I. INTRODUCTION

In telecommunications, geophysical explorations, and diagnostics, insulated cylindrical antennas have often been located in lossy media such as soil, water, or biological tissue [1]. The electromagnetic characteristics of antennas and wave propagation in inhomogeneous media have been analyzed using the finite-difference time-domain (FDTD) method [1–4]. However, since the standard FDTD is based on the time and space discretization of Maxwell’s equations, the fine geometries of the antennas should be modeled as fine grids with sufficiently small cell sizes relative to the minimum wavelength. This results in low computational efficiency due to the large number of cells. One the other hand, thin-wire FDTD (TW-FDTD) treats a coarse grid with the pre-correction of near-field behavior around thin electrically insulated antennas [3, 4]. Therefore, TW-FDTD can provide sufficient accuracy, equivalent to fine-grid FDTD, while maintaining higher computational efficiency. In [3, 4], the loading effect of both the insulation and surrounding media was considered by using discrete-time boundary condition (DTBC) formulations. These were derived from the dielectric constitutive relation on the material interface between the lossy media under the uniform field approximation (UFA) over each time step. In this paper, to achieve higher accuracy, an improved DTBC is formulated from Maxwell’s equations under the linear field approximation (LFA) and subsequently corrected in the TW-FDTD update equation. By comparing the input impedances of Teflon-insulated cylindrical monopole antennas located in wet soils, we show that the proposed approach provides higher accuracy than previous techniques.

Abstract

For the thin-wire (TW) finite-difference time-domain (FDTD) analysis of lossy insulated antennas surrounded by lossy media, an improved discrete-time boundary condition (DTBC) at the interface is proposed here. In previous TW-FDTD techniques, the DTBC formulations on the material discontinuity between the lossy insulation and lossy surrounding media were derived from the dielectric constitutive relation under the uniform field approximation (UFA) over each time step. In this paper, to achieve higher accuracy, an improved DTBC is formulated from Maxwell’s equations under the linear field approximation (LFA) and subsequently corrected in the TW-FDTD update equation. By comparing the input impedances of Teflon-insulated cylindrical monopole antennas located in wet soils, we show that the proposed approach provides higher accuracy than previous techniques.

Key Words: Discrete-Time Boundary Condition, Finite-Difference Time-Domain Methods, Insulated Cylinders, Thin Wires.
TW-FDTD update equation. By comparing the input impedances of Teflon-insulated cylindrical monopole antennas located in wet soil, we show that this approach is more accurate than previous techniques.

II. IMPROVED DTBC FORMULATION FOR TW-FDTD

Fig. 1 shows a FDTD unit cell for the TW modeling of a lossy insulated cylinder in a lossy surrounding medium. A conductive cylinder of outer radius \( a \) lies along the \( z \)-axis and is insulated with a lossy dielectric material of outer radius \( \rho_o \), permittivity \( \varepsilon_o \), and conductivity \( \sigma_o \). The insulated cylinder is surrounded by a lossy dielectric medium of permittivity \( \varepsilon_i \) and conductivity \( \sigma_i \). Since the geometry of the cylinder is rotationally symmetric along the \( \phi \)-direction, we use the two-dimensional (2D) cylindrical FDTD of the discrete space \( (\rho, z) \rightarrow (i \Delta \rho, j \Delta z) \equiv (i, j) \) and discrete time \( t = n \Delta t \equiv n \) [4]. Here, \( \Delta \rho \) and \( \Delta z \) are the spatial steps along the \( \rho \) and \( z \) axes, respectively, and \( \Delta t \) is the time step. The variables \( (i, j) \) and \( n \) are the integer indices of the space and time discretization, respectively.

The LFA over each time step can be represented as the central-difference and the time-averaging schemes in the differential form of Ampere-Maxwell’s law at \( t = (n - 0.5) \Delta t \) as

\[
\nabla \times \vec{H}^{n-0.5}(\rho, z) = \varepsilon \frac{\partial \vec{E}^{n-0.5}(\rho, z)}{\partial t} + \sigma \vec{E}^{n-0.5}(\rho, z) \\
= \left( \frac{\varepsilon + \sigma}{\varepsilon} \right) \vec{E}^n(\rho, z) - \left( \frac{\varepsilon + \sigma}{\varepsilon} \right) \vec{E}^{n-1}(\rho, z).
\]

(1)

In Fig. 1, the tangential electric and magnetic fields on the material interface \( (\rho = \rho_o) \) between the insulating and the surrounding media should be continuous:

\[
E_{\theta,i}^n(\rho_o, z) = E_{\theta,o}^n(\rho_o, z) \\
H_{\phi,i}^{n-0.5}(\rho_o, z) = H_{\phi,o}^{n-0.5}(\rho_o, z),
\]

(2)

where the subscripts \( i \) and \( s \) denote the insulating and surrounding media, respectively. Applying (2) and (3) to (1), an improved DTBC for the discontinuity of the normal electric fields on the interface can be obtained:

\[
\left( \frac{\varepsilon_i + \sigma_i}{\varepsilon_i} \right) E_{\phi,i}^n(\rho_o, z) - \left( \frac{\varepsilon_i + \sigma_i}{\varepsilon_i} \right) E_{\phi,i}^{n-1}(\rho_o, z) \\
= \left( \frac{\varepsilon_i + \sigma_i}{\varepsilon_i} \right) E_{\phi,o}^n(\rho_o, z) - \left( \frac{\varepsilon_i + \sigma_i}{\varepsilon_i} \right) E_{\phi,o}^{n-1}(\rho_o, z).
\]

(4)

From (4), the normal electric field at \( t = n \Delta t \) in the surrounding medium on the interface can be given as

\[
E_{\phi,o}^n(\rho_o, z) = K_{is} E_{\phi,i}^n(\rho_o, z) + L_{is} T_{ss}^n(\rho_o, z)
\]

(5)

\[
T_{ss}^n(\rho_o, z) = \sum_{m=1}^{n-1} M_{ss}^{m-1} T_{ss}^{m-1}(\rho_o, z)
\]

(6)

\[
K_{is} = \frac{\varepsilon_i + \sigma_i \Delta t / 2}{\varepsilon_o + \sigma_o \Delta t / 2}
\]

(7)

\[
L_{is} = -\frac{(\varepsilon_i - K_{is}\varepsilon_o \sigma_i \Delta t / 2)}{\varepsilon_o + \sigma_o \Delta t / 2}
\]

(8)

\[
M_{ss} = \frac{\varepsilon_o - \sigma_o \Delta t / 2}{\varepsilon_o + \sigma_o \Delta t / 2}
\]

(9)

In (5), the first term on the right-hand side is the DTBC of the present time \( t = n \Delta t \), and the second term is the DTBC that includes the convolution effects of past times \( t = (n - 1) \Delta t, \ldots, \Delta t \), and 0. Table 1 shows a comparison of the DTBC coefficients used in previous versions of the technique and the proposed TW-FDTD framework. All TW-FDTD
equations, except for those for the DTBC coefficients, are the same as those in [4]. Therefore, they were omitted here for brevity.

III. COMPARISON RESULTS

To evaluate the computational accuracy of the proposed TW-FDTD technique using the improved DTBC formulation, we calculate the input impedances \( Z_{in} = R_{in} + jX_{in} \) of Teflon-insulated cylindrical monopole antennas in wet soils. The conductive cylinder of an antenna has \( a = 0.635 \) mm, an axial length of \( 100a \), and \( \rho_i = 1.614a \) and is insulated with Teflon \( (\varepsilon_i = 2.1\varepsilon_0, \sigma_i = 5.0 \mu S/m [4]) \). The insulated antennas are surrounded by 5%–25% wet soil and are fed by a 50 \( \Omega \) coaxial line. In all FDTD simulations, the spatial steps along the radial and axial directions are \( \Delta \rho = 3.23a \) and \( \Delta z = a \), respectively. Under the stability condition, we use a time step of \( \Delta t = \min(\Delta \rho, \Delta z)/2v \), where \( v \) is the wave velocity in the medium. First, in the case of the Teflon-insulated monopole antenna inserted in 15% wet soil \( (\varepsilon_x = 5.3\varepsilon_0 \) and \( \sigma_x = 0.117 \) S/m [5]), the results of our approach are compared with those of previous TW-FDTD models [3, 4] and with fine-grid finite-element method (FEM) data, as shown in Fig. 2. It can be seen that the results of previous TW-FDTD models show some errors compared with the FEM data. This is because [3] and [4] are based on the first-term DTBC and full-term DTBC under the UFA over each time step, respectively. Since the proposed TW-FDTD technique uses the full-term DTBC under the LFA over each time interval, it provides high accuracy, comparable with the FEM data. Next, the effect of the wet soil as a function of the volumetric moisture content is investigated, as shown in Fig. 3. We calculate the input impedances of the Teflon-insulated monopole antennas inserted in 5%–25% wet soils \( (\varepsilon_x = 2.8\varepsilon_0 - 10.2e_0 \) and \( \sigma_x = 0.039 - 0.218 \) S/m [5]). One can observe that the results of the proposed TW-FDTD model are in good agreement with the FEM data.

IV. CONCLUSION

An improved DTBC formulation for the TW-FDTD modeling of insulated antennas located in lossy media is proposed. The improved DTBC between the insulation and surrounding media was derived from Maxwell’s equations under the LFA over each time step. Then, the DTBC was corrected in the TW-FDTD equations. In a comparative study of the input impedances of Teflon-insulated monopole antennas in wet soils, we show that the proposed approach has higher accuracy than previous techniques.

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REFERENCES

HYUN: IMPROVED DISCRETE-TIME BOUNDARY CONDITION FOR THE THIN-WIRE FDTD ANALYSIS OF LOSSY INSULATED...


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