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Determination of the Electromagnetic Field Created by Line Current and Sheet Current Source at the Earth's Surface

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Abstract

The electromagnetic field that generated by line current and sheet current at the surface of the earth can be expressed in analytical form. The line current created at the earth's surface by an infinitely long line current is given by the inverse Fourier integrals over a horizontal wave number. The sheet current can be obtained by integrating the line current expansions using a Neumann and Struve functions; these functions have known mathematical properties, including the series expansions. The series expansions are exact with neglecting the displacement currents. Assuming a uniform earth and that there is no propagation, the three nonzero field components can be expressed in terms of the Neumann and Struve functions. The integrals of line current expansions are calculated by using the numerical methods. The results represented graphically and illustrated by figures. Results can be used to evaluate numerical solutions of more complicated modeling algorithms.

1. Introduction

In the last few decades, there has been increased interest in the behavior of electromagnetic systems which are operated near a conducting earth. Many of these systems have been successfully used to measure the electromagnetic properties of the earth. That is, if the field of a transmitting source can be calculated in terms of idealized earth models, then measurements of actual fields near a real earth can be interpreted in terms of these

models. This method is known as the induction method of geophysical exploration [1] [2]. A part of the integrand may be inverse Fourier integral form using the fast Fourier transforms such that the resulting integrals are known [3]. However, they presented only a particular form of decomposition of the integrand. Other studies have been applied to the probing of the fields in geological media [4]-[6], determination of the current in a lightning return stroke [7], the detection of nuclear bursts Johler [8], and the discrimination of a radar scattered [9]. In the present study, we will focus on the effects caused by the presence of the earth's surface. We are interested in the problem of electromagnetic field. Also, few electro-magnetic problems have been investigated along these lines [10], [11].

Electromagnetic boundary conditions at the surface of the wire were leading to a characteristic equation that determines the propagation constant along the wire [12]. Furthermore, Bishay *et al.* [13] computed the transient electromagnetic field of a vertical dipole on a two-layer conducting earth. Sami [14] calculated the influence of a magnetically permeable surface layer on transient electromagnetic field of a vertical magnetic dipole on a two-layer conducting earth. Bishay and Sami [15] studied Time-domain study of transient fields for a thin circular loop antenna. However, using a quasi-static approach, Wait [16] has derived closed-form solutions for the fields of loops above the surface of a two-layered earth, that are valid at sufficiently late times. A classical work in this subject is the remarkable book [17] and Wait [18], for the electromagnetic fields of a phased line current over a conducting half-space. A very readable contemporary review was written by Olsen [19] who provides many significant references. Pirjola [20] considered the general case of a propagation current wave and derived formulas which give the electromagnetic field at the surface of the earth in an inverse Fourier integral form. The surface fields are also affected by currents induced within the ground and influenced by the conductivity of the Earth. This also has to be taken into account. Neglecting the currents displacement, thus making the quasi-static approximation, which is always permissible in geophysical applications, and assuming a uniform earth and that there is no propagation, the three nonzero field components can be expressed in terms of the Neumann and Struve functions. These functions have known mathematical properties, including their series expansions. The latter are utilized in this work to derive expressions for the electromagnetic field. In the previous work, the magnetic X and Z components are obtained from the electric Y component at the earth's surface, neglecting the real part of electric field, and imaginary part of magnetic field.

The main objective of paper is to determine the electromagnetic field due to a line current and sheet current. Sheet current having a finite width implies a more realistic model. It can be obtained by integrating the line current expansions using a Neumann and Struve functions. These functions have known mathematical properties [21], including the series expansions. The medium in which the line current lies in non-conducting (the air), and the other half-space is conducting (the earth). In this paper, the electric X and Z components are obtained from the magnetic Y component at the earth's surface, we are considering the real and imaginary parts of electric field components and taking into account.

