A Study on an Impact of Tower Surge Impedance Against Lightning Surge Phenomena

Chakki Satchathampitak\textsuperscript{1,}\textsuperscript{a}, Rongrit Chatthawon\textsuperscript{2,}\textsuperscript{b} and Amnart Suksri\textsuperscript{3,}\textsuperscript{c*}

\textsuperscript{1}Department of Electrical Engineering, Faculty of Engineering, Khon Kaen University, Khon Kaen, Thailand.
\textsuperscript{2,3}Center of Alternative Energy Research and Development, Faculty of Engineering, Khon Kaen University, Khon Kaen, Thailand.

Email: \textsuperscript{a}chakkris@kkumail.com, \textsuperscript{b}rongch@kku.ac.th., \textsuperscript{c}samnar@kku.ac.th.

Abstract. Lightning strikes creates damages to the electrical power system utilization and equipment. To reduce the effect of lightning strikes in the tower transmission, the ground resistance of the tower must be kept to a low value of less than 5 Ω. This research is a study of tower surge impedance using additional conductor line connected by parallel two overhead ground wire at the top of the tower transmission line. The additional of ground wire which is connected from the top of the tower utilizes copper and aluminium alloy for the simulation. Calculation of tower surge impedance using finite element method by COMSOL in 3D simulation based on traditional electromagnetism equations. Surge impedance values were calculated, and it was found that the calculation results obtained with less than 0.5 % error when using finite element method compare with conventional numerical method. Aluminium alloy conductor was found to have an effect on reducing the overvoltage magnitude of lightning strikes at the tower transmission line when compare with copper conductor.

1. Introduction
Lightning is a natural phenomenon that occurs at the time of rain or thunderstorms. In the case of lightning, there are four types of lightning: occurring within clouds, between clouds, between clouds and air and occurring between the cloud and ground, respectively. The lightning incident on the transmission tower will damage the equipment resulting to insulators that will be damaged first. But if protection is not taken, the effect of overvoltage will flow into the system and causes widespread of electrical failure catastrophe. [1]

In the past, the surge impedance of tower transmission line was measured by direct measurements. This is a difficult task and very expensive method. Later, Surge impedance of tower transmission line was calculated using approximated equation. The values based on vertical cylinder, conical and combination of solids as same height as actual tower and radius which is equal to equivalent radius of the tower based on Fig. 1. Surge impedance is calculated by this method, there are errors when compared to the direct measurement. Later, computer system became more modern, Finite element method (FEM) was employed to calculate the Surge impedance of tower transmission line. [2]

In the present work, we use the double circuit 230kV transmission line using finite element computer simulation method to compute for the surge impedance of the tower.
The surge impedance of tower was estimated by electrostatic energy and magnetic energy using electrostatic field and magnetic field interface in COMSOL Multiphysics software. [3]
2. Methodologies

2.1 Analytical method.

The first theoretical formulation to the surge impedance of the transmission tower was proposed by Jordan [4]. According to Jordan’s formulation, the image method was considered, the author committed an error in the direction of the current in an image conductor, resulting of the mirror image of the tower surge impedance. Fig. 1 shows the transmission tower and some simple geometric approaches.

The traditional equations for the tower surge impedance are shown in the table 1. Some assumptions were made considering a perfectly conducting ground, the cylindrical conductor is completely perpendicular to the ground plane and lossless conductor was employed. Many researchers in the past have proposed the equations to represent the transmission tower by using these simple geometries. The surge impedance using analytical method is shown in table 3. It uses tower model in the Fig. 2. The tower has a high (h) of 39.250 meter and radius (r) is equal to 5.84 meter.

![Fig. 1.](image1.png)  
Fig. 1. (a) Tower Profile. Approximations by: (b) cylindrical (c) conical (d) combination of the solids. [3]

![Fig. 2.](image2.png)  
Fig. 2. Proposed transmission tower 230 kV profile.
Table 1. Tower surge impedance calculation equations from researchers (1-9).

