Modeling of Composite Transmission Tower under Direct Lightning Strokes Based on Electromagnetic Field Energy Principle

Youpeng Huangfu[1], Shuhong Wang[1], Xi Tao[1], Guolin Wang[1], Jian Wu[2]

[1]State Key Laboratory of Electrical Insulation and Power Equipment, School of Electrical Engineering
Xi'an Jiaotong University, Xi'an, 710049, China
[2]State Grid Shaanxi Electric Power Research Institute, 123 North Wenyi Road, Xi'an, 710054, China
shwang@mail.xjtu.edu.cn

In this paper, an equivalent model for composite transmission line (TL) tower under direct lightning strokes based on electromagnetic field energy principle is comprehensively presented. There are four parts in the model: double vertical grounding conductor, main legs, cross arms and bracings. The impedances of the vertical grounding conductors and main legs of the composite tower are obtained combining the theory of conical antenna. The influence of composite material and bracings on the wave impedance are considered based on the electromagnetic field energy principle. The metal ground-wire cross arm is equivalent as a two parallel conductors. The composite phase-cross arm is regarded as a lumped capacitance which is determined by using three-dimensional (3D) Finite Element Method (FEM). An accurate model for extended grounding structure (EGS) of the tower base considering the soil ionization is used. The lightning overvoltage characteristic of the equivalent model is compared with the hybrid model in literature which verifies the validity of the model.

***Index Terms*—Composite Transmission Line Tower, Conical Antenna, Direct Lightning Strokes, Finite Element Method.**

I. Introduction

Several traditional metal tower models have been developed by using theoretical approach [1] or based on experimental works [2]. However, there are few literatures researching the modeling of composite TL tower. In engineering design, the additional vertical grounding conductor is used to propagate the lightning energy into the earth [3]. The composite material in tower head and soil ionization around the EGS are omitted when modeling the tower in [3] and [4]. There is expensive and difficult to obtain the overvoltage characteristics for composite tower using field experimental measurement. Therefore, it is of great significance to model a composite tower model in theory.

The electromagnetic field energy around the composite tower is depends on its structure. In physical, the tower structure reflects the inductance and capacitance of each part or between each other of the tower. Therefore, the electromagnetic field energy principle can be used to determine the influence of composite material and bracings on the impedance for the tower.

In this paper, an equivalent model for composite tower under direct lightning strokes based on electromagnetic field energy principle is presented. The influence of composite material and bracings on the wave impedance are considered by introducing correction coefficients based on electromagnetic field energy principle. The metal ground-wire cross arm is equivalent as a two parallel conductors. The composite phase-arm is regarded as a capacitance determined by FEM. The lightning overvoltage characteristic of the tower is performed considering the soil ionization of EGS. The simulation results are compared with the hybrid model in [4] which verifies the validity of the model.

II. The Under Study Composite Tower

Fig. 1 (a) presents the composite tower head. Pink and orange, blue colors are representing the metal and composite materials, respectively. What's more, orange and blue colors are on behalf of bracings and main legs. The metal ground wire cross arms and bottom part of the tower body are connected by double vertical grounding conductors.

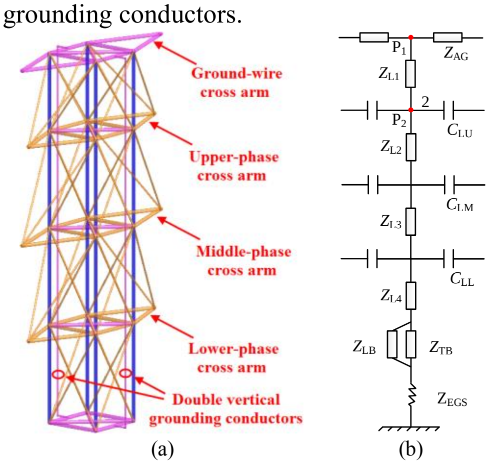


Fig. 1. (a) Schematic diagram of the composite transmission line tower head, and (b) equivalent model of the tower.

III. Modeling of the Equivalent Tower Model

The modeling of the impedance for the double grounding conductors, composite main legs and bracings between the grounding-wire and upper-phase arm is presented as follows.

A. *Impedance of double vertical grounding conductors*

The double vertical grounding conductors can be reduced to a single one by using the electromagnetic field energy method as shown in Fig. 2 (a).

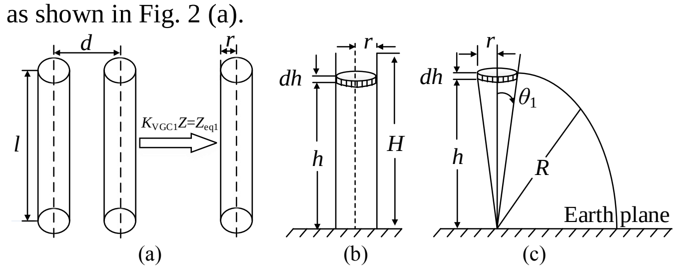


Fig. 2. (a) Schematic diagram of the double vertical grounding conductors reduction to a single one, (b) a differential element of a vertical cylindrical, and (c) its conical antenna model.

The wave impedance Z_{eq1} of the double vertical grounding conductors can be expressed by multiplying an impedance correction coefficient K_{VGC1} before the impedance Z of single vertical grounding conductor. The correction coefficients for the inductance and capacitance can be obtained further more.

$$Z_{\text{eq1}} = K_{\text{VGC1}} Z = \sqrt{K_L L} / \sqrt{K_C C} \tag{1}$$

where, K_L and K_C are the correction coefficients for the inductance and capacitance, respectively.

