Analysis and Estimation of Surge Impedance of Tower

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Abstract **–** Different mathematical formulas and analytical values of surge impedance of communication tower including high voltage transmission and distribution tower are presented. Those values and formulas have been utilized since 1934. Recently, the surge impedance of communication tower under the influence of direct and indirect lightning hit has drawn a lot of attention. Such value of lightning surge impedance and its associated parameters are becoming important factors for the protection system design in substation as well as low voltage communication equipments including home appliances.

I. INTRODUCTION

Several models have been proposed to estimate the surge impedance of vertical structures (tower), following either a transmission line [1-6], a numerical electromagnetic [7, 8], or an experimental approach [9-12], though in some cases, more than one approach is used [13-16]. Jordan, in 1934, published one of the precursor works in this field [1]. Jordan's formula to calculate the surge impedance of vertical conductors remained as the main reference to estimate the transient behavior of transmission towers subjected to lightning currents until the proposition of new theories in the 1960s (e.g.,[2,3]). It was later found that Jordan's derivation contained a mistake and a correction was proposed [17].

Recently, the interaction of lightning with elevated strike objects has been attracting a lot of attention in the scientific community (e.g.,[18-24]). As a consequence, the development of simplified models to simulate transients in vertical metallic structures has gained importance. In this context, the equations and values of surge impedance derived theoretically or measured experimentally appear to be very promising, because they give insightful information for the designing and installing protection system against lightning surge.

This paper presents investigation on surge impedance of an elevated structure with simple approximation to the shape of structure. 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. This paper also summarizes the methods of excitation that have been considering in a lightning surge analysis by the technical community.

II. JORDAN'S ORIGINAL FORMULA FOR TOWER SURGE IMPEDANCE

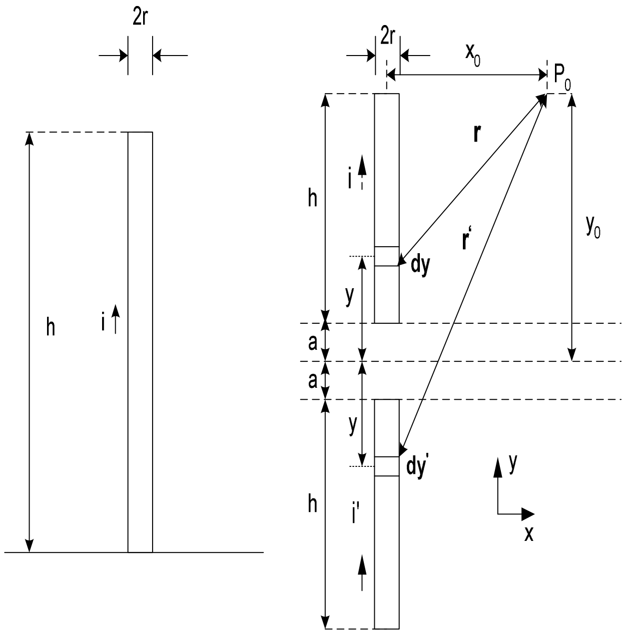
The surge impedance of a tower can be approximated by considering the tower as a vertical cylinder having a length equal to the height above the ground plane of the actual tower, and a radius equal to the mean equivalent radius of the actual tower [1]. This equivalent cylinder should also be regarded as having its base located at the same elevation above the true ground plane as the ground-line base of the actual tower. In accordance with the theory of images, there should be conceived as associated with the equivalent cylinder an identical image cylinder located symmetrically with respect to the true ground plane. For such a system, it can be shown that the inductance of an element dy of the tower equivalent cylinder as shown in Fig. 1(b), at an elevation y above the true ground plane is,

$$dL = \left[\log_e \frac{\sqrt{(h+a-y)^2 + r^2} + (h+a-y)}{\sqrt{(h+a+y)^2 + r^2} + (h+a+y)} + \log_e \frac{\sqrt{(a+y)^2 + r^2} + (a+y)}{\sqrt{(a-y)^2 + r^2} + (a-y)} \right] dy, \quad (1)$$

where h = length of tower equivalent cylinder (height of tower above ground plane).
r = radius of tower equivalent cylinder (mean equivalent radius of tower).
a = depth of true ground plane below earth's surface.

