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LETTER

Equivalent circuits of transmission lines sag above lossy ground excited by external electromagnetic fields

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Abstract To obtain actual responses of nonlinear terminations for the transmission lines sag above lossy ground, it imperatively need to build the equivalent circuits of transmission lines sag. In this paper, the multi-conductor transmission lines sag above lossy ground are divided into a sequence of smaller segments, each of which is approximate equal height. Equivalent circuit of the transmission lines sag is composed of each segment in series. And the simplified equivalent circuit of transmission lines sag above lossy ground excited by the external electromagnetic fields is built by combined the neighboring elements. The proposed method is compared with the result obtained by the FDTD method, a good agreement is observed. And the amplitude of the response is less than the results when the transmission lines are considered as the straight lines.

Keywords: equivalent circuit, electromagnetic field, lossy ground, transmission lines, sag
Classification: Electromagnetic theory

1. Introduction

By building equivalent circuits of transmission lines, we can obtain the time domain response of nonlinear termination loads [1, 2, 3, 4, 5, 6, 7]. For the transmission lines above lossy ground excited by external electromagnetic fields, the equivalent circuits have been built in [8, 9]. The overhead transmission lines are considered as the straight lines in these papers [10, 11, 12, 13, 14, 15, 16]. Actually, the line is not straight and does not parallel to the ground level due to the sag produced by the weight of the line, etc [17, 18, 19, 20, 21, 22]. To obtain actual responses of nonlinear terminations for the transmission lines sag above lossy ground, it imperatively need to build the equivalent circuits of transmission lines sag.

In this paper, the multi-conductor transmission lines above lossy ground with sag are divided into a sequence of smaller segments, each of which is approximate equal height. Equivalent circuit of the transmission lines sag is composed of each segment in series. And the simplified equivalent circuit of transmission lines sag above the lossy ground excited by the external electromagnetic fields is built by combined the neighboring elements.

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2. Sag calculated

The sag for one line of multi-conductor transmission lines above lossy ground is shown in Fig. 1 [17]. The sag height difference $h'(x)$ with respect to the point x can be calculated as:

$$h'(x) = 2\frac{\sigma_0}{g} sh\left(\frac{g}{2\sigma_0}x\right) sh\left(\frac{g}{2\sigma_0}(L-x)\right) \quad (1)$$

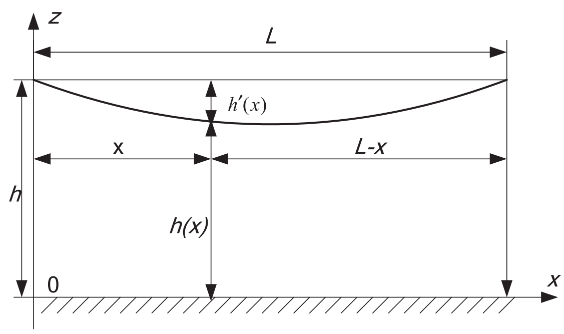

Fig. 1. Geometry of sag

Where σ_0 is the horizontal stress of the line at the lowest point, g is the load of the line per unit area, L is the length of line, x is the horizontal distances of the point x to the left neighboring towers, h is the height of the tower. So the actual height of line sag at the point x given by:

$$h(x) = h - h'(x) \quad (2)$$

3. Proposed equivalent circuit

From [9], we can see that the per-unit-length inductance matrix $\boldsymbol{L}$, the per-unit-length conductance matrix $\boldsymbol{C}$, and ground impedance $\boldsymbol{Z}(s)$ will be vary with the actual height $h(x)$, for the multi-conductor transmission lines sag above lossy ground. The multi-conductor transmission lines sag above lossy ground can be divided into a sequence of smaller segments, each of which is approximate equal height [23, 24, 25, 26]. The per-unit-length parameter matrices of every segment are regarded as constant value. Assumed that the multi-conductor transmission lines sag are considered as a cascade of N segments. For the k segment, the multi-conductor transmission lines above lossy ground excited by external electromagnetic fields can be represented by Telegrapher's equations in the frequency-domain as:

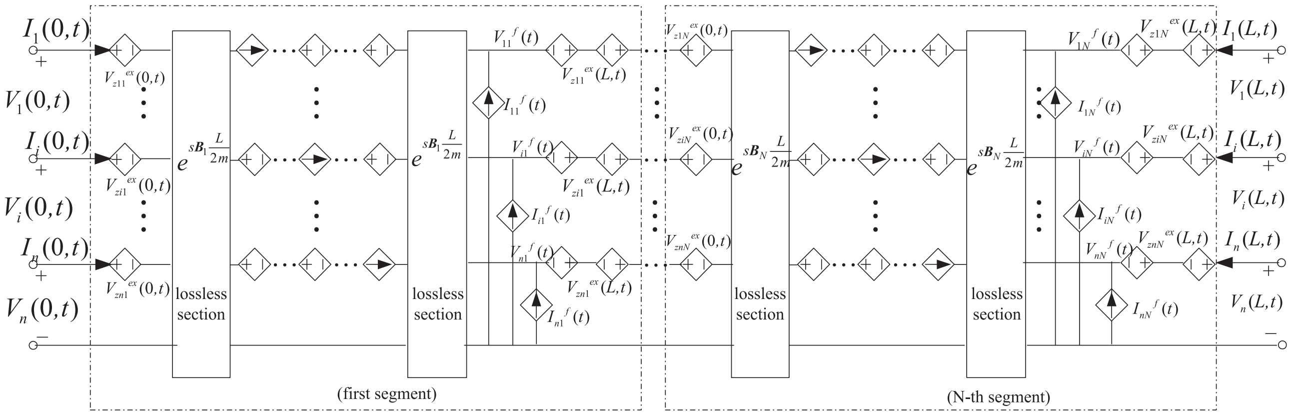

Fig. 2. Equivalent circuit of the multiconductor transmission lines sag above the lossy ground excited by the external electromagnetic fields

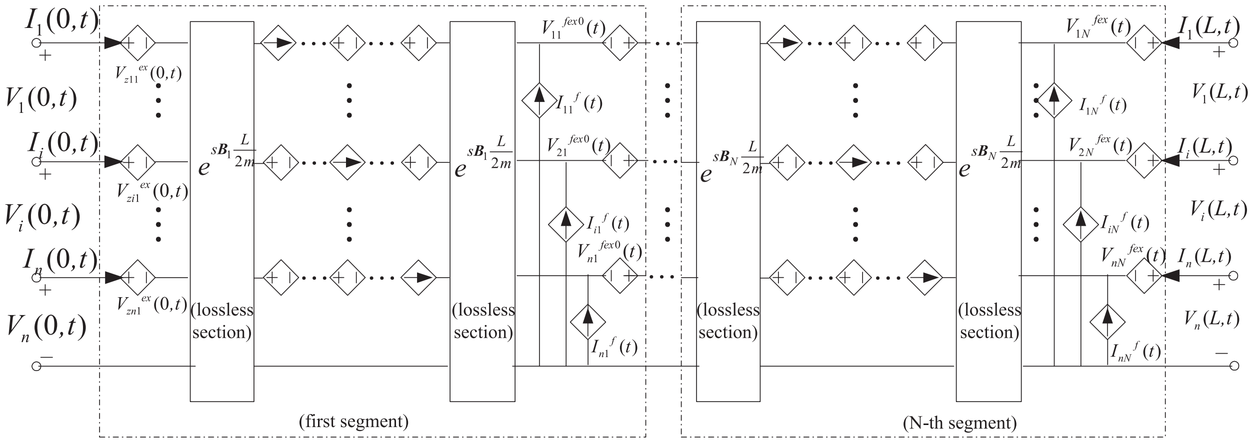

Fig. 3. Simplified equivalent circuit of the multiconductor transmission lines with sag above the lossy ground excited by the external electromagnetic fields

$$\begin{bmatrix} \boldsymbol{V}_k(L,s) \\ \boldsymbol{I}_k(L,s) \end{bmatrix} = e^{\boldsymbol{Q}_k(s)L} \left\{ \begin{bmatrix} \boldsymbol{V}_k(0,s) \\ \boldsymbol{I}_k(0,s) \end{bmatrix} - \begin{bmatrix} \boldsymbol{V}_{zk}{}^{ex}(0,s) \\ 0 \end{bmatrix} \right\} + \boldsymbol{J}_k{}^{sca}(s) + \begin{bmatrix} \boldsymbol{V}_{zk}{}^{ex}(L,s) \\ 0 \end{bmatrix} \tag{3}$$

Equivalent circuit of the multiconductor transmission lines sag is composed of every segment in series, as Fig. 2. Where:

$$\boldsymbol{J}_k{}^{sca}(s) = \begin{bmatrix} \boldsymbol{V}_k{}^f(s) \\ \boldsymbol{I}_k{}^f(s) \end{bmatrix} = \int_0^L e^{\boldsymbol{Q}_k(s)(L-x)} \tilde{\boldsymbol{F}}_k{}^{sca}(x,s)\mathrm{d}x \tag{4}$$