2. Line Current Model

In the Cartesian coordinate system (x, y, z), we assume that the earth's surface is the xy plane, and the line current J flows is parallel to the y-axis at a height $z = -d$. The line current oscillating harmonically in time $\exp(i\omega t)$ above a uniform half-space. The earth, characterized by a conductivity σ, a permittivity ϵ, a permeability μ, and a propagation constant K, where

$$K = \sqrt{\omega^2 \mu \in -i\omega\mu\sigma} . \tag{1}$$

A model containing an infinitely long line current parallel to the surface between two half-spaces is frequently used in electromagnetic applications extending from geophysics. The medium in which the line current lies is nonconducting (the air), and the other half-space is conducting (the earth). The line current flows parallel to the y-axis at a height $Z = -d$. Neglecting displacement current effects, and assuming that μ_o is the vacuum permeability, then the propagation constant k of the earth is defined by

$$k \approx \sqrt{-i\omega\mu_o\sigma} . \tag{2}$$

The magnetic field has only the magnetic field component H_y, and the non-zero electric field components are E_z and E_x, now we shall give the expressions for the electromagnetic field as [22]

$$H_y = \frac{-i\omega \in_o J}{2\pi} \int_0^\infty (1-R)\frac{e^{-\lambda d}}{\lambda}\sin(\lambda x)d\lambda , \tag{3}$$

$$E_Z = \frac{-J}{2\pi} \int_0^\infty (1-R) e^{-\lambda d} \cos(\lambda x) d\lambda ,$$ (4)

$$E_x = \frac{J}{2\pi} \int_0^\infty (1+R) e^{-\lambda d} \sin(\lambda x) d\lambda .$$ (5)

R is the reflection coefficient at the earth's surface is depending on the conductivity structure of the earth, and is given by,

$$R(\lambda) = \frac{k-\lambda}{k+\lambda},$$ (6)

and J gives the magnitude of the line current oscillating harmonically in time $e^{i\omega t}$. To get the electric and magnetic fields at the earth's surface, then from Equations (3)-(5) we get,

$$H_y = \frac{-i\omega \in_o Je^{i\omega t}}{\pi} \int_0^\infty \frac{e^{-\lambda d}}{\lambda+k} \sin(\lambda x) d\lambda,$$ (7)

$$E_Z = \frac{-Je^{i\omega t}}{\pi} \int_0^\infty \frac{\lambda e^{-\lambda d}}{\lambda+k} \cos(\lambda x) d\lambda,$$ (8)

$$E_x = \frac{Je^{i\omega t}}{\pi} \int_0^\infty \frac{k e^{-\lambda d}}{\lambda+k} \sin(\lambda x) d\lambda.$$ (9)

The components of the electric fields are expressed in terms of H_Y through the relations

$$E_z = \frac{1}{i\omega \in_o} \frac{\partial H_y}{\partial x},$$ (10)

$$E_x = \frac{Jde^{i\omega t}}{\pi (x^2+d^2)} - \frac{1}{i\omega \in_o} \frac{\partial H_y}{\partial d}.$$ (11)

Equation (7) can be written in Terms of Struve function of the first order H_1 and the Neumann function of the first order Y_1 [20]:

$$H_y = \frac{-i\omega \in_o Je^{i\omega t}}{4} \left[\frac{y_1(k(x+id)) - H_1(k(x+id))}{k(x+id)} + \frac{y_1(k(-x+id)) - H_1(k(-x+id))}{k(-x+id)} + \frac{4(x^2-d^2)}{\pi k^2 (x^2+d^2)^2} \right].$$ (12)

The Neumann function $Y(u)$ and the Struve function $H(u)$ can be expressed as a series expansion [20],

$$Y(u) = \frac{2}{\pi} \left[\ln\left(\frac{u}{2}\right) + C_{Euler} - \frac{1}{2} \right] J_1(u) - \frac{u}{2\pi} \sum_{m=1}^\infty S_m u^{2m} - \frac{2}{\pi u},$$ (13)

$$H(u) = \frac{u^2}{2} \sum_{m=0}^\infty C_m u^{2m} ,$$ (14)

where $J_1(u)$ denotes the Bessel function of the first order, C_{Euler} is Eulers constant (≈ 0.5772) and S_m is given by

$$S_m = \frac{(-1)^m}{2^{2m} m!(m+1)!} \sum_{p=1}^m \left(\frac{1}{p} + \frac{1}{p+1} \right), \ (s_{m=0} = 0).$$ (15)

The function $J_1(u)$ has the series expansion

$$J_1(u) = \frac{u}{2} \sum_{m=0}^\infty g_m u^{2m},$$ (16)

where g_m is given by [21]

$$g_m = \frac{(-1)^m}{2^{2m} m!(m+1)!}.$$ (17)

and C_m is defined by

$$C_m = \frac{(-1)^m}{2^{2m}\Gamma\left(m+\frac{3}{2}\right)\Gamma\left(m+\frac{5}{2}\right)}. \tag{18}$$

The gamma function Γ satisfies,

$$\Gamma\left(m+\frac{3}{2}\right)\Gamma\left(m+\frac{5}{2}\right) = \left(m+\frac{3}{2}\right)\left(\sqrt{\pi}\cdot\frac{3}{2}\cdot\frac{3}{2}\cdot\frac{3}{2}\cdots\frac{2m+1}{2}\right)^2. \tag{19}$$

The expansions of the Neumann and Struve functions Equation (13) and (14) with (16) may now be substituted into (12) to obtain a series representation for the magnetic field H_y, which is straight forward algebra. It appears that the terms resulting from the function on the right-hand side of (13) exactly cancels the last term in (12), and the final series expansion can be written as

$$H_y = \frac{-i\omega \in_o Je^{i\omega t}}{4}\sum_{m=0}^{\infty}\left\{f_m(u_1)u_1^{2m} + f_m(u_2)u_2^{2m}\right\}, \tag{20}$$

where

$$f_m(u_i) = \frac{g_m}{\pi}\left[\ln\left(\frac{u_i}{2}\right) + C_{Euler} - \frac{1}{2}\right] - \frac{C_m u_i}{4} - \frac{s_m}{2\pi}, \quad (i=1,2), \tag{21}$$

and

$$u_1 = k(x+id), \tag{22}$$

$$u_2 = k(-x+id). \tag{23}$$

By applying the series expression of H_y in (10) and (11) the series expansions of the components of the electric fields E_z and E_x are obtained in a straightforward manner as

$$E_z = \frac{-Je^{i\omega t}k}{4}\sum_{m=0}^{\infty}\left\{\left(2mf_m(u_1)+\left(\frac{g_m}{\pi}\right)\right)u_1^{2m-1} - \left(\frac{c_m}{4}\right)u_1^{2m} - \left[\left(2mf_m(u_2)+\left(\frac{g_m}{\pi}\right)\right)u_2^{2m-1} - \left(\frac{c_m}{4}\right)u_2^{2m}\right]\right\}, \tag{24}$$

$$E_x = \frac{Je^{i\omega t}ik}{4}\sum_{m=0}^{\infty}\left\{\left[2mf_m(u_1)+\left(\frac{g_m}{\pi}\right)\right]u_1^{2m-1} - \left(\frac{c_m}{4}\right)u_1^{2m} + \left[2mf_m(u_2)+\left(\frac{g_m}{\pi}\right)\right]u_2^{2m-1} - \left(\frac{c_m}{4}\right)u_2^{2m}\right\} + \frac{Jde^{i\omega t}}{\pi(x^2+d^2)}. \tag{25}$$

3. Sheet Current Model

To determine the electromagnetic field created by the sheet current source at the surface, a sheet current can be lies in non-conducting (the air), and the other half-space is conducting (the earth). The sheet current having a finite width implies a more realistic model. It can be obtained by integrating the line current expansions using Neumann and Struve functions. We now consider an infinitely long sheet current on surface of the Earth. Let $J\beta(x)e^{i\omega t}$ be the current distribution in the sheet. If the function $\beta(x)$ can be normalized as follow,

$$\int_{-\infty}^{\infty}\beta(x)dx = 1. \tag{26}$$

Applying [(7)-(9)] for each line current $\beta(x')e^{i\omega t}dx'$ lying at $x=x'$, the following formulas are obtained for the electric and magnetic fields at the Earth's surface at a location determined by x can be written in the form

$$H_y = \frac{-i\omega \in_o Je^{i\omega t}}{\pi}\int_{-\infty}^{\infty}dx'\beta(x')\int_0^{\infty}\frac{e^{-\lambda d}}{\lambda+k}\sin(\lambda(x-x'))d\lambda, \tag{27}$$

$$E_z = \frac{-Je^{i\omega t}}{\pi}\int_{-\infty}^{\infty}dx'\,\beta(x')\int_0^{\infty}\frac{\lambda e^{-\lambda d}}{\lambda+k}\cos(\lambda(x-x'))d\lambda, \tag{28}$$

$$E_x = \frac{Je^{i\omega t}}{\pi} \int_{-\infty}^{\infty} dx' \, \beta(x') \int_0^{\infty} \frac{ke^{-\lambda d}}{\lambda + k} \sin\left(\lambda(x-x')\right) d\lambda . \tag{29}$$

The electric field by (28) and (29) is expressible in terms of the magnetic field (28)

$$E_z = \frac{1}{i\omega \in_o} \frac{\partial H_y}{\partial x} , \tag{30}$$

$$E_x = \frac{Jde^{i\omega t}}{\pi} \int_{-\infty}^{\infty} \frac{\beta(x')}{(x-x')^2 + d^2} dx' - \frac{1}{i\omega \in_o} \frac{\partial H_y}{\partial d} . \tag{31}$$

Rewriting (20) with x and K replaced by $(x-x')$ and k_u, this yields

$$H_y = \frac{-i\omega \in_o Je^{i\omega t}}{4} \int_{-\infty}^{\infty} dx' \beta(x') \sum_{m=0}^{\infty} \left[f_m'(u_1') u_1'^{2m} + f_m'(u_2') u_2'^{2m} \right] , \tag{32}$$

where

$$u_1' = K_u \left(x - x' + id \right) , \tag{33}$$

and

$$u_2' = K_u \left(-x + x' + id \right) , \tag{34}$$

$$f_m'(u_i') = \frac{g_m}{\pi} \left[\ln\left(\frac{u_i'}{2}\right) + C_{Euler} - \frac{1}{2} \right] - \frac{C_m u_i'}{4} - \frac{s_m}{2\pi} \quad (i = 1, 2), \tag{35}$$

where K_u is the equivalent propagation constant and defined as

$$K_u = \frac{\omega\mu_0}{z_u} , \tag{36}$$

and if we assume that the wave number $\lambda \ll |K_u|$, then the plane wave surface impedance can be written as

$$Z_u = \frac{\omega\mu_0}{K_u} . \tag{37}$$

Let us define the functions $C_1(n,\gamma)$ and $C_2(n,\gamma)$ by

$$C_1(n,\gamma) = \int_{-\infty}^{\infty} \beta(x')(x'+\gamma)^n \ln(x'+\gamma) dx' , \tag{38}$$

and

$$C_2(n,\gamma) = \int_{-\infty}^{\infty} \beta(x')(x'+\gamma)^n dx' . \tag{39}$$

We know that

$$a_m = \frac{g_m}{\pi} k_u^{2m} , \tag{40}$$

$$q_m = \left(\frac{g_m}{\pi} \left(C_{Euler} - \frac{1}{2} + \ln\left(\frac{-k_u}{2}\right) \right) - \frac{s_m}{2\pi} \right) k_u^{2m} \tag{41}$$

$$\upsilon_m = \frac{C_m}{4} k_u^{2m+1} , \tag{42}$$

and

$$r_m = \left(\frac{g_m}{\pi} \left(C_{Euler} - \frac{1}{2} + \ln\left(\frac{k_u}{2}\right) \right) - \frac{s_m}{2\pi} \right) k_u^{2m} . \tag{43}$$

