Electromagnetic Field Computation for Power Transmission Lines Using Quasi-Static Sub-Gridding Finite-Difference Time-Domain Approach


Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, Batu Pahat, Johor, Malaysia
Antennas and Applied Electromagnetics Research Group, Electronics Communications and Information Systems Engineering, University of Bradford, Bradford, West Yorkshire, UK
Engineering, Sport and Sciences (ESS) Academic Group, University of Bolton, Bolton, Lancashire, UK
Glyndwr University, Wrexham, Wales, UK

Abstract A new approach to the modeling of electromagnetic wave propagation and penetration in and around electrically small objects is presented. The traveling electromagnetic wave from a source is simulated by the finite-difference time-domain solution of Maxwell's equations, and a sub-gridding technique is imposed at points of interest in order to observe the electromagnetic field at high resolution. The computational burden caused by the requirement for a large number of time steps has been ameliorated by implementing the state-of-the-art quasi-static approach. The method is demonstrated by finding the induced electromagnetic fields near a buried pipeline that runs parallel to 400-kV power transmission lines; results are presented and discussed.

Keywords quasi-static electromagnetic fields, finite-difference time-domain method, sub-gridding, induced electromagnetic fields, power transmission lines

1. Introduction
Sharing of routes by power transmission lines and buried utility pipelines have become quite common. This prompts the question of the effect of parallel transmission lines on underground pipelines. In some situations, the latter may be in very close proximity to transmission lines, and it is thus necessary to take into account the electromagnetic fields

Received 31 January 2013; accepted 21 July 2013.
Address correspondence to C. H. See, Engineering, Sport and Sciences (ESS) Academic Group, University of Bolton, Bolton, Lancashire, BL3 5AB, UK. E-mail: c.see@bolton.ac.uk
Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/aeem.
induced above the pipelines (Peabody & Verhiel, 1971). Electromagnetic interference can be generated in the pipelines due to the induction between the underground pipelines and the transmission lines when they are close to each other. This may lead to significant potentials on the pipelines, which may lead to hazards to maintenance personnel or the general public.

This work presents the development of a new approach for modeling the source excitation and the penetration of structures (including the ground) by continuous propagating electromagnetic plane waves. The technique incorporates the finite-difference time-domain (FDTD) computational solution of Maxwell's equations and the initial value problem as the structures are illuminated by the waves (assumed plane).

In this work, the FDTD method has been used due to its proven flexibility to treat complex-geometry structures in the very large calculation region required (Taflove & Hagness, 2005). This method of solving Maxwell's differential equations was first proposed for two-dimensional problems (Yee, 1966) and then utilized in three-dimensional applications (Mur, 1981). However, the standard FDTD method generates excessive computational loads if fine details of the geometry need to be modeled due to the need for a global fine mesh. As a result, the total number of cells in the mesh increases dramatically. The time step must then be reduced to fulfill the Courant stability condition, causing the computational time to increase significantly. The discretization of the time steps is crucial for accurate determination of the results and must be small enough to resolve different dielectric or metal structures.

Frequency-domain integral equation methods, such as the method of moments, are well suited for modeling complex electromagnetic radiators in free space (Makarov et al., 2006); their strength is in effectively solving perfect electric conducting (PEC) structures. Generally, they employ a method of weighted residuals; all such techniques begin by establishing trial functions with one or more adjustable parameters, and the residuals are obtained from the differences between trial and true solutions. The parameters are found using minimization to give the best fit of the trial function. In contrast, the time-domain FDTD technique is best suited for modeling electromagnetic fields inside and outside inhomogeneous media, such as the ground. The presence of arbitrary inhomogeneous objects inside the computational domain does not seriously impact the number of unknowns to be determined.