The Eq. (3) and Eq. (4) can be combined and sorted as:

$$\begin{bmatrix} \boldsymbol{V}_k(L,s) \\ \boldsymbol{I}_k(L,s) \end{bmatrix} = e^{\boldsymbol{Q}_k(s)L} \left\{ \begin{bmatrix} \boldsymbol{V}_k(0,s) \\ \boldsymbol{I}_k(0,s) \end{bmatrix} - \begin{bmatrix} \boldsymbol{V}_{zk}{}^{ex}(0,s) \\ 0 \end{bmatrix} \right\} + \begin{bmatrix} \boldsymbol{V}_k{}^{fex}(s) \\ \boldsymbol{I}_k{}^f(s) \end{bmatrix} \tag{5}$$

Where:

$$\boldsymbol{V}_k{}^{fex}(s) = \boldsymbol{V}_k{}^f(s) + \boldsymbol{V}_{zk}{}^{ex}(L,s) \tag{6}$$

For the conductor i, the time domain $V_{ik}{}^{fex}(t)$ can be obtained by the vector fitting method [27, 28], and be realized using voltage controlled voltage source also [29, 30, 31]. The neighboring $V_k{}^{fex}(t)$ and $V_{z(k+1)}{}^{ex}(0,t)$ can be combined as $V_k{}^{fex0}(t)$, $1 \le k < N$.

So the simplified Equivalent circuit as Fig. 3. In the following, we will verify the equivalent circuit.

4. Application of equivalent circuit

We choose two lines sag located at a height $h = 3.3\,\mathrm{m}$ above lossy ground as the example. The length is 40 m, and the radius is 2.5 mm. The parameters of the ground are $\sigma_g = 0.016\,\mathrm{S/m}$, $\varepsilon_r = 10$ and $\mu_r = 1$, $\sigma_0 = 20\,\mathrm{Mpa}$ $g = 0.057\,\mathrm{N/m{\cdot}mm^2}$, $Z_{11} = Z_{12} = Z_{21} = Z_{22} = 50\,\Omega$. The waveform of the electric field is described by a double exponential $E_0(t) = 1000(e^{-10000t} - e^{-400000t})\,\mathrm{V/m}$ with $\alpha = 0$, $\phi = 0$ and $\psi = \pi/6$. Fig. 4 depicts transient responses of voltage induced at the line end by the proposed method and the FDTD method.

From Fig. 4, we can see that the transient responses obtained by the proposed method and the FDTD method are excellent agreement. Contrast with the results without sag, as Fig. 5.

From Fig. 5 we can see that the amplitude of the response with sag is less than the without sag.

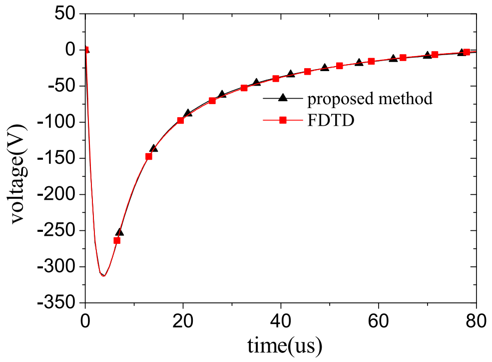

Fig. 4. Transient response of voltage induced at the line end.

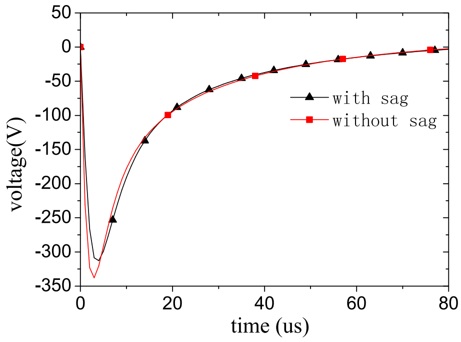

Fig. 5. Transient responses for the lines with and without sag.

5. Conclusion

For the transmission lines sag above lossy ground, the equivalent circuit model is built in this paper. The multi-conductor transmission lines sag above lossy ground are divided into a sequence of smaller segments, each of which is approximate equal height. Equivalent circuit of the transmission lines sag is composed of each segment in series. And the simplified equivalent circuit of transmission lines sag above the lossy ground excited by the external electromagnetic fields is built by combined the neighboring elements. The proposed method is compared with the result obtained by the FDTD method, a good agreement is observed. And the amplitude of the response is less than the results when the transmission lines are considered as the straight lines.

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