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Surge behavior at the discontinuity of a vertical line over the ground

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ABSTRACT

This paper discusses the surge propagation at the discontinuity of a vertical line over the ground. Similar to a traditional transmission line, surge transmission at the discontinuity can be determined by its surge impedances. However, the surge impedances of a vertical line are different from the characteristic impedance of the transmission line. They respond differently to incident, transmitted and reflected waves, and vary with time. In this paper, these surge impedances are discussed in detail, and the methods for impedance evaluation are presented. The formulas of voltage and current transmission coefficients at the discontinuity are presented. A numerical example is presented to illustrate the surge impedances of a vertical line and to verify the formula of the transmission coefficients at the discontinuity.

1. Introduction

Lightning surges over a conductor system are an important issue in the design of electric power systems and communication systems. In case of parallel conductors or the conductors running in parallel with the ground surface, the lightning surges are analyzed using transmission line theory [1]. At the discontinuity of a line, transmission and reflection of a surge can be described with characteristic impedance of the line. For a single conductor or a vertical conductor above the ground, the associated electromagnetic fields are not in TEM mode. The classic transmission line theory is then inapplicable. A modified transmission line theory would be necessary in order to address lightning surges on vertical conductors over the ground.

Surge propagation on a vertical line over the ground has been increasingly of concern in the recent years. It is noted in [2] that the electromagnetic field is a spherical TEM when an unattenuated current propagates along a vertical line with the speed of light. In case of nonzero radius for the line the unattenuated current propagation could not be supported [3]. This current attenuation is primarily caused by the presence of "scattering" current arising from the boundary condition on the conductor surface, or can be interpreted with the internal "reflection" of a nonuniform transmission line.

Surge impedance of a vertical conductor has been addressed significantly in the past decade. The impedance at the time when the reflected surge travels back to the top of the conductor has been extensively discussed. A number of theoretical formulas have been derived [4], using either basic circuit theory or transmission line theory. More rigorous analysis of surge impedance has been made recently using numerical electromagnetic approaches, such as PEEC [5], FDTD, MOM (NEC2 and TWTD) and others [6–8]. Note that surge impedance of a vertical conductor is time-dependent. It increases with time even if the conductor is perfectly conducting [9]. It is also found in [10] that the current waveform has a significant influence on surge impedance. Single-value impedance would be insufficient in traveling wave analysis. When a surge encounters a discontinuity, reflection and transmission of the surge are observed. These transmitted and reflected waves can be determined by characteristic impedance of the line in classic transmission line theory. Specially, the surge reflection at the ground surface is discussed in [11,12]. The authors tried to interpret the current attenuation of the reflected surge in the 'scatter theory' and improved the lightning model. However, the reflection and transmission of a surge on the vertical line has not been well addressed.

In this paper, the surge behavior at the discontinuity of a vertical line over the ground is discussed. The line conductor has a nonzero radius, and may or may not be perfectly conducting. Similar to the classic transmission line theory, the reflection and transmission at the discontinuity are determined by surge impedances of the conductor. However, these are not the single-value impedances. They are defined against the nature of the waves on the line. In Section

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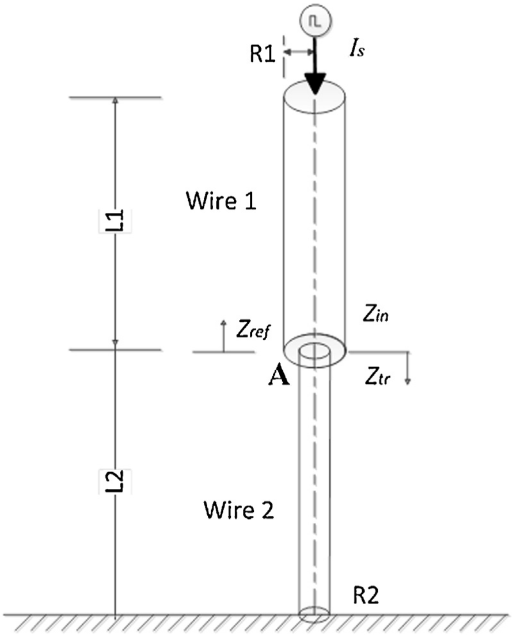

Fig. 1. Configuration of a vertical line over the ground.

2, three surge impedances are respectively introduced for incident wave, transmitted wave and reflected wave. Modified transmission coefficients at the discontinuity are then derived. These surge impedances are further discussed in Section 3. Finally, numerical verification using the Partial Element Equivalent Circuit (PEEC) method is presented.