| Author                      | Equation                                                                 | Reference |
|-----------------------------|--------------------------------------------------------------------------|-----------|
| 1. Jordan A.D.1934          | $Z = 60 \ln \left( \frac{h}{r} + 90 \left( \frac{r}{h} \right) \right) - 60$ | (1) [5]  |
| 2. Wanger and Hilleman A.D.1960 | $Z = 60 \ln \left( \frac{\sqrt{2} h}{r} \right)$                        | (2) [6]   |
| 3. Sargent and Darveniza A.D.1969 | $Z = 60 \ln \left( \frac{2 \sqrt{2} h}{r} \right)$                      | (3) [7]   |
| 4. Chisholm et al. A.D.1983 and 1985 | $Z = 60 \ln \left( \frac{\left( h^2 + \sqrt{h^2 + r^2} \right)^2}{r^2} \right) \cdot \frac{1}{2}$ | (4) [8, 9] |
| 5. CIGRE A.D.1991           | $Z = 60 \ln \left( \cot \left( \frac{r}{h} \right) \right) \cdot -1$     | (5) [10] |
| 6. Hara A.D.1996            | $Z = 60 \ln \left( \frac{\sqrt{2} h}{r} \cdot 2 \right)$               | (6) [11] |
| 7. Ametani A.D.1997*        | $Z = 60 \ln \left( \frac{\left( b + \sqrt{b^2 + 4r^2} \right)^2}{r^2} \right) + 3r_{eq} + \frac{4r^2 + r_{eq}^2 - 4h^2 + r_{eq}^2}{2h}$ | (7) [12] |
| 8. Sargent and Darveniza A.D.1969 | $Z_{scmeq} = 60 \ln \left( \frac{\sqrt{2h^2 + 2r^2}}{r} \right)$        | (8) [7]   |
| 9. Chisholm et al. A.D.1983 and 1985* | $Z_{scmeq} = 60 \ln \left[ 0.5 \arctan \left( \frac{r_{eq}}{h} \right) \right]$ | (9) [8, 9] |

*From Fig. 1. (d) $r_{eq}$ can be found by $r_{eq} = \frac{r_h + r_e (h_e + h_2) + r_e h_1}{h_1 + h_2}$

2.2 Proposed method.

Since the surge impedance of an actual transmission tower is difficult to measure, this research proposed a method to calculate tower surge impedance by Finite Element Method (FEM), calculated by a computer simulation program. It can give the result relatively close to the Surge impedance measurement of the actual transmission towers.

For the present research, we use the double circuit 230kV transmission line for finite element method. The surge impedance of tower was estimated by electrostatic energy by equation (10) and magnetic energy by equation (11). These equations calculate the inductance and the capacitance at each height of the tower, and it is computed through equation (12) and (13). From a relationship of equation (12) and (13) we can then calculate the surge impedance of transmission tower by equation (14). [2]

$$W_e = \frac{1}{2} \int \mu H^2 \, dv$$  \hspace{1cm} (10)

$$W_m = \frac{1}{2} \int \varepsilon_0 E^2 \, dv$$  \hspace{1cm} (11)
Where:

- \( W_m \) is Magnetic energy (\( \mu J \))
- \( W_e \) is Electric energy (\( nJ \))
- \( H \) is Magnetic Field Intensity (A t/m)
- \( L_i \) is Inductance (H)
- \( C_i \) is Capacitance (F)
- \( \mu \) is Electrical Permeability of Tower (2 H/m)
- \( \varepsilon_0 \) is Electrical Permittivity of air (8.854 \times 10^{-12} F/m)
- \( V \) is Volume of External Limit (m³)

\[
L_i = \frac{2W_m}{I^2} \tag{12}
\]

\[
C_i = \frac{2W_e}{U^2} \tag{13}
\]

Where:

- \( I \) is Current imposed on the tower (A)
- \( U \) is Voltage imposed on the tower (V)

\[
Z_t = \sqrt{\frac{L_i}{C_i}} \tag{14}
\]

Utilizing this method, we use lightning current as in equation (15) and is shown in Fig. 3. It has the peak current equal to 25.780 kA. The lightning current uses for magnetic simulation was excited at the top of tower. The values of \( i_{01} \) and \( i_{02} \) as well as time constant were taken from reference [13].

\[
i_{(01)} = \frac{\eta_1}{\eta_2} \left( \frac{t}{\tau_{11}} \right)^{\gamma_1} e^{-\frac{t}{\tau_{11}}} + \frac{\eta_2}{\eta_1} \left( \frac{t}{\tau_{21}} \right)^{\gamma_2} e^{-\frac{t}{\tau_{21}}} \tag{15}
\]

Where:

- \( i_{(01)} \) is Lightning current at time \( t \) (A)
- \( i_{01} \) is Current amplitudes = 14.800 kA
- \( i_{02} \) is Current amplitudes = 6.860 kA
- \( n_1 \) is Exponents = 2
- \( n_2 \) is Exponents = 2
- \( \eta_1 \) is equal -0.41973, **
- \( \eta_2 \) is equal -0.45344, **
- \( \tau_{11} \) is Representing the front time constants (0.244 \( \mu \)s)
- \( \tau_{12} \) is Representing the front time constants (2.770 \( \mu \)s)
- \( \tau_{31} \) is Representing the decay time constants (4.180 \( \mu \)s)
- \( \tau_{22} \) is Representing the decay time constants (40.66 \( \mu \)s)
\[ n_1 = \left[ -\left( \frac{\tau_{11}}{\tau_{12}} \right) \left( \frac{\tau_{12}}{\tau_{11}} \right)^{-1} \right] \]

\[ n_2 = \left[ -\left( \frac{\tau_{21}}{\tau_{22}} \right) \left( \frac{\tau_{22}}{\tau_{21}} \right)^{-1} \right] \]