Integrating equation (1) between the limits $y = h + a$ and $y = a$, dividing by h, multiplying by the speed of light to convert from inductance to impedance (as $Z = Lc\ \Omega$, $c = 1/\sqrt{LC}$ = speed of light), and finally simplifying, the mean value of surge impedance over the cylinder equivalent to tower is, [1]

$$Z_s = 1382\ [\ \log_0 \frac{h(h+2a)}{r(h+a)} + \frac{a}{h} \log_0 \frac{(h+2a)^2}{(h+a)(2a+\sqrt{4a^2+r^2})}]$$
$$+\frac{30}{h}[\sqrt{4a^2+r^2} - 2(h+a-r)\ ]\quad \Omega . \tag{2}$$



(a) (b)

Fig. 1. Vertical conductor system. (a) Original system. (b) Equivalent representation.

For the special case where the depth of true ground plane below the earth's surface (e.g. a as in Fig. 1(b)) is close to zero, then equation (2) reduces to the comparatively simple expression, [1]

$$Z_s = 138.2\ \log_{10}\frac{h}{r} + 90\frac{r}{h} - 60\ \ \Omega$$
$$= 60\ \ln\frac{h}{r} + 90\frac{r}{h} - 60\ \ \Omega. \tag{3}$$

The equivalent radius for a complex structure such as GSM tower, high voltage transmission tower etc. is difficult to compute precisely. At the outset, it is necessary to disregard the cross arms, and confine attention to the tower mast and hence, the expression, $r = \text{perimeter of section}/2\pi$ offers one method of approximating the equivalent radius [1]. Thus for square tower sections having a face width A, the equivalent radius would be $r = 4A/2\pi = 0.637A$; for triangular sections with face width A, the equivalent radius would be $r = 3A/2\pi = 0.478A$; and for rectangular sections with face widths A and B, the equivalent radius of the structure would be $r = 2(A+B)/2\pi = 0.318(A+B)$.

III. IEEE/CIGRE FORMULA OF TOWER SURGE IMPEDANCE

A number of tower models have been proposed, but most of them are not general, i.e., a tower model shows a good agreement with a specific case explained in the paper where the model is proposed.

The following IEEE/CIGRE formula of the tower surge impedance is well known and is widely adopted in a lightning surge simulation [25-26] (Fig. 2),

$$Z_t = 60\ \ln\left[\cot\left\{0.5\tan^{-1}\left(\frac{R}{h}\right)\right\}\right]\ \ \Omega, \tag{4}$$

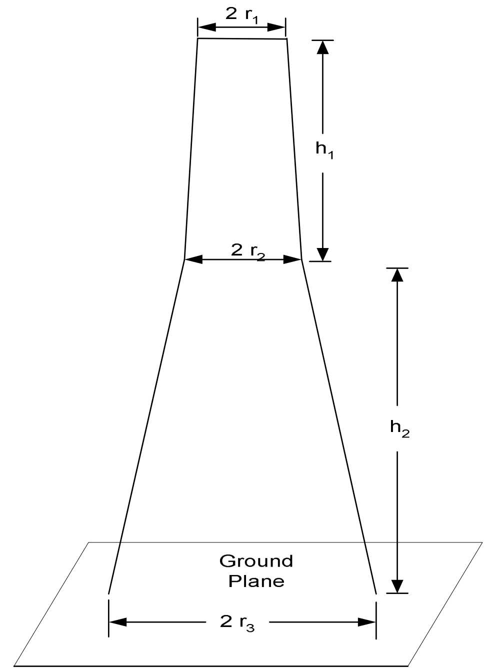


Fig. 2. Tower model proposed by IEEE/CIGRE.

where $R = (r_1h_1 + r_2h + r_3h_2)/h$ is the equivalent radius of the tower represented by a truncated cone, $h = h_1 + h_2$, and

r_1, r_2, r_3 tower top, midsection and base radii [m],
h_1 height from the midsection to top [m],
h_2 height from base to midsection [m].