2. Modified transmission equations at a discontinuity

When a vertical line is struck by lightning, a current surge is injected into the line and a voltage surge is generated on this line [10]. Surge impedance is then defined as the ratio of the voltage over the current on the line. Unlike the impedance defined for a TEM transmission line, this surge impedance is not constant, and varies with time and position on the line.

It is noted in [10] that the surge impedance varies with the surge waveform. At the discontinuity the waveforms of transmitted and reflected waves are generally different from the incident wave. Three distinct surge impedances are then introduced, as illustrated in Fig. 1. They are the incident wave impedance Z_{in}, transmitted wave impedance Z_{tr} and reflected wave impedance Z_{ref}, as follows:

$$Z_{in}(t)=\frac{V_{in}(t)}{I_{in}(t)}$$
$$Z_{tr}(t)=\frac{V_{tr}(t)}{I_{tr}(t)} \qquad (1)$$
$$Z_{ref}(t)=\frac{V_{ref}(t)}{I_{ref}(t)}$$

where V_{in} and I_{in} are respectively the voltage and current of the incident wave on Wire 1 before the wave reaches the discontinuity, V_{ref} and I_{ref} the voltage and current of the transmitted wave on Wire 2 at the discontinuity, and V_{tr} and I_{tr} the voltage and current of the reflected wave on Wire 1 from the discontinuity.

At the discontinuity (Point A) the following conditions for voltages and currents hold

$$V_{in}+V_{ref}=V_{tr},\ I_{in}+I_{ref}=I_{tr} \qquad (2)$$

The relationship between corresponding voltages and currents is given by

$$V_{in}=I_{in}Z_{in}$$
$$V_{tr}=I_{tr}Z_{tr} \qquad (3)$$
$$V_{ref}=-I_{ref}Z_{ref}$$

Transmission coefficients α_V for voltage and α_I for current are defined, as follows:

$$\alpha_V=\frac{V_{tr}}{V_{in}} \qquad (4a)$$

$$\alpha_I=\frac{I_{tr}}{I_{in}} \qquad (4b)$$

Substituting (3) into (2) yields

$$\alpha_V=\frac{Z_{tr}(Z_{in}+Z_{ref})}{Z_{in}(Z_{tr}+Z_{ref})} \qquad (5a)$$

$$\alpha_I=\frac{(Z_{in}+Z_{ref})}{(Z_{tr}+Z_{ref})} \qquad (5b)$$

When the line is terminated with an open circuit, that is, $Z_{tr}=\infty$, the voltage transmission coefficient α_V becomes

$$\alpha_V=\frac{V_{tr\_open}}{V_{in}}=\frac{(Z_{in}+Z_{ref})}{Z_{in}}. \qquad (6)$$

And when the line is terminated with a short circuit, that is, $Z_{tr}=0$, the current transmission coefficient α_I becomes

$$\alpha_I=\frac{I_{tr\_short}}{I_{in}}=\frac{(Z_{in}+Z_{ref})}{Z_{ref}}. \qquad (7)$$

It is noted that these transmission coefficients are different from those in a transitional transmission line. However, they are identically the same if $Z_{ref}=Z_{in}$.

3. Surge impedances of vertical conductors

Transmission coefficients are determined by incident, reflected and transmitted wave impedances. These impedances are totally different from characteristic impedance of a traditional transmission line. It is necessary to know how these impedances are calculated. Generally speaking, these impedances can be obtained analytically or numerically. In this paper, the numerical method using the retarded partial element electrical circuit (PEEC) approach is employed. Note that surge impedance is a function of time. A time-domain solution of voltage will be required under the line configuration for particular impedance, given by a source of current.

3.1. Incident wave impedance

Incident wave impedance Z_{in} is evaluated with voltage V_{in} and current I_{in} at the position of discontinuity, assuming the source current continues to prorogate along the same conductor. Note that the voltage at a point along a line is also affected by the current on the upstream wire. A uniform line model for both Wire 1 and 2 is adopted for the evaluation of Z_{in}, as illustrated in Fig. 2(a). The length of Wire 2 should be selected in such a way that the backward wave if any in Wire 2 has not reached the discontinuity during the time period of concern. Note that the current attenuates as it propagates along a vertical line, and the surge impedance is critically affected by the waveform of the incident source. The source current and the length of Wire 1 should be the same as those in the original model.