The impedance Z of single vertical grounding conductor is obtained based on the conical antenna theory [1].

A differential element of a vertical cylindrical with radius r at a height h above a perfect earth plane and its conical antenna model are shown in Fig. 2 (b) and (c), respectively.

The wave impedance Z_{e} of the differential element is

$$Z_{\text{e}} = \frac{1}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}\ln[\frac{\sqrt{h^2+r^2}+h}{r}] \tag{2}$$

where, μ and ε are the permeability and permittivity of the metal.

Based on the electromagnetic field energy method, the inductance correction coefficient K_L is

$$K_L = \frac{1}{2} + \frac{1}{8} \times \frac{2d - 2\sqrt{l^2+d^2} - l\ln(-l+\sqrt{l^2+d^2})}{r - \sqrt{l^2+r^2} + l\ln\frac{l+\sqrt{l^2+r^2}}{r}} \tag{3}$$

The determination of correction coefficient of capacitance K_C will be stated in the full paper.

B. Considering composite material and bracings

The influence of the composite material and bracings on the impedance of the double vertical grounding conductors is considered through introducing a correct coefficient K_{G1} based on the electromagnetic field energy method.

$$Z_{\text{G1}} = K_{\text{G1}} Z_{\text{eq1}} \tag{4}$$

where, Z_{G1} and Z_{eq1} are the impedance with and without the composite material and bracings, respectively; and K_{G1} is the correction coefficient given as

$$K_{\text{G1}} = \frac{Z_{\text{G1}}}{Z_{\text{eq1}}} = \frac{\sqrt{L_{\text{G1}}/C_{\text{G1}}}}{\sqrt{L_{\text{eq1}}/C_{\text{eq1}}}} = \sqrt{\frac{L_{\text{G1}}}{L_{\text{eq1}}}} \times \sqrt{\frac{C_{\text{eq1}}}{C_{\text{G1}}}} = K_{\text{G1L}} K_{\text{G1C}} \tag{5}$$

where, K_{G1L} and K_{G1C} are correction coefficients of inductance and capacitance, respectively, which given as

$$\begin{cases} K_{\text{G1L}} = \sqrt{W_{m2}} / \sqrt{W_{m1}} \\ K_{\text{G1C}} = \sqrt{W_{e1}} / \sqrt{W_{e2}} \end{cases} \tag{6}$$

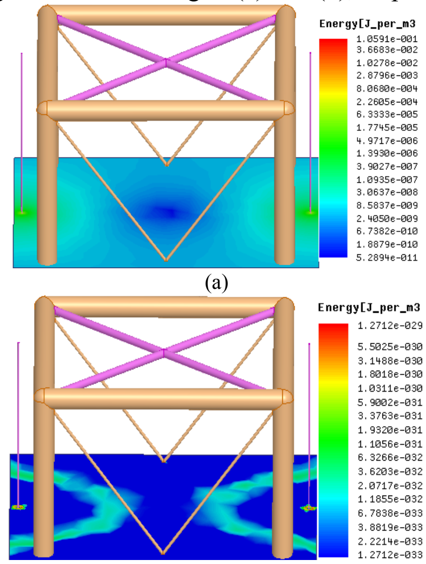
where, W_{m2} and W_{m1} are magnetic field energy with and without the composite material and bracings, respectively; W_{e2} and W_{e1} are the electric field energy with and without the composite material and bracings, respectively.

Those electromagnetic field energy calculated by using 3D FEM are shown in TABLE I when 1 A and 1 V applied on the vertical grounding conductors, respectively.

TABLE I
ELECTROMAGNETIC FIELD ENERGY

Energy (J)	W_{m1}	W_{m2}	W_{e1}	W_{e2}
	1.4027×10^{-4}	1.4021×10^{-4}	1.1071×10^{-31}	5.8638×10^{-31}

The middle cross-section of the magnetic and electric field energy intensity distribution considering composite material and bracings are shown in Fig. 3 (a) and (b), respectively.



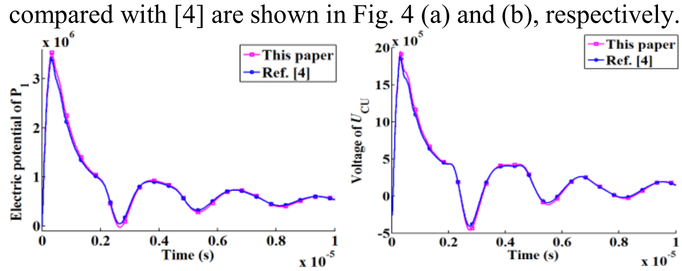
(a)
(b)
Fig. 3. Energy intensity distribution of (a) Magnetic field, (b) electric field.

The modeling of the metal grounding cross-arm, tower body and composite phase cross-arm will be demonstrated in detail. The influence of the number of the segments of the tower and the soil ionization of the EGS on its overvoltage characteristic will be discussed in the full paper.

IV. ANALYSIS RESULTS

A standard bi-exponential lightning surge with the waveform of 140 kA (2.6/50 μs) is injected into the tower top. The used composite tower model with 5 segments is shown in Fig. 1 (b).

The electric potential of tower top P_1 and the voltage between the vertical grounding conductor and upper-phase wire U_{CU} compared with [4] are shown in Fig. 4 (a) and (b), respectively.



(a) (b)
Fig. 4. (a) Electric potential of P_1, and (b) voltage of U_{CU}.

V. REFERENCES

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