When the tower is not a cone but a cylinder, then the above equation is rewritten by,

$$Z_t = 60\ \ln\left(\frac{h}{r}\right)\ \ \Omega, \tag{5}$$

where r is the radius of a cylinder representing a tower.

IV. JORDAN'S REVISED FORMULA

In [1], Jordan introduced the expression given by equation (3) to represent the surge impedance of a vertical conductor. Although the derivation of equation (3) is not entirely available in [1], one can suppose that Jordan applied the magnetic vector potential to calculate the inductance of a vertical cylinder. The system of Fig. 1(a) was equivalently represented as that in Fig. 1(b), where i is the current in the real conductor, i' is the current in the image conductor, and P_0 is a generic point with coordinates (x_0, y_0) where one wish to calculate magnetic vector potential $\vec{A}$. The parameter a is defined by Jordan [1] as the depth of true ground below the earth's surface, which is assumed to be, as in [5], conceptually equivalent to the complex skin depth p introduced by Deri *et al*. [27] to represent losses due to finite ground conductivity.

According to the method of images, i and i' must have the same direction and sign, as illustrated in Fig. 1(b) [28]. Consequently, $\vec{A} = \vec{A_r} + \vec{A_i}$, where $\vec{A_r}$ is the magnetic vector potential associated with the real conductor, and $\vec{A_i}$ is the magnetic vector potential associated with the image conductor. Nevertheless, in the derivation of equation (3), Jordan considered the opposite sign for the current in the image conductor, and therefore, its contribution to the total magnetic vector potential became subtractive and not additive, as it should be. Consequently, the surge impedance given by equation (3) is underestimated. To evaluate the correct value of surge impedance of a vertical conductor following Jordan's approach, a new expression is then required.

Based on the system of coordinates of Fig. 1(b) and disregarding propagation effects, one can write the total magnetic vector potential at the generic point P_0 as,

$$\vec{A} = \frac{\mu_0 i}{4\pi}\left[\int_a^{a+h} \frac{dy}{\sqrt{(y_0-y)^2 + x_0^{\,2}}} + \int_a^{a+h} \frac{dy}{\sqrt{(y_0+y)^2 + x_0^{\,2}}}\right]\hat{y} \quad (6)$$

where the first integral in the right-hand side term corresponds to $\vec{A_r}$, the second integral corresponds to $\vec{A_i}$, and $\hat{y}$ is the unit vector in the y-axis direction. After solving the integrals in equation (6) and knowing that $dL = A\ dy / i$, one can write,

$$dL = \frac{\mu_0}{4\pi}\Big[\log_e \frac{\sqrt{(h+a-y_0)^2 + x_0^{\,2}} + (h+a-y_0)}{\sqrt{(a-y_0)^2 + x_0^{\,2}} + (a-y_0)} + \log_e \frac{\sqrt{(h+a+y_0)^2 + x_0^{\,2}} + (h+a+y_0)}{\sqrt{(a+y_0)^2 + x_0^{\,2}} + (a+y_0)}\Big]\, dy_0, \quad (7)$$

where dL is the differential inductance element. Note that if $\vec{A} = \vec{A_r} - \vec{A_i}$ is incorrectly assumed, equation (7) becomes equal to the expression obtained by Jordan to represent dL [1].