A straightforward algebraic manipulation now allows for expressing (32) as

$$H_y = \frac{-i\omega \in_o Je^{i\omega t}}{4} \sum_{m=0}^{\infty} \left[\alpha_1(m) + \alpha_2(m)\right], \tag{44}$$

the quantities $\alpha_1(m)$ and $\alpha_2(m)$ given by

$$\alpha_1(m) = \frac{-g_m\beta_0}{\pi k_u} \frac{\eta_2^{2m+1}}{(2m+1)} \left[C_{Euler} - \frac{1}{2} - \frac{S_m}{2g_m} - \frac{1}{2m+1} + \ln\left(\frac{\eta_2}{2}\right)\right]$$
$$+ \frac{g_m\beta_0}{\pi k_u} \frac{\eta_1^{2m+1}}{(2m+1)} \left[C_{Euler} - \frac{1}{2} - \frac{S_m}{2g_m} - \frac{1}{2m+1} + \ln\left(\frac{\eta_1}{2}\right)\right] + \frac{C_m\beta_0}{4k_u} \left[\frac{\eta_2^{2m+2}}{(2m+2)} - \frac{\eta_1^{2m+2}}{(2m+2)}\right], \tag{45}$$

and

$$\alpha_2(m) = \frac{-g_m\beta_0}{\pi k_u} \frac{\xi_2^{2m+1}}{(2m+1)} \left[C_{Euler} - \frac{1}{2} - \frac{S_m}{2g_m} - \frac{1}{2m+1} + \ln\left(\frac{-\xi_2}{2}\right)\right]$$
$$+ \frac{g_m\beta_0}{\pi k_u} \frac{\xi_1^{2m+1}}{(2m+1)} \left[C_{Euler} - \frac{1}{2} - \frac{S_m}{2g_m} - \frac{1}{2m+1} + \ln\left(\frac{-\xi_1}{2}\right)\right] \tag{46}$$
$$+ \frac{C_m\beta_0}{4k_u} \left[\frac{\xi_2^{2m+2}}{(2m+2)} - \frac{\xi_1^{2m+2}}{(2m+2)}\right].$$

where

$$\left.\begin{aligned} \eta_1 &= (x - x_1 + id)k_u, \\ \eta_2 &= (x - x_2 + id)k_u, \\ \xi_1 &= (x - x_1 - id)k_u, \\ \xi_2 &= (x - x_2 - id)k_u. \end{aligned}\right\} \tag{47}$$

We now consider a uniform sheet located between $x = x_1$ and $x = x_2$, then

$$\beta(x') = \begin{cases} 0 & x' < x_1 \text{ or } x' > x_2 \\ \beta_0 & x_1 \le x' \le x_2 \end{cases} \tag{48}$$

Assuming $\int_{-\infty}^{\infty} \beta(x')\,dx' = 1$ to be valid, $\beta_0 = \dfrac{1}{x_2 - x_1}$, then the electric field components are obtained as:

$$E_z = \frac{-Je^{i\omega t}}{\pi} \sum_{m=0}^{\infty} \left[\alpha_3(m) + \alpha_4(m)\right], \tag{49}$$
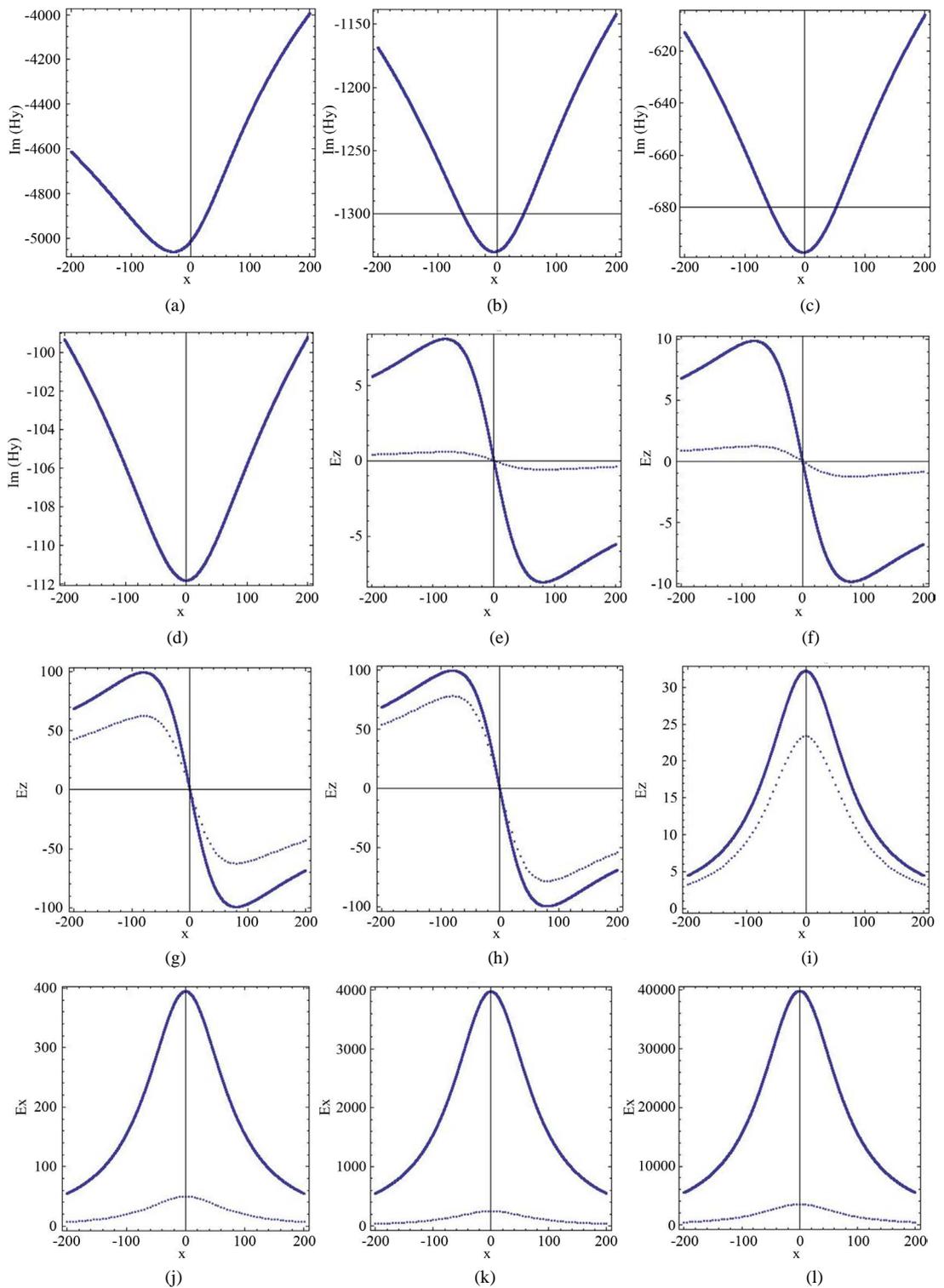
$$E_x = \frac{Je^{i\omega t}}{4} \left\{\frac{4\beta_0}{\pi} \left[\arctan\left(\frac{x-x_2}{d}\right) - \arctan\left(\frac{x-x_1}{d}\right)\right] + i\sum_{m=0}^{\infty}\left[\alpha_3(m) - \alpha_4(m)\right]\right\}, \tag{50}$$

where

$$\alpha_3(m) = \frac{\partial \alpha_1(m)}{\partial x} = \frac{-g_m\beta_0\eta_2^{2m}}{\pi} \left[C_{Euler} - \frac{1}{2} - \frac{S_m}{2g_m} + \ln\left(\frac{\eta_2}{2}\right)\right]$$
$$+ \frac{g_m\beta_0\eta_1^{2m}}{\pi} \left[C_{Euler} - \frac{1}{2} - \frac{S_m}{2g_m} + \ln\left(\frac{\eta_1}{2}\right)\right] + \frac{iC_m\beta_0}{4}\left[\eta_2^{2m+1} - \eta_1^{2m+1}\right], \tag{51}$$

and

$$\alpha_4(m) = \frac{\partial \alpha_2(m)}{\partial x} = \frac{-g_m\beta_0\xi_2^{2m}}{\pi} \left[C_E - \frac{1}{2} - \frac{S_m}{2g_m} + \ln\left(\frac{-\xi_2}{2}\right)\right]$$
$$+ \frac{g_m\beta_0 i\xi_1^{2m}}{\pi} \left[C_E - \frac{1}{2} - \frac{S_m}{2g_m} + \ln\left(\frac{-\xi_1}{2}\right)\right] + \frac{iC_m\beta_0}{4}\left[\xi_2^{2m+1} - \xi_1^{2m+1}\right]. \tag{52}$$

Figures 1. (a)-(d) represent the imaginary part of the magnetic field component Hy due to a line current of 1 MA with different values of distance *x* at the periods 10 s, 50 s, 100 s, and 700 s, respectively. (e)-(h) represent real and imaginary parts of the electric field component *Ez*, and (j)-(l) represent real and imaginary parts of the electric field component *Ex*, at the earth's surface due to a line current of 1 MA with different values of x at the periods 10 s, 50 s, 100 s, and 700 s, respectively. The continuous and dots curves correspond to the real and imaginary part of the electric field, respectively.
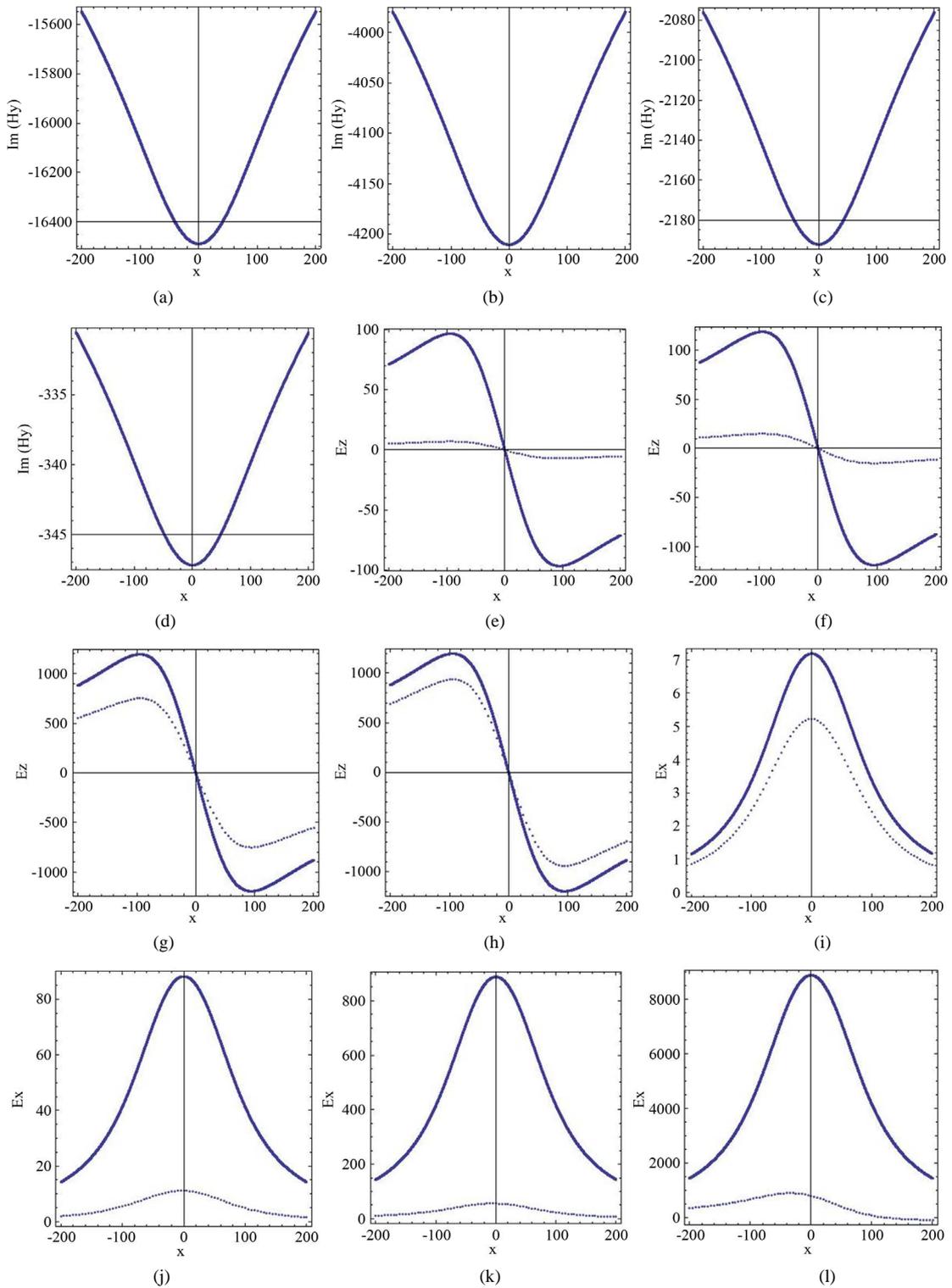
Figures 2. (a)-(d) represent the imaginary part of the magnetic field component Hy due to sheet current of 1 MA with different values of distance *x* at the periods 10 s, 50 s, 100 s, and 700 s, respectively. (e)-(h) represent real and imaginary parts of the electric field component component *Ez*, and (j)-(l) represent real and imaginary parts of the electric field component *E*x, at the earth's surface due to sheet current of 1 MA with different values of *x* at the periods 10 s, 50 s, 100 s, and 700 s, respectively. The continuous and dots curves correspond to the real and imaginary part of the electric field, respectively.

4. Numerical Results

Numerical computation of the electromagnetic field that generated by line current and sheet current at the surface of the earth can be easily performed, based on the Equations [(12), (24) and (25)] and [(44), (49) and (50)], respectively. The following parameters have been chosen to draw the curves shown by **Figures 2(a)-(l)**: $J = 1\,\text{MA}$, $d = 80\,\text{km}$, $x_2 = -x_1 = 50\,\text{m}$, and conductivity $\sigma = 10^{-3}\,\Omega^{-1} \cdot \text{m}^{-1}$.

The electromagnetic field defined as a function of x coordinate at the surface of the earth due to line current and sheet current and plotted against the distance x.

For line current, **Figures 1(a)-(d)** represent the imaginary part of magnetic field component H_y, **Figures 1(e)-(h)** describe the real and imaginary part of electric field components E_z, and E_x, at the periods 10 s, 50 s, 100 s, and 700 s, respectively.

For sheet current, **Figures 2(a)-(d)** represent the imaginary part of magnetic field component H_y, **Figures 2(e)-(h)** describe the real and imaginary part of electric field components E_z, and E_x, at the periods 10 s, 50 s, 100 s, and 700 s, respectively.

The magnetic and electric fields were treated as complex quantities, the real part of the right-hand side of Equations (3)-(19) is ignored. It is seen that the magnetic field component H_y is dominated by the imaginary part, and the real part of the electric field components E_z and E_x are larger than the imaginary part.

The results we obtained that with increasing in the period indicate to increase in the imaginary part of magnetic field component H_y, and with increasing in period corresponding increasing in the values of the real and imaginary parts of the electric field components E_z and E_x.

We compared the magnetic and electric fields at the surface of a uniform earth with those produced by line current and sheet current.

In the sheet current, the values of the imaginary part of the magnetic field component H_y are less than the values of the imaginary part of the magnetic field component H_y in the line current. The real and imaginary parts of the electric field component E_x in the sheet current are less than the electric field component E_x which obtained in the line current for the periods 10 s, 50 s, 100 s, and 700 s, respectively.

From a physical point of view, this means that the series expansions including the propagation constant k_u is reasonable, the propagation constant k_u depends on the surface impedance. The absolute values of u_1' and u_2' are less with k_u. While the sheet current of 1 MA parallel to the y-axis at height $z = -d$, the values of the real and imaginary parts of the electric field component E_z, is greater than the values of the real and imaginary parts of E_z in the line current, for the periods 10 s, 50 s, 100 s, and 700 s, respectively.

5. Conclusions

We conclude that the electromagnetic field at the earth's surface created by line current can be expressed in terms of the Neumann and Struve functions, and take the conductivity of the earth into consideration.

The magnetic and electric fields were derived in new series expansions and computations. Also we present the magnetic and electric fields due to sheet current obtained by integrating the line current expansion. The results are represented graphically. We compared the results of the magnetic and electric fields values at the surface of a uniform earth with those produced by line current with sheet current.

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