 kHz when 1-A current is injected at the left end.

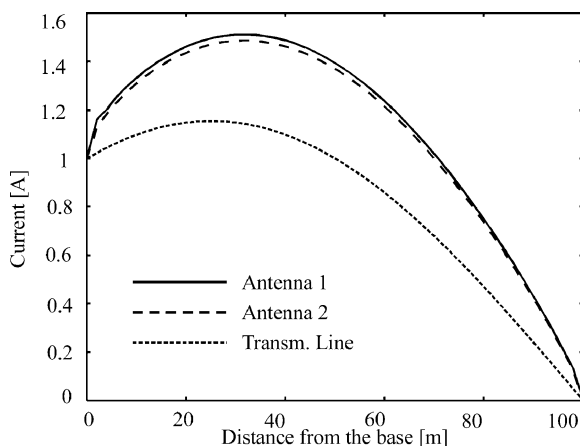


Fig. 6. Current distribution along the tower at 1 MHz.

lightning electromagnetic pulse has significant components at low frequencies (down to dc) [31]. It is interesting to observe that the differences are noticeable even at this low frequency. The transmission-line theory predicts uniform current distribution, while the antenna theory gives nonuniform distribution due to two effects: asymmetry related to the earth and the effects at the ends of the tower.

The differences due to the asymmetry can be explained considering the two current components along a horizontal transmission line, namely an “antenna mode” current and a “transmission-line mode” current [29]. The antenna mode current is originated essentially from asymmetries and it disappears for symmetrical configurations [29], [30]. This is illustrated in Fig. 5, where the current distribution along a horizontal wire parallel to a perfectly conducting earth is computed using both antenna theory and transmission-line approximation. In this case, due to the symmetry of the configuration, the current distribution predicted by the transmission-line theory is in very good agreement with the antenna theory results; only some differences due to the end effects subsist. It should be noted that the effects of the nonuniform distribution could be taken into account by nonuniform transmission-line approach [15].

Figs. 6 and 7 present the current distribution along the tower at higher frequencies, namely 1 MHz (Fig. 6) and 2 MHz (Fig. 7).

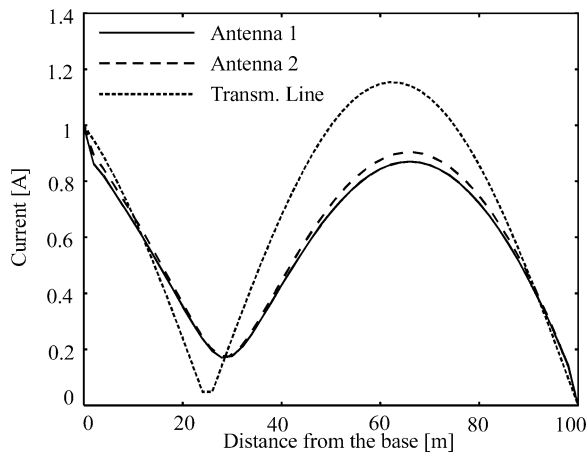


Fig. 7. Current distribution along the tower at 2 MHz.

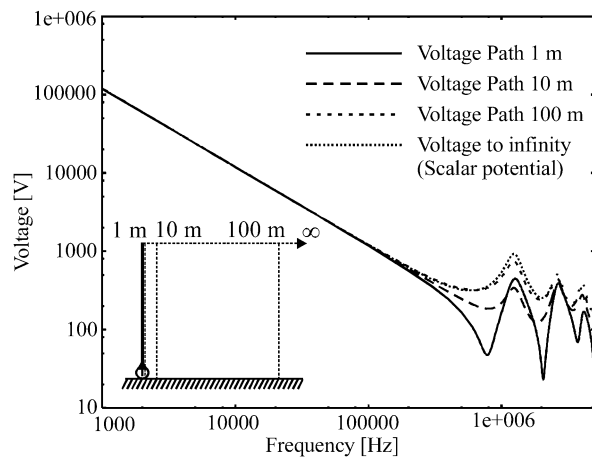


Fig. 9. Voltage to ground at the top of the tower along different paths.

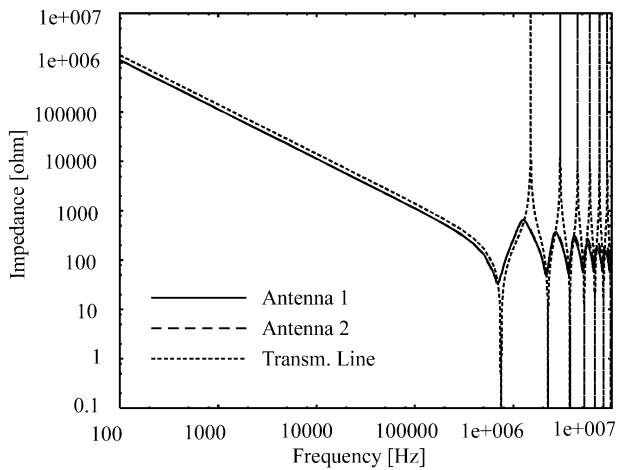


Fig. 8. Input impedance at the base computed by antenna codes [25] (antenna 1) and [26] (antenna 2) and transmission-line theory [using (12)].