To calculate the external inductance L per unit length of the vertical conductor, it is necessary to integrate equation (7) in the interval $a \le y_0 \le a+h$, at $x_0 = r$, and then to divide the result by h. To simplify, as in [1], an infinite ground conductivity is now assumed, making $a = 0$ in equation (7). As a result,

$$L = \frac{\mu_0}{4\pi}\left\{2\log_e \frac{2h + \sqrt{4h^2 + r^2}}{r} + \frac{r}{h} - \frac{\sqrt{4h^2 + r^2}}{h}\right\}. \quad (8)$$

Equation (8) can be further simplified if $h >> r$. Also if losses are neglected and a transverse electromagnetic (TEM) field structure is assumed, the surge impedance Z_s of the vertical conductor can be obtained by multiplying equation (8) by the speed of light, resulting in,

$$Z_s = 60\ \ln\frac{4h}{r} - 60\ \Omega \quad (9)$$

which is the same expression obtained by Takahashi [17] but in a slightly different derivation. The theoretical formula of surge impedance with vertical wave incidence derived from Takahashi [17] and validated by Goni *et al.* [29] is,

$$\begin{aligned} Z_s &= 60\left(\ln\sqrt{2}\,\frac{2h}{r}\right) - 92.4\ \Omega \\ &= 60\cdot\left\{\left(\ln\sqrt{2}\,\frac{2h}{r}\right) - 1.54\right\}\Omega. \end{aligned} \quad (10)$$

And with horizontal wave incidence,

$$Z_s = 60\cdot\left\{\left(\ln\sqrt{2}\,\frac{2h}{r}\right) - 1.832\right\}\Omega \quad (11)$$

which is very close to the empirical formula of Hara *et al.* [9],

$$Z_s = 60\cdot\left\{\left(\ln\sqrt{2}\,\frac{2h}{r}\right) - 2\right\}\Omega. \quad (12)$$

Also, equation (9) is similar to the expression independently derived by Wagner and Hileman [2] to calculate the average surge impedance of a vertical cylinder that was later modified by Sargent and Darveniza [3], reaching the final form,

$$Z_{WH} = 60\ \ln\left(\sqrt{2}\,\frac{2h}{r}\right) - 60\ \Omega = 60\ \ln\left(\sqrt{2}\,\frac{ct}{r}\right) - 60\,\Omega\cdot$$

In the derivation of Wagner and Hileman [2], a step or rectangular current was assumed to be injected at the top of vertical cylinder, and as a consequence, only the first term in the right-hand side of the above equation was obtained.

V. APPROXIMATION OF LATTICE TOWER

As an alternative to the frequently used cylindrical approximation of a steel tower, a conical representation has also been used. The use of a cone as a simplification of the tower element is not an unrealistic approximation as is shown in Fig. 3, where the cylindrical and conical representations are compared with the actual tower structure. Analyses of the response of these structures were performed using field theory concepts and will be mentioned in the succeeding sections.

VI. ANALYSIS OF THE SURGE RESPONSE OF A CYLINDRICAL TOWER TO A RECTANGULAR WAVE OF CURRENT

If $\boldsymbol{E_i}$ is the electric field due to currents at a point at any instant, and $\boldsymbol{s}$ is the distance along a curve through the point, then,

$$\oint \overline{E}_i \cdot \overline{ds} = -\oint \frac{\partial \overline{A}}{\partial t} \cdot \overline{ds}$$

where $\boldsymbol{A}$ is the vector magnetic potential at the point.

Consider an isolated cylindrical tower of height h and radius r normal to a perfectly conducting horizontal earth plane as shown in Fig. 4. Consider a rectangular wave of current I impressed on the tower at $x = 0$ at time $t = 0$. Then the surface current density is,

$$J_s = \frac{I}{2\pi r} \ .$$

Consider an element dx of the tower as shown in Fig. 4, then the vector magnetic potential at a point (d, r) is,

$$\overline{A} = \frac{\mu_0}{4\pi} \oint\oint \frac{\overline{J_s(x,\beta,t-r'/c)}}{r'} dS$$

where dS is the element of surface $(dx \cdot r \cdot d\beta)$ and r' is the distance from dS to the point (d, r).

Hence,

$$\vec{A} = \frac{\mu_0}{4\pi} \int_0^{2\pi} \int_0^{y} \frac{I}{2\pi r} \cdot \frac{r dx \cdot d\beta}{\sqrt{(x-d)^2 + r^2}} \, \widehat{a}_d \ .$$

Therefore,

$$\int_{d=0}^{d=p} \vec{E}_i \cdot d\vec{s} = -\frac{\mu_0 I c}{4\pi} \ln \frac{ct}{ct-p} = -I \cdot \left[60 \cdot \ln\left(\sqrt{2}\, \frac{ct}{r} \right) \right] \cdot$$

Note that the expression in brackets is of the form of a surge impedance, for $ct >> r$. Thus, following Wagner and Hileman, the transient surge impedance,

$$Z = 60 \ln\left(\sqrt{2}\, \frac{ct}{r} \right) = 60 \ln\left(\sqrt{2}\, \frac{2h}{r} \right) \cdot \qquad (13)$$

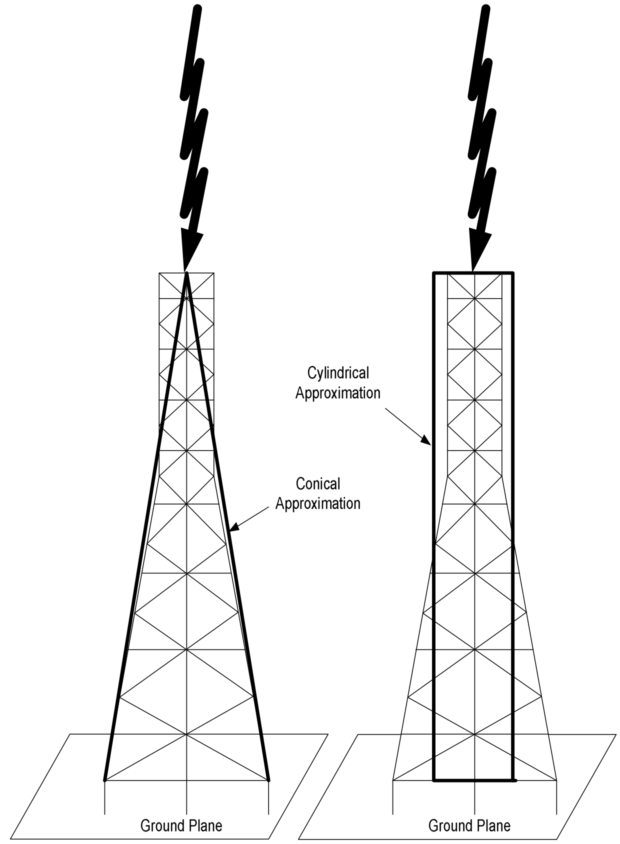


Fig. 3. Comparison of conical and cylindrical approximations of steel lattice communication tower.

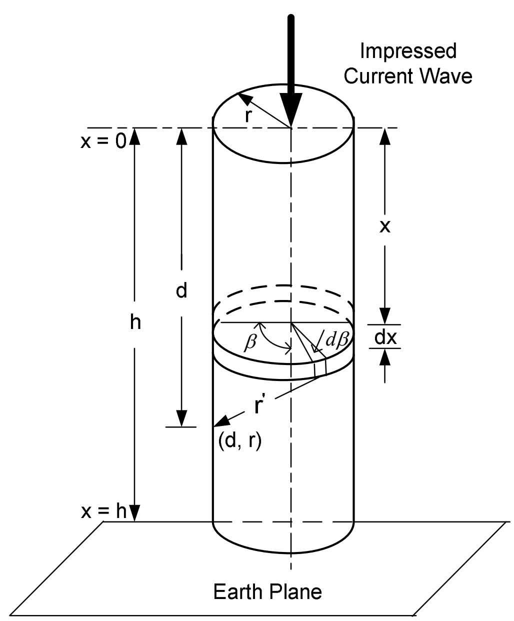


Fig. 4. Cylindrical tower used in field theory analyses.

VII. ANALYSIS OF THE SURGE RESPONSE OF A CYLINDRICAL TOWER TO A RAMP WAVE OF CURRENT, *I* = *KT*

Consider the cylindrical tower of Fig. 4, with a ramp current wave impressed at x = 0 at time t = 0. Then the time retarded, surface current density is,

$$J_s\left(x,\ t-\frac{r'}{c}\right)=\frac{K}{2\pi r}\left(t-\frac{x}{c}-\frac{r'}{c}\right).$$

Using the nomenclature defined in Fig. 4 the vector magnetic potential at a point (d, r) is,

$$\vec{A}=\frac{\mu_0}{4\pi}\int_0^{2\pi}\int_0^{y}\frac{K}{2\pi r}\left(t-\frac{x}{c}-\frac{r'}{c}\right)\cdot\frac{r\cdot dx\cdot d\beta}{r'}\,\hat{a}_d\,.$$

Integrating the electric field due to currents over the height of the cylinder, and for $ct >> r$

$$\int_0^p \vec{E}_i\cdot d\vec{s}=-Kt\left[60\cdot\left\{\ln\left(\sqrt{2}\,\frac{ct}{r}\right)-1+\frac{r}{2ct}+\left(\frac{r}{2ct}\right)^2\right\}\right]$$

Again the term in brackets is of the form of a surge impedance. Hence the transient surge impedance of a cylindrical tower, derived by Sargent and Darveniza for a ramp current wave impressed, may be defined as,

$$\begin{aligned}Z&=60\ \ln\left(\sqrt{2}\,\frac{ct}{r}\right)-60=60\ \ln\left(\sqrt{2}\,\frac{2h}{r}\right)-60\\&=60\cdot\left\{\ln\left(\sqrt{2}\,\frac{2h}{r}\right)-1\right\}.\end{aligned}\tag{14}$$

VIII. ANALYSIS OF THE SURGE RESPONSE OF A CONICAL TOWER

The conventional double-circuit steel lattice tower can be conveniently approximated by a right cone of appropriate half-angle.

Consider a conical tower of height *h* and half-angle *θ*, as shown in Fig. 5. A rectangular wave of current is impressed at the tower top (*x* = 0) at time *t* = 0, and consider an element of the tower at x (measured in a vertical direction) from the tower top. It is necessary to determine the vector magnetic potential at a general point (*d*, *r*) on the cone.

Consider the contribution $|\delta A|$ to the vector magnetic potential at (*d*, *r*) of an element (*du*, *dβ*) as shown in Fig. 5. Then,

$$\begin{aligned}|\delta A|&=\frac{\mu_0}{4\pi}\frac{|J[x,t-(r/c)]|}{r'}du\cdot\alpha\cdot d\beta\\&=\frac{\mu_0}{4\pi}\cdot\frac{I}{2\pi}\cdot\frac{du\cdot d\beta}{r'}.\end{aligned}$$

Therefore the vector magnetic potential at (*d*, *r*), in the direction of the unit vector ***û*** is,

$$\vec{A_u}=\frac{\mu_0}{4\pi}\cdot\frac{I}{2\pi}\int_0^{2\pi}\int_0^{y}\cdot\frac{K\cdot b\cdot du\cdot d\beta}{\sqrt{x^2+d^2-2b\cdot d\cdot x}}\,\hat{u}\ .$$

Hence, $\dfrac{\partial\vec{A_u}}{\partial t}=-\vec{E}_{iu}=\dfrac{\mu_0}{4\pi}\cdot\dfrac{I}{2\pi}\displaystyle\int_0^{2\pi}\frac{Kcb}{Kct-bd}d\beta$.

Therefore

$$\begin{aligned}\int_{u=0}^{u=ct}\vec{E}_{iu}\cdot du&=-\frac{\mu_0}{4\pi}\cdot\frac{I}{2\pi}\int_0^{2\pi}\int_0^{ct}\frac{cb}{ct-bu}du\cdot d\beta\\&=-\frac{30\,I}{2\pi}\int_0^{2\pi}\ln\left(\frac{1}{[2S^2\sin^2(\beta/2)]}\right)d\beta\\&=-I\cdot\{60\cdot\ln(\sqrt{2}/S)\}.\end{aligned}$$

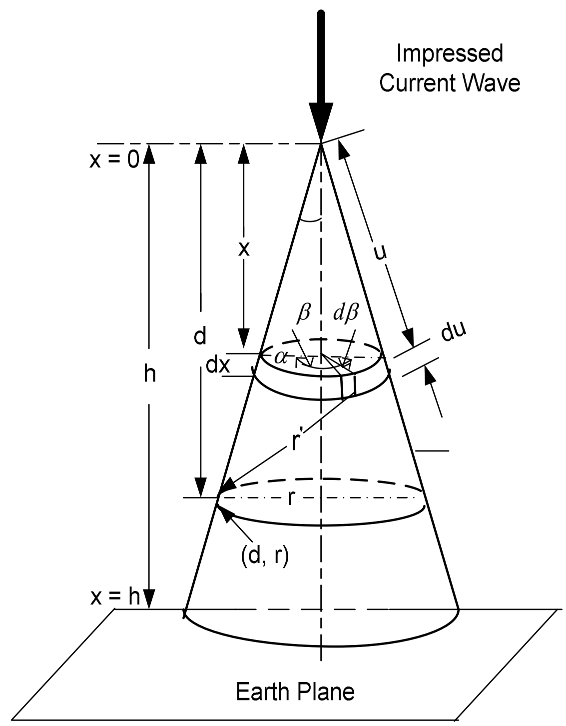


Fig. 5. Conical tower used in field theory analyses.

The expression in above braces is of the form of a surge impedance. Hence the transient surge impedance of a cone is defined as,

$$Z=60\ \ln\left(\sqrt{2}/S\right).\tag{15}$$

where ***S*** is the sine of the half-angle of the cone. This equation provides realistic estimates of the surge impedance of a steel lattice tower because it is in excellent agreement, both in magnitude and time-invariance characteristics, with values measured experimentally using geometric model technique [3].

IX. CONCLUSION

Different equations to calculate the surge impedance of vertical conductors including lattice tower are analyzed starting with Jordan's original formula. The performed analyses indicate that Jordan's revised formula is more than adequate to simulate electromagnetic transients in vertical conductors than the Jordan's original formula. Furthermore, the value of surge impedance depends on the shape of triggered lightning current pulse. The validity of the Jordan's equation has been tested by the well-known recent experimental and other analytical results mentioned in Table 1.

The investigation reported here several ways to evaluate and compare the surge impedance of complex structure which is of greater interests for practical applications and future developments for insulation coordination and protection system designing.

Table 1. Comparison of analytical values of surge impedance of steel lattice communication tower.

Source	Technique or Equation	Tower Representation	Current Waveshape	Surge Impedance
Jordan	equation (3)	cylinder	any	125
IEEE/CIGRE	equation (5)	cylinder	ramp	179
Revised Jordan's Formula	equation (9)	cylinder	step	201
Takahashi	equation (10)	cylinder	step(vertical injection)	148
Takahashi	equation (11)	cylinder	Step (horizontal injection)	122
Hara et al.	equation (12)	cylinder	Step(horizontal injection)	121
Wagner and Hileman	equation (13)	cylinder	Step	240
Sargent and Darveniza	equation (14)	cylinder	ramp and double exponential	180
Sargent and Darveniza	equation (15)	cone	any	130—150

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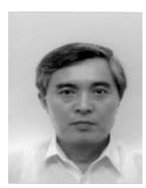

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