Modeling of Tesla's Transmitter using the Wire Antenna Theory with Ground Effects Included

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Abstract – **According Tesla's idea his magnifying transmitter has been designed not only to efficiently emit Hertzian waves, but also to transmit power at large distances. Analysis of Tesla's transmitter by using the wire antenna theory and reflection coefficient approximation is carried out in this work. The radiating part of the Tesla's transmitter is represented by an equivalent monopole antenna driven by an ideal current source thus replacing the Tesla's transformer. The frequency domain formulation is based on a homogeneous Pocklington integro-differential equation. The ground effects are taken into account via the corresponding reflection coefficient appearing within the integral equation kernel. Solving the Pocklington equation via the Galerkin Bubnov variant of the Indirect Boundary Element Method (GB-IBEM) the current distribution along the monopole antenna is assessed. Knowing the current distribution along the vertical monopole the radiated electric field is obtained by integrating the induced current. Numerical results for the monopole current and the related irradiated field are presented in the paper. The case studies of free space, perfect ground and imperfectly conducting half-space have been considered. This paper should be regarded as an extension of the previous work on the subject.**

Keywords – **Tesla's transmitter, Monopole antenna model, Integral equation approach, Reflection coefficient approximation, Boundary element method**

1. INTRODUCTION

It is well known in the history of electricity that Nikola Tesla unfortunately never finished his Long Island project and never put his famous transmitter in a full operation.

The scientific man does not aim at an immediate result. He does not expect that his advanced ideas will be readily taken up. His work is like that of a planner-for the future. His duty is to lay foundation of those who are to come and point the way.
Nikola Tesla

The invention of radio definitely belongs to Nikola Tesla. Nevertheless, the majority of scientific community has still not fully recognised his important role in the subject. One of the main reasons was the notorious fact that Tesla never accepted Hertz's theory and had considered the radio waves produced by a Hertzian dipole as longitudinal shock waves in space, rather than transversal [1]. Anyway, Tesla extraordinary ideas and various achievements still live on their own life, in physicists and engineers who got in touch with his work. Unfortunately, Tesla was never able to fully understand the gap between great ideas and the completely different and rather difficult process to make them real and getting them to commercialization [2].

Tesla had a dream, a rather remarkable idea, to develop a particular radio transmitter for a wireless transmission of not only communication signals, but also electrical energy at large distances. He had designed his magnifying transmitter [3], [4] by which he had been able to efficiently emit either Hertzian waves or, in his own words, *currents through the earth* which had been subjected to the device design [5], [6]. However, according to his strong belief Tesla considered wireless transmission by the Hertzian waves as rather less efficient method compared to his own concept. Once, he compared Hertzian waves to his earth waves like cutting the butter with blunt instead with sharp edge of a knife. A trade-off between the Hertzian wave and *the current wave* can be found elsewhere, e.g. in [7]. However, Tesla had never completed his Long Island transmitter station and had never got a chance to confirm his assumptions.

In spite of a number of proofs that he had played an important essential role in the development of radio, particularly in its infancy Tesla's name was unfortunately not listed among six radio pioneers selected by the European Broadcasting Union in 1996 [8].

Regardless of the fact that contemporary science considers Tesla's theory more or less fallacious [9], there are still some attempts not only to explain Tesla's work carried out in Colorado Springs [10] and Long Island [11], but also to follow on his work. One of the most acceptable theories within the present state of the art, is the one relaying on coupling to the Schumann cavity [11].

It is worth emphasizing that the measurements results of cavity parameters (e.g. resonant frequencies, coherence time, etc.) obtained by Tesla are very close to the experimental results obtained much later. The experiments Tesla intended to perform were not carried out until the 1960s [13], when it was found that the Earth resonances at 8, 14 and 20Hz [14]. Tesla's predictions expected the resonances to occur at 6, 18 and 30Hz. Unfortunately, Nikola Tesla never presented full details how his *World System* would function [15]. What he provided were just some general concepts and ideas on propagation mechanism.

Frankly, there are only a fair number of reasons confirming a real necessity to continue the research on the subject.

An interesting work on Tesla's transmitter has been carried out by K. Corum and J. Corum [16], [17]. Using the model of

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slow-wave helical resonator transmission line [16] the magnifying effect is achieved by the standing waves in the secondary. In the same work the transmission line (TL) mode T_0 is presented and standing wave formation explained. It is worth noting that the very similar explanations can be also found in many Tesla's papers.

The drawback of the TL models with lumped source voