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The mutual impedance of thin circular loop antennas on an N-layered conducting medium at high frequency

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Abstract: The measurement of the mutual impedance of thin circular loop antennas on an N-layered conducting medium at high frequency is calculated. The horizontal, vertical coplanar, perpendicular and vertical coaxial loop antennas have been presented, the comparison between them and the numerical results have been calculated. The displacement currents in free space and in the conducting medium are taken into consideration. The measuring system and the method of interpreting measurement results were described and the results of field measurements were presented.

Index Terms: mutual impedance, geophysical method, loop antennas.

1. Introduction

In recent years, the mutual impedance of loop antennas situated near a conducting half space has been studied at low frequency [1-3] where displacement currents are negligible. In general the problem is complicated, since a solution of the Helmholtz wave must be found which satisfies the boundary conditions at the interfaces between the different media. The mutual impedance of a horizontal coplanar antenna array laid on the surface of a homogenous conducting medium [4-6]. Few papers are devoted to the analysis of the mutual impedance of an antenna system operating at a high frequency where displacement currents cannot be ignored [7]. [8 ,9] described a simple technique of determining a homogenous conducting medium's conductivity and permittivity through the measurement of the mutual impedance of horizontal coplanar loops laid on its surface. [10], they studied the mutual impedance of a horizontal co-planar antenna array operating at high frequency, laid on the surface of a conducting medium. In their expressions, the displacement currents have been neglected.

Several papers [11-13] deal with the application employing high frequency electromagnetic techniques to the sounding of the earth's near surface layers. The transient electromagnetic fields of a vertical magnetic dipole on a two-layer conducting earth and time-domain study of transient fields for a thin circular loop antenna have been treated in [14,15], respectively. [16] studied the transient fields of a vertical electric dipole on an M-layered dielectric medium. The present study is how to obtain the mutual impedance of thin circular loop antennas of a vertical magnetic dipole on an N-layered conducting medium at high frequency by different EM systems (horizontal coplanar, perpendicular, vertical coplanar and vertical coaxial). The displacement currents are taken into consideration.

2. Geometrical structure of the problem

The vertical dipole on an **N**-layered conducting medium in free space with parameters $\in_o, \mu_o$ at **z = 0,** oriented along the **z**-axis. Each layer of the medium is characterized by parameters $\in_i, \sigma_i$ and thickness of layered is d_i. The magnetic permeability of each layer is assumed be the same μ_o as shown in Fig.1. Considering a cylindrical coordinate, the dipole can be represented by small loop of current of area **dA** carrying a circulating current I(t) . The magnetic field components $H_\varphi = 0$, H_z and H_ρ of vertical magnetic dipole are given by [17]:

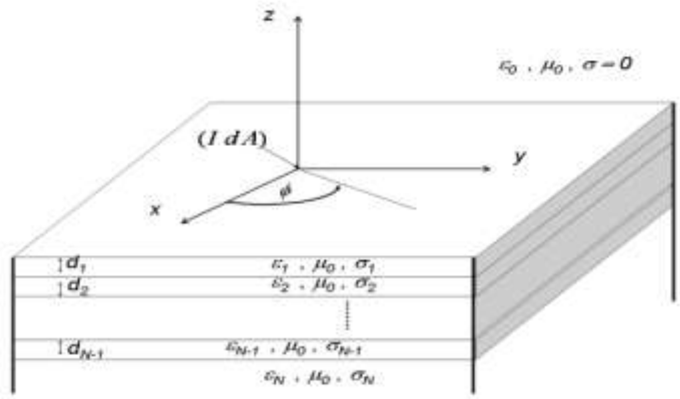

Fig. 1: Configuration of the problem

$$H_\rho(\rho, z) = \frac{\partial^2 \Pi_z(\rho, z)}{\partial\rho\,\partial z}, \tag{1}$$

$$H_z(\rho, z) = \left(\frac{\partial^2}{\partial z^2} - \gamma_o^2\right)\Pi_z(\rho, z) \tag{2}$$

The Hertz vector $\vec{\Pi}$ satisfies the wave equation:

$$(\nabla^2 + \gamma_i^2)\underline{\Pi}(\underline{\rho}) = 0. \tag{3}$$

The components of the Hertz potential in the free space are given by the following:

$$\Pi_{zo} = \frac{I(s)\,dA}{8\pi}\int_0^\infty \mathrm{A}(\lambda)\,\mathrm{e}^{\mathrm{u}_o z}\; J_o(\lambda\,\rho)\,d\lambda,\;\; 0 \le z, \tag{4}$$

and in the particular layers they assume in the form:

$$\Pi_{zi} = \frac{I(s)\,dA}{8\pi}\left[\int_0^\infty B_i(\lambda)\,\mathrm{e}^{-\mathrm{u}_i z} + \int_0^\infty \mathrm{C}_i(\lambda)\,\mathrm{e}^{\mathrm{u}_i z}\right] J_1(\lambda\,\rho)\,d\lambda, \qquad \sum_{i=1}^{N}\mathrm{d}_i \le z \le \sum_{i=1}^{N} d_{i-1} \tag{5}$$

finally, in the last layer it expressed by the following form:

$$\Pi_{zN} = \frac{I(s)\,dA}{8\pi}\int_0^\infty \mathrm{D}_N(\lambda)\,\mathrm{e}^{-\mathrm{u}_N z}\, J_1(\lambda\,\rho)\;d\lambda\,, \qquad \sum_{i=1}^{N}\mathrm{d}_i \le z, \tag{6}$$

where J_o and J_1 are the Bessel functions and the factors $A(\lambda)$, $B_i(\lambda)$, $C_i(\lambda)$, $E_i(\lambda)$, and $\mathrm{D}_N(\lambda)$ are calculated by using the boundary conditions which must be satisfied at the boundaries of the layers.

The magnetic field components needed to determine the mutual impedance of horizontal coplanar loops and perpendicular loops [18]. Applying the Sommerfeld transformation [19], the components assume the following form:

$$H_z = \frac{I\,dA}{8\pi}(T_1 + \int_0^\infty \lambda^2 R(\lambda)\; J_o(\lambda\,\rho)\,d\lambda)$$

$$H_\rho = \frac{I(s)\,dA}{8\pi}\,(T_2 - \int_0^\infty \lambda^2 R(\lambda)\; J_1(\lambda\,\rho)\,d\lambda)$$

where $T_1 = \dfrac{2(z-d_i)^2 - \rho^2}{\left[(z-d_i)^2 + \rho^2\right]^{\frac{5}{2}}}$, $\qquad T_2 = \dfrac{3\,\rho\,(z-d_i)}{(z-d_i)^2 + \rho^2}$,

and the generalized expressions for $R(\lambda)$ is calculated from the equation:

$$R_{i-1,N}(\lambda) = \frac{R_{i-1,i} + R_{i,N}(\lambda)\exp(-2u_i d_i)}{1 + R_{i-1,i}R_{i,N}(\lambda)\exp(-2u_i d_i)}, \tag{7}$$

and $R_{N,N}(\lambda) = 0$, $\qquad R_{i,N} = \dfrac{(u_i - u_N)}{(u_i + u_N)}$. (8)

where $\qquad u_i^2 = \gamma_i^2 + \lambda^2$, (9)

and $\gamma_o^2 = -\omega^2 \mu_o \in_o$, $\qquad \gamma_i^2 = s^2 \mu_o \in_i + s\,\mu_o \sigma_i$ (10)

are the propagation constants in the i-th layer, and i = 1, 2,…, N is the number of a layers.

3. The mutual impedance of thin circular loop antennas

The mutual impedance of antenna arrays located of multilayered conducting medium can be written as [1]:

I. Horizontal coplanar antennas:

$$\frac{z}{z_2} = 1 - k\,\rho^3 \int_0^\infty \lambda^2 R(\lambda) J_o(\lambda\rho)\, d\lambda] \tag{11}$$

II. Perpendicular antennas:

$$\frac{z}{z_1} = -k\,\rho^3 \int_0^\infty \lambda^2 R(\lambda) J_1(\lambda\rho)\, d\lambda \tag{12}$$

III. Vertical coplanar antennas:

$$\frac{z}{z_2} = 1 + k\,\rho^2 \int_0^\infty \lambda\, R(\lambda) J_1(\lambda\rho)\, d\lambda \tag{13}$$

IV. Vertical coaxial antennas:

$$\frac{z}{z_1} = 1 - \frac{k\,\rho^2}{2} \int_0^\infty \lambda R(\lambda) J_1(\lambda\rho)\, d\lambda + \frac{k\,\rho^3}{2} \int_0^\infty \lambda^2 R(\lambda) J_o(\lambda\rho)\, d\lambda \tag{14}$$

where $k = \dfrac{e^{-\gamma_o \rho}}{\rho^2 \gamma_o^2}$, and ρ is the distance between the transmitter and the receiver. Z_1, Z_2 are the impedances of vertical coaxial and coplanar antennas, respectively, located in the free space, given by the following equations:

$$Z_1 = -\frac{i\mu_o \omega\, N_1 N_2 R_1^2 R_2^2}{2\pi\rho^3}, \qquad Z_2 = \frac{i\mu_o \omega\, N_1 N_2 R_1^2 R_2^2}{4\pi\rho^3}$$

where N_1 and N_2 are numbers of turns of antennas, R_1 and R_2 are the radii of the antennas.

Then mutual impedance of antenna can be written as [18]:

I. Horizontal coplanar antennas:

$$Z = \frac{(i\mu_o \omega\, k\, N_1 N_2 R_1^2 R_2^2)}{2\pi\rho^3} \left[\gamma_o^3 \rho^3 + 4\gamma_o^2 \rho^2 + 9\gamma_o \rho + 9\right] \tag{15}$$

II. Perpendicular antennas:

$$Z = \frac{(i\mu_o \omega\, k\, N_1 N_2 R_1^2 R_2^2)}{\pi\rho^3} [\gamma_o^2 \rho^2 (I_1 K_1 - I_o K_o) + 4\gamma_i \rho (I_1 K_o - I_o K_1) + 16 I_1 K_1] \tag{16}$$

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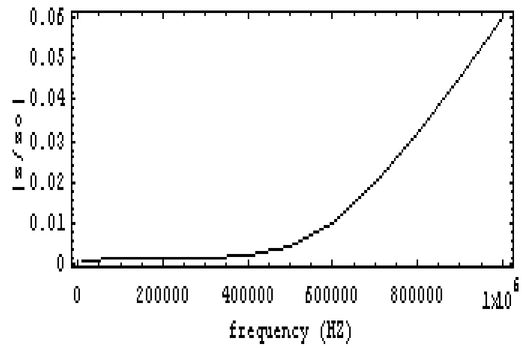
III. Vertical coplanar antennas:

$$Z = \frac{(i\mu_o \omega k\, N_1 N_2 R_1^2 R_2^2)}{2\pi\rho^3} \left[\gamma_o^2 \rho^2 + 3\gamma_o \rho + 3\right] \quad (17)$$

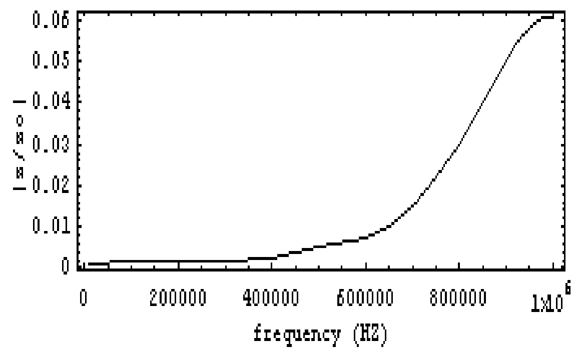
IV. Vertical coaxial antennas:

$$Z = \frac{(i\mu_o \omega k\, N_1 N_2 R_1^2 R_2^2)}{\pi\rho^3} \left[\gamma_o^3 \rho^3 + 5\gamma_o^2 \rho^2 + 12\gamma_o \rho + 12\right] \quad (18)$$