Many researchers have investigated sub-gridding techniques as an analysis approach to resolve fine detail in the interaction between source and scatterer (Ramli et al., 2013; Xiao et al., 2007; Ohtani et al., 2004; Krishnaiah & Railton, 1999; Wang et al., 2002; Kapoor, 1997). In general, this technique is used to condense the lattice at a point of interest locally and does not require any analytical formula to be taken into account; hence, it is appropriate for objects of any shape. The residue of the space is filled with coarser grids. The fields on the boundary between coarse and fine grids are coupled using spatial and temporal interpolations. The regions of the coarse and fine grids are computed by the FDTD method and are kept in time step. A stable sub-gridding algorithm can refine the mesh locally and improve the accuracy of the result without increasing the computational effort significantly.

The FDTD technique is conventionally applied to radio and microwave frequencies, but it has also been applied to high-voltage power transmission line analysis in the published literature. The computation of transient electromagnetic fields due to switching within a typical high-voltage air-insulated substation (AIS) was undertaken with the FDTD method (Musa et al., 2010). Dedkova and Kritz (2009) proposed a new approach to evaluate the distribution of voltage and current along a nonlinear transmission line
using the FDTD method. An improved technique was proposed by Tang et al. (2007) to calculate the transient inductive interference in underground metallic pipelines due to a fault in nearby power lines. The frequency-dependent problem in the analysis of transient interference was solved in the phase domain based on the FDTD method. Lu and Cui (2000) used the FDTD method to calculate the wave processes of voltage and current distribution along three-phase 500-kV busbars and the unloaded power lines in a substation linked to multi-conductor transmission lines (MTLs). Iterative formulas were presented to determine the boundary conditions at the nodes of the branches. The work was extended to transmission line networks and non-uniform lines (Lu et al., 2003). A vector fitting method was adopted in the FDTD to treat frequency-dependent parameters (Lu et al., 2004). In this case, the corresponding voltage and current recursion formulations in the FDTD technique were presented based on the recursive algorithm for time-domain convolution. A comparison of transient analysis methods using Bergeron's method, the FDTD method, and the time-domain finite-element (TDFE) method was discussed in Jiao and Sun (2009). Numerical results of MTL simulations based on Laplace transforms and the FDTD method were presented and compared in Dedkova and Brancik (2008).

The above-mentioned FDTD and sub-gridding method has two main advantages relative to other modeling approaches. First, it is simple to implement for complicated dielectric or metal structures since arbitrary electrical parameters can be assigned to each cell on the grid. Second, the entire computational space does not need to be discretized with a fine grid, thus preventing an unreasonable burden on computer processing time. The ultimate objective of research in this area is to assess the appropriateness of the method in determining the amount of electromagnetic coupling between transmission lines and an underground utility pipeline. The three-phase transmission lines are modeled as the AC sources and the pipeline and ground as the dielectric material. In this case, the pipeline is defined by a fine grid and the residual space by a coarse grid in the computational space. The fields between these two grids are unknown in nature and have to be computed. An interpolation algorithm is thus required between the grids. The aim of the present work is to develop the general code for solving the electric and magnetic fields within arbitrary metal or dielectric structures while applying a boundary with low reflection levels. To minimize redundant computation, the model is implemented in two dimensions.

2. Summary of Methods

2.1. Quasi-Static Theorem

The FDTD technique is not normally a practical scheme when low frequencies are involved due to lengthy simulation times. The computational burden cannot usually be made manageable, even for reasonable spatial resolutions. For example, if the model requires a spatial resolution of $\Delta x = \Delta y = \Delta z = 1 \text{ cm}$ at 50 Hz power line frequency, the duration of time steps required is given from the Courant stability criterion as $\Delta t = \Delta x/c \sqrt{3} = 1.92 \text{ ns}$. In order to cover one complete cycle, the number of time steps needed is $N = 1/(f\Delta t) \approx 10^7$. Since the simulation of many cycles will be required, and the number of spatial points to be simulated is very large at this resolution, the solution time becomes unviable even when run on a fast machine. However, a method known as quasi-static approximation, proposed by Moerloose et al. (1997), can be used to solve the difficulties. The formulation takes into account the wavelength being much
greater than the size of the object of study. There have been some early efforts of using
the quasi-static idea to study the interaction between living tissues exposed to extremely
low-frequency (ELF) electric fields in the published literature, such as Kaune and Gillis
(1981), Guy et al. (1982), and Golestani-Rad et al. (2007). The basis of this research
verifies the effectiveness of the quasi-static scheme at very low frequency. FDTD was
brought into play when researchers in Gandhi and Chen (1992), Stuchly and Dawson
(1997), Dawson et al. (1998), and Potter et al. (2000) applied the same principles. In
this case, the dimensions of the object of study were a small fraction of the wavelength.
An attempt to implement a similar scheme using the same technique but at much higher
frequencies of 900 and 1,800 MHz was made by See et al. (2007, 2008). The theoretical
method discussed in Kaune and Gillis (1981), Guy et al. (1982), and Golestani-Rad et al.
(2007) has been realized in the present work to approximate the quasi-static FDTD sub-
gridding. In general, two conditions must be satisfied before applying the quasi-static
formulation:

i. the size of the object is smaller than the wavelength by a factor of 10 or more
and
ii. \(|\sigma + j\omega \varepsilon| \gg \omega \varepsilon_0\),

where
\(\sigma\) is the conductivity of the object (S/m),
\(\varepsilon\) is permittivity of the object (F/m),
\(\omega\) is the angular frequency (measured in radians per second, with units s\(^{-1}\)), and
\(\varepsilon_0\) is the free space permittivity (8.85 x 10\(^{-12}\) F/m).

From the conditions stated above, the electric field components tangential to the
surface of the structure and the internal fields are roughly zero compared to the applied
field. The external electric field components can be viewed as orthogonal to the structure.
From Maxwell's equation \(\text{div } D = \rho\), the boundary condition for the normal electric field
components at the surface of the region of interest is given by the expression (Guy et al.,
1982; Golestani-Rad et al., 2007; Gandhi & Chen, 1992):

\[ j\omega \varepsilon_0 \hat{h} \cdot \overline{E}_{\text{air}} = (\sigma_{\text{tissue}} + j\omega \varepsilon_{\text{tissue}}) \hat{h} \cdot \overline{E}_{\text{tissue}}. \]  \(1\)

From this equation, with the two stated conditions satisfied, the scaling relationship can
be deduced:

\[ \overline{E}_{\text{tissue}}(f) = \left( \frac{\omega}{\omega'} \right) \left[ \frac{\sigma'(f') + j\omega' \varepsilon'(f')}{\sigma(f) + j\omega \varepsilon(f)} \right] \overline{E}_{\text{tissue}}(f'). \]  \(2\)

where
\(\overline{E}_{\text{tissue}}(f)\) is the resultant internal electric field (V/m),
\(\overline{E}_{\text{tissue}}(f')\) is the scaled internal electric field (V/m),
\(f\) is the frequency of interest (Hz),
\(f'\) is the scaled frequency (Hz),
\(\omega\) is the angular frequency of interest (s\(^{-1}\)),
\(\omega'\) is the scaled angular frequency (s\(^{-1}\)).
\( \sigma \) is the conductivity of the object (S/m), and
\( \sigma' \) is the scaled conductivity of the object (S/m).

Assuming that \( \omega \varepsilon(f) \ll \sigma(f) \) and \( \omega \varepsilon'(f') \ll \sigma'(f') \), then Eq. (2) can be approximated as (See et al., 2007, 2008)

\[
\overline{E}_{\text{tissue}}(f) \approx \left[ \frac{f \sigma'(f')}{f \sigma(f)} \right] \overline{E}_{\text{tissue}}(f').
\]  

(3)

It can be concluded from this equation that a scaled higher working frequency \( f' \) that still falls within the quasi-static region can be chosen to excite the model to reduce the computational burden. Hence, the scaled internal electric field, which is calculated at the much higher frequency, can be shifted back to the actual power line frequency.

2.2. Validation of Sub-Gridding Method

The main grid of the computational domain was divided into sub-grids around regions of especial interest, and the missing fields on the boundary between grid domains were predicted using temporal and spatial interpolations. The average electrical characteristics were considered between the main grid cells and the fine grid (sub-gridding cells) when dielectric material (in this case the pipeline) was present on the interface surface. The field components were updated on both the main grid and sub-gridding cells, as shown in Figure 1.

The sub-gridding technique was validated by illustrative examples in two cases. Case 1 considered when the observed field was located inside the sub-grid area with two conditions: (1) without a sub-grid and (2) with a sub-grid, as shown in Figure 2 (refers to the x symbol inside the grid region). Case 2 considered when the observed field was located outside the sub-grid area with two conditions: (1) without a sub-grid and (2) with

![Figure 1. Proposed sub-gridding model with field component distribution between two different media.](image-url)
a sub-grid, as depicted in Figure 2 (refers to the x symbol outside the grid region). In both cases, the problem space is bounded by Berenger’s perfect matched layer (PML). The problem space was excited by a sinusoidal wave and a Gaussian pulse at 1,800 MHz. The electric fields at the same point for Cases 1 and 2 were observed and compared as illustrated in Figure 3(a). The magnetic fields at the same point for Cases 1 and 2 were also observed and compared as illustrated in Figure 3(b).

The electric fields in the sub-grid region ($E_{zg}$) and in the normal grid ($E_z$) for Case 1 were found to be identical to each other, thus confirming the proof of concept, as shown in Table 1. The electric fields $E_z$ with and without sub-grid for Case 2 were also found to be identical to each other. A similar observation also applies for the magnetic fields for both Cases 1 and 2. The results in Figure 4 illustrate the stability of the simulation inside the problem space. The electric field remained at 0.23 V/m when using different values of sub-grid cell sizes, justifying that the results converge with the mesh size in the computational domain.

3. Results and Discussion

A source code was written to implement the analysis of the interaction between overhead high-voltage power transmission lines and buried utility pipeline. Fortran 90 (Intel
Corporation) was used as a programming language platform. The model was confined to a two-dimensional transverse magnetic case. Figure 5 illustrates the cross-section and dimensions of a common corridor in which a buried utility pipeline runs parallel to a 400-kV overhead power transmission line using low height towers, such that the height from the ground to the bottom conductors is 17 m.

The distance from the overhead ground wire to the earth surface is 32 m. Phase A conductors at the top were collocated horizontally with a separation of 3.0 m. The bottom conductors of phase B, phase B to C, and phase C were collocated horizontally...
### Table 1

Observed fields in numerical values

<table>
<thead>
<tr>
<th>Number of time steps</th>
<th>Inside sub-grid</th>
<th>Outside sub-grid</th>
<th>Inside sub-grid</th>
<th>Outside sub-grid</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E_z$ at sub-grid</td>
<td>$E_z$ at normal grid</td>
<td>$E_z$ at sub-grid</td>
<td>$E_z$ at normal grid</td>
</tr>
<tr>
<td>1</td>
<td>-0.1400</td>
<td>-0.1400</td>
<td>-0.1900</td>
<td>-0.1900</td>
</tr>
<tr>
<td>1,000</td>
<td>-0.1523</td>
<td>-0.1527</td>
<td>-0.2088</td>
<td>-0.2095</td>
</tr>
<tr>
<td>2,000</td>
<td>0.1067</td>
<td>0.1154</td>
<td>0.1881</td>
<td>0.2014</td>
</tr>
<tr>
<td>3,000</td>
<td>0.1994</td>
<td>0.2113</td>
<td>0.3301</td>
<td>0.3483</td>
</tr>
<tr>
<td>4,000</td>
<td>-0.0135</td>
<td>-0.0091</td>
<td>0.0038</td>
<td>0.0105</td>
</tr>
<tr>
<td>5,000</td>
<td>-0.2440</td>
<td>-0.2477</td>
<td>-0.3494</td>
<td>-0.3550</td>
</tr>
<tr>
<td>6,000</td>
<td>-0.1781</td>
<td>-0.1794</td>
<td>-0.2483</td>
<td>-0.2504</td>
</tr>
<tr>
<td>7,000</td>
<td>0.0899</td>
<td>0.0980</td>
<td>0.1624</td>
<td>0.1747</td>
</tr>
<tr>
<td>8,000</td>
<td>0.1869</td>
<td>0.1983</td>
<td>0.3110</td>
<td>0.3285</td>
</tr>
<tr>
<td>9,000</td>
<td>-0.0233</td>
<td>-0.0192</td>
<td>-0.0111</td>
<td>-0.0049</td>
</tr>
<tr>
<td>10,000</td>
<td>-0.2520</td>
<td>-0.2559</td>
<td>-0.3616</td>
<td>-0.3676</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of time steps</th>
<th>Inside sub-grid</th>
<th>Outside sub-grid</th>
<th>Inside sub-grid</th>
<th>Outside sub-grid</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$H_y$ at sub-grid</td>
<td>$H_y$ at normal grid</td>
<td>$H_y$ at sub-grid</td>
<td>$H_y$ at normal grid</td>
</tr>
<tr>
<td>1</td>
<td>0.1000</td>
<td>0.1000</td>
<td>0.0067</td>
<td>0.0067</td>
</tr>
<tr>
<td>1,000</td>
<td>0.1428</td>
<td>0.1441</td>
<td>0.0571</td>
<td>0.0588</td>
</tr>
<tr>
<td>2,000</td>
<td>-1.0701</td>
<td>-1.1052</td>
<td>-1.5602</td>
<td>-1.6070</td>
</tr>
<tr>
<td>3,000</td>
<td>-0.3365</td>
<td>-0.3496</td>
<td>-0.5820</td>
<td>-0.5995</td>
</tr>
<tr>
<td>4,000</td>
<td>0.4586</td>
<td>0.4693</td>
<td>0.4781</td>
<td>0.4925</td>
</tr>
<tr>
<td>5,000</td>
<td>0.2316</td>
<td>0.2356</td>
<td>0.1755</td>
<td>0.1808</td>
</tr>
<tr>
<td>6,000</td>
<td>-0.6922</td>
<td>-0.7160</td>
<td>-1.0563</td>
<td>-1.0879</td>
</tr>
<tr>
<td>7,000</td>
<td>-1.0271</td>
<td>-1.0609</td>
<td>-1.5028</td>
<td>-1.5479</td>
</tr>
<tr>
<td>8,000</td>
<td>-0.3028</td>
<td>-0.3149</td>
<td>-0.5371</td>
<td>-0.5532</td>
</tr>
<tr>
<td>9,000</td>
<td>0.4859</td>
<td>0.4975</td>
<td>0.5145</td>
<td>0.5300</td>
</tr>
</tbody>
</table>

Magnetic field inside sub-grid and normal grid

The three phase steel lattice transmission high-voltage suspension tower was designed with six cables. These cables were used as the source signal, which propagates inside the problem space. Each of the two cables carries the same phase of the AC current. The general equations of phase $A$, phase $B$, and phase $C$ cables were given, respectively, by
Figure 4. Electric field distribution for different numbers of sub-grid cells in one main FDTD cell.

Figure 5. Outline of standard circuit 400-kV steel lattice transmission high-voltage suspension towers with normal span of 300 m (low height construction design, not to scale) (Pansini, 2005; Goulty, 1990).

The expressions:

\[ \text{Phase } A = \sin(2\pi ft), \]
\[ \text{Phase } B = \sin \left( 2\pi ft + \frac{2}{3}\pi \right), \]
\[ \text{Phase } C = \sin \left( 2\pi ft + \frac{4}{3}\pi \right). \]
where \( f \) is the frequency (Hz) and \( t \) is the time (sec). The pipeline was separated by a distance of 100 m from the steel lattice suspension towers and buried 2 m beneath the surface of the earth. It was made from metal with a very high conductivity of \( 4.75 \times 10^6 \) S/m. The radius of the pipeline was 25 cm.