2.3 Material characteristic comparison between copper and aluminium alloy.

In this work, we choose the copper wire (residual resistivity ratio of 30) conductor and aluminium alloy wire (ASTM B625) conductor. These wire materials have 5 cm in diameter, and it is connected from the top of tower to ground as shown in fig. 4. Lightning strike current is energized at the top of the transmission tower. The relative permittivity of copper and aluminium alloy is chosen for a simulation value of 1 and reference value of resistivity for copper and aluminium alloy is $1.68 \times 10^{-8} \, \Omega \cdot \text{m}$ and $2.82 \times 10^{-8} \, \Omega \cdot \text{m}$ respectively. The Tangent coefficient of thermal expansion is 0.0034 K$^{-1}$. The conductivity of copper is 397 S/m and aluminium alloy is at 238 S/m.
3. Simulation results

3.1 Results of COMSOL simulation shown below are for the magnetic and electric field distribution using equation (10) to (14) for analytical.

Fig. 5. Distribution of (a) front view of the magnetic field at the top of the tower, and (b) front view of the electric field.

Table 2. Electric and magnetic energy values before improvement of additional conductors.

|                     | Electric Energy | Magnetic Energy |
|---------------------|-----------------|-----------------|
|                     | 1.477 (nJ)      | 19.408 (μJ)     |

Comparison of surge impedance values from analytical method according to other researcher and our proposed method is shown in the table 3.

Table 3. Tower surge impedance of 230 kV model computed by analytical method.

| Author                      | Surge Impedance (Ω) |
|-----------------------------|----------------------|
| 1. Jordan A.D.1934           | 67.704               |
| 2. Wanger and Hilleman A.D.1960 | 176.696              |
| 3. Sargent and Darveniza A.D.1969 | 173.454              |
For our proposed method, the surge impedance uses the electric and magnetic energy from table 2 and calculate the tower surge impedance from equation (14). The surge impedance obtained from our proposed method using COMSOL finite element is equal to 114.618 Ω. According to analytical method shown in table 3, it was found that equations (4) and (8) were relatively close to the COMSOL finite element simulation. Equation (4) has an error of 16.042% and equation (8) has an error value of 18.450% when compare with the simulation.

3.2 Tower surge impedance comparison of copper and aluminium alloy materials.
Results of COMSOL simulation shown below are the magnetic and electric field distribution using equation (10) to (14) when an additional of extra wire conductors were added.

![Magnetic and electric field distribution](image)

**Fig. 6.** Magnetic and electric field distribution after connecting the additional conductor at the top of the tower (a) front view of the magnetic field at the tower top, and (b) front view of the electric field.
From Fig 6., it can be observed that, the magnetic field has increased as in Fig. 6(a) because of copper and aluminum alloy permeability properties combined with tower high-strength alloy steel. On the other hand, the electric field distribution has reduced as in Fig. 6(b). It is because of electrostatics simulation considers the resistivity properties for each material. Table 4 shows the electric and magnetic energy after improvement using copper and aluminum alloy wires.

**Table 4.** Electric and magnetic energy after improvement using copper and aluminum alloy.

| Materials       | Electric energy | Magnetic energy |
|-----------------|-----------------|-----------------|
| Copper          | 1.549(nJ)       | 19.460(μJ)      |
| Aluminium Alloy | 1.552(nJ)       | 19.460(μJ)      |

After the Electric and magnetic energy were obtained, tower surge impedance can then be computed, and it is shown in the table 5. It can be seen that the tower surge impedance value was reduce from 114.618 Ω to 112.069 Ω when copper wire was used. Also, when an aluminum alloy wire was used, the tower surge impedance is further reduced to 111.951 Ω. Reduction of tower surge impedance can reduce the magnitude of the lightning overvoltage that will occur at the tower.

**Table 5.** Tower surge impedance value after improvement using additional copper and aluminum alloy wires.

| Copper          | Aluminium Alloy |
|-----------------|-----------------|
| 112.069 (Ω)     | 111.951 (Ω)     |

4. Conclusion
The tower surge impedance of transmission towers used in 230 kV transmission line was computed using FEM simulation. By using analytical method equation, the obtained result does not give realistic value when compare with the finite element method. After the addition of wires connected from the top of the tower to ground, the surge impedance was reduced from 114.618 (Ω) to 111.951 (Ω) when aluminum alloy wire was chosen. It is suggested that an addition of aluminum alloy wire conductor as well as copper conductor can further reduce the tower surge impedance to improve lightning protection in cooperation with overhead ground wire. Reduction of tower surge impedance is one of an alternative solution to further reduce the effect of lightning strike and to minimize backflashover so that to minimize catastrophic failure of the entire electrical network system.

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Appendix A 230 kV transmission line.