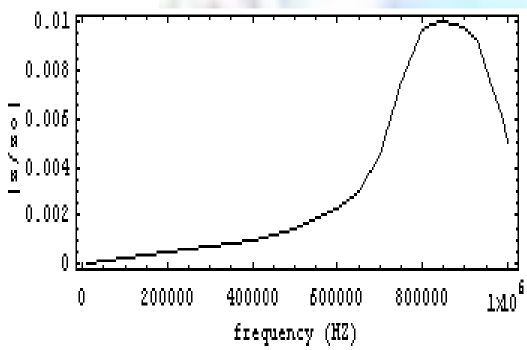
I_o, I_1, K_o *and* K_1 are modified Bessel functions.



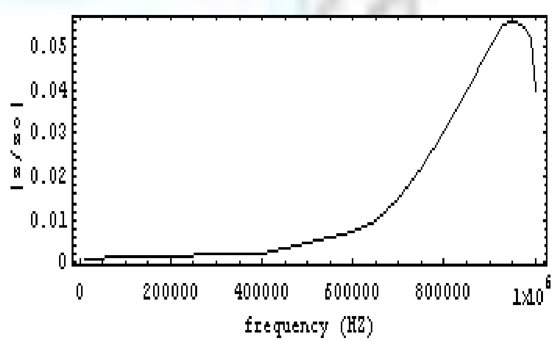
(I) Mutual impedance for horizontal coplanar antennas.



(II) Mutual impedance for perpendicular antennas.



(III) Mutual impedance for vertical coplanar antennas.



(IV) Mutual impedance for vertical coaxial antennas.

Fig. 2: The response of the frequency rate of change of the mutual impedance, calculated for: I) horizontal coplanar antennas, II) perpendicular antennas, III) vertical coplanar antennas and IV) vertical coaxial antennas.

Numerical Results

The measurement of the mutual impedance of loop antennas situated on an N-layered conducting medium at high frequency is describing and can be used in geophysical investigations. The frequency range for the equipment was determined on the basis of two numerical analyses are an analysis of the mutual impedance function's sensitivity and an analysis of the influence of displacement currents on the electromagnetic wave's propagation constant. The sensitivity of the impedance functions of all the antenna systems was analyzed for the conducting medium model, shown in Fig.2, it measures magnitude of mutual impedance horizontal coplanar, the perpendicular, the vertical coplanar, and the vertical coaxial antennas system, respectively at high frequency more than 1 MHz.

The frequency of antenna system was selected on the basis of a numerical analysis of the influence of displacement currents on wave propagation in the conducting half space and the displacement currents in free space and in the conducting medium are taken into consideration. The sensitivity of the mutual impedance function for thin layers with a low contrast increases for frequencies equal or greater than 1 MHz. The measuring system parameters: f = 30 MHz, ρ =1m, situated at $\mathbf{z = 0}$ on a conducting medium, where mutual impedances of loop antennas are described by relationships (15)-(18).

Conclusions

The mutual impedance of loop antennas placed on the surface of an inhomogeneous conducting half space was given. The operating frequency of antenna system, equal or greater than 1 MHz, was selected on the basis of a numerical analysis of the influence of displacement currents on wave propagation in the conducting half space. The measuring system and the method of interpreting measurement results were described. The sensitivity of the impedance functions of all the antenna systems was analyzed for the conducting medium model, shown in Fig. 2.
The measurement of the mutual impedance of loop antennas operating at a high frequency introduces limitations which make the examination of the deep layers of a conducting medium impossible. A multi-frequency system overcomes these limitations to some extent.

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