The results show different behavior for transmission-line and antenna theory approaches depending on the differences related to the resonance visible on Fig. 8. Currents predicted by the transmission-line theory might be much higher or much smaller than those predicted by antenna theory depending on the frequency. Differences could become very significant, especially near resonant frequencies.

Fig. 8 shows the input impedance computed by the two antenna codes and simple transmission-line theory (12). Two different methods for evaluation of the voltage to ground at feed point, required for the impedance, are applied. In the modified code [25], the voltage to ground is determined as the voltage across the current source, while in the modified code [26], the voltage to ground is determined as the scalar potential at the surface of the tower at the feed point, leading to equivalent results. It can be seen that all models predict similar behavior at low frequencies up to the first resonant frequency at 0.75 MHz, although the consistent difference of the values at lower frequencies may be attributed to the difference in current distribution. On the other side, differences for higher frequencies are distinct. Lossless transmission-line model unrealistically predicts zero or infinite impedances at resonance, while the antenna models pre-

dict shallow maximums and minimums. Although the applied simple antenna models also treat lossless conductors, the differences at resonance may be attributed to radiation losses, which antenna models take into account. This is an indication that use of the transmission-line theory should be checked especially for higher frequencies whenever impulses have frequency content in that range, such as, for example, impulses with time to maximum of about $1 \mu\text{s}$ and smaller, typical of subsequent return strokes [31]. Differences in frequency domain at a higher frequency range will lead to quite different results in the early time region when often the maximum values of the impulses occur.

This leads to one possible use of antenna theory in improving the circuit and transmission-line models. For example, the circuit model behavior at resonance might be improved by inserting a small resistive component to account for the losses.

VII. ANALYSIS OF THE VOLTAGE PATH DEPENDENCE IN FREQUENCY DOMAIN

Fig. 9 shows the voltage between the top of the tower and a point at the earth's surface, computed by integrating the electric-field vector along different paths for a wide range of frequencies. Four different paths are analyzed, the first starts at the top and after 1 m in parallel with the earth's surface, goes vertically to the earth's surface, while the second goes 10 m and the third 100 m in parallel to the earth's surface. The fourth path goes to infinity in parallel with the earth's surface. The voltage for this case is equivalent to the scalar potential at the top. The path dependence of the voltage is visible at frequencies as low as 200 kHz.³ When such voltages are used for the definition of impedances, the method of evaluation should be carefully examined for the effect of path dependency that may not lead to unique values of the voltages, and hence, of the impedances.

One alternative to cope with this problem of path dependence is to use the scalar potential instead of the voltage as the integral of the electric field over a given path [9]. The advantage of such an approach is that the scalar potential is uniquely defined. In addition, at lower frequencies, the scalar potential reduces to the traditional quasi-static definition of the voltage.

³It is worth noting that a frequency of 300 kHz corresponds, for the considered case, to a wavelength equal to ten times the height of the tower.

The scalar potential concept is used and illustrated in Figs. 8 and 9 for the input impedance and voltage to ground at the top of the tower, respectively.

VIII. CONCLUSION

Different expressions for the time-domain surge impedance that are usually adopted for characterization of the transient behavior of towers are dependent on the excitation waveshape. Furthermore, there is no consensus on a unique definition of the voltage and the current waveshape used in the definition of such surge impedance.

Frequency-domain harmonic impedance does not depend on the excitation and is a function solely of the geometry and the electromagnetic properties of the system. Therefore, it is better suited to represent tower transient behavior. If needed, consistent time-domain surge impedance may be obtained from the harmonic impedance.

Uniquely defined impedances require uniquely defined voltages. In due course, special attention should be paid to path dependence of the voltages at higher frequencies.

Special attention should also be paid to voltages between distant points such as the voltage at the top of the tower. To guarantee unique value, either path of the integration of the electric-field vector should be uniquely defined or scalar potential should be used. The latter is recommended because it does not depend on the geometry, and furthermore, it reduces to the traditional quasi-static definition at low frequencies. Such problems diminish if the voltage along the insulator string is of primary interest, since its terminals are much closer and the path of integration is determined.

However, it should be noted that the harmonic impedance concept is not suited for nonlinear phenomena. Also, practical digital computations require application of discrete transforms, which should be applied carefully with a thorough understanding of their limits.

Antenna theory approach might be used for an accurate computation of voltages. It might be also used for validation and improvement of simpler circuit and transmission-line models. Examples discussed in the paper illustrate possible improvements of the behavior at resonance and the use of nonuniform lines.

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