The soil in the common corridor was designed to be inhomogeneous. It was modeled with variable relative permittivity by means of a random number generator. It was known that the relative permittivity of soil varies from 1 to 5 at 460 kHz, whereas the conductivity is kept at \( 2.0 \times 10^{-3} \) S/m (Middleton & Valkenburg, 2002). Figure 6 represents a histogram that indicates the frequency of occurrences of soil with respective values of random relative permittivity from 1 to 5. Figure 7 depicts the cumulative distribution function (CDF) of soil relative permittivity; the plot is based on Eq. (7). The representation of
Figures 6 and 7 clearly indicates that the soil was designed as arbitrarily inhomogeneous. The CDF is given by

$$CDF(x) = \int_1^{x_1} \frac{1}{4} dx,$$  \hspace{1cm} (7)

where $x_1$ is the variable that must be determined by using a random number generator, given by the expression

$$R_g(0 \rightarrow 1) = \frac{1}{4}(x_1 - 1),$$  \hspace{1cm} (8)

where $R_g(0 \rightarrow 1)$ is the random number generator that generates numbers from zero to one. Rearranging Eq. (8), the $x_1$ term can be deduced as

$$x_1 = 4R_g(0 \rightarrow 1) + 1.$$  \hspace{1cm} (9)

In addition, the conductivity of soil mainly depends on the water content in it and slightly on the granularity. In general, its value was very small, typically in the order of $2.0 \times 10^{-3}$ S/m or less (Middleton & Valkenburg, 2002). Homogeneous soil also was used in order to compare the correlation between the neighboring cells. It was modeled with $\varepsilon_r = 3.0$, while its conductivity remained at the same value as before. The computational region over the coarse grids was discretized at a spatial resolution of 2,609 cells per wavelength ($\Delta y = \Delta z = 25$ cm). The computational space for the main region was 521 cells $\times$ 185 cells (130.25 m $\times$ 46.25 m), as shown in Figure 8. The sub-grid computational space was 40 sub-grid cells $\times$ 40 sub-grid cells, as illustrated in Figure 9; here there are many colors that represent the random distribution of the soil. In contrast, the non-color (white area) depicts the pipeline. The values for the other parameters are summarized in Table 2. The distribution of ground surrounding the pipeline was generated by using random numbers to simulate the inhomogeneity of the media. The fine grids were discretized at a spatial resolution of 10,435 cells per wavelength ($\Delta y = \Delta z = 6.25$ cm), and hence the ratio of the coarse to the fine grids was 4:1. The discretization of the coarse grids remained at $3.83 \times 10^{-4}$ wavelengths. The discretization of the fine grids remained at $9.58 \times 10^{-5}$ wavelengths. The induced EM fields above the pipeline were observed for 30 cells $\times$ 20 cells (7.5 m $\times$ 5 m). The Courant stability

![Figure 8](image-url)
condition for the 2D case is given by

\[ \Delta t \leq \frac{h}{c\sqrt{2}} \]  

(10)

where \( h \) is the spatial homogeneous FDTD grid discretization \( (h = \Delta y = \Delta z) \), and \( c \) is the speed of light in free space. According to this equation, the time step was set at 0.4 ns to satisfy the Courant stability condition. The simulation was run for 21,160 time steps to allow for the wave to fully traverse the spatial domain for 4 cycles.

A scaled frequency of 460 kHz was employed to get the fields before they were altered back to 50 Hz. Figure 10 shows the three-phase 400-kV sinusoidal sources separated by 120° phase shift. The fields \( E_{zg} \), \( H_{yg} \), and \( H_{xg} \) were observed at the point \((31.25 \text{ cm}, 31.25 \text{ cm})\) within the sub-gridded section. The distributions of these

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source frequency</td>
<td>460 kHz</td>
</tr>
<tr>
<td>Coarse grids</td>
<td>25 cm</td>
</tr>
<tr>
<td>Fine grids</td>
<td>6.25 cm</td>
</tr>
<tr>
<td>Refinement factor</td>
<td>4</td>
</tr>
<tr>
<td>Time step</td>
<td>0.4 ns</td>
</tr>
<tr>
<td>Number of time steps</td>
<td>21,160</td>
</tr>
<tr>
<td>Number of cycles</td>
<td>4</td>
</tr>
<tr>
<td>Sub-grid spatial resolution</td>
<td>40 sub-grid cells ( \times 40 ) sub-grid cells</td>
</tr>
<tr>
<td>Induced EM fields spatial resolution</td>
<td>30 cells ( \times 20 ) cells</td>
</tr>
</tbody>
</table>
fields are plotted in Figure 11 for homogeneous and randomly distributed soil. The EM wave that travels from the suspension tower to the pipeline varies from $2.24 \times 10^{-7}$ V/m ($-133$ dBV/m) to $6.3 \times 10^9$ V/m ($76$ dBV/m). The distribution of the electric field $E_x$ and magnetic fields $H_y$ and $H_z$ through the simulated FDTD computational space are given in Figures 12(a), 12(b), and 12(c), respectively. In the sub-grid region, the distribution of $E_{xg}$, $H_{yg}$, and $H_{zg}$ are illustrated in Figures 13(a), 13(b), and 13(c), respectively. Here, the fields inside the metallic pipeline were also found to be zero. The reason for this phenomenon was due to the conductivity of the metal preventing any significant proportion of the incoming propagating waves from penetrating the pipeline.

It was shown that the electric field distribution surrounding the pipeline varies from $7.9 \times 10^{-7}$ V/m ($-122$ dBV/m) to $7.9 \times 10^{-4}$ V/m ($-62$ dBV/m), which shows good conformity with Amer (2005). The difference in relative distance of each phase from the nearby pipeline can create phase imbalance in the transmission line. Under fault conditions, the currents on the faulty phases of the transmission lines can be very high, causing increased induced AC voltage on the pipeline. The induced field will not contribute to shock hazards under normal (non-fault) conditions. Figures 14(a), 14(b), and 14(c) illustrate the induced EM fields for $E_x$, $H_y$, and $H_z$, respectively. As can be seen, the current amplitude induced on the pipe varies ($H_y$ magnetic fields in Figure 14(b)) from $1.8 \times 10^{-8}$ A/m ($-155$ dBA/m) to $1.3 \times 10^{-7}$ A/m ($-138$ dBA/m) and ($H_z$ magnetic fields in Figure 14(c)) from $5.6 \times 10^{-8}$ A/m ($-145$ dBA/m) to $4.0 \times 10^{-7}$ A/m ($-128$ dBA/m). It is noteworthy that these currents do not produce any sudden risk to a nearby person.

4. Conclusion

An approach to model the interaction between overhead transmission lines and an underground utility pipeline at power line frequency has been presented. This method uses the FDTD technique for the whole structure of the problem combined with a sub-gridding method at the object of interest, particularly the underground pipeline. By implementing a modified version of Berenger's PML, the reflection on the boundary layers inside the spatial FDTD computational region has been successfully decreased, although it is surrounded by lossy penetrable media. The computational burden due to the potential
need for a huge number of time steps in the order of tens of millions has been eased to tens of thousands by employing a quasi-static approximation scheme. In addition, the use of inhomogeneous soil in the common corridor permits a nontrivial proximity region of authentic ground properties to be simulated. Investigation of the interaction between electromagnetic fields and natural or utility infrastructure with varying electrical characteristics at different levels of spatial resolution can be facilitated by such tools. The combination of the frequency scaling sub-gridded FDTD approach with an arbitrary inhomogeneous dielectric volume and the modified Berenger’s PML offers a good candidate model for EM field interaction modeling for complex geometries at low frequencies.
Figure 12. EM field distributions in the main FDTD grid: (a) $E_z$, (b) $H_y$, and (c) $H_x$ components.
Figure 13. EM field distributions in the sub-grid region: (a) $E_x$, (b) $H_x$, and (c) $H_y$ components.
Figure 14. Induced EM fields 1.75 m above the metallic pipeline: (a) $E_z$, (b) $H_y$, and (c) $H_x$ components.
References

Amer, G. M. 2005. Novel technique to calculate the effect of electromagnetic field of H.V.T.L. on the metallic pipelines by using EMT program. 18th International Conference and Exhibition on Electricity Distribution (CIRED), Turin, Italy, 6-9 June, 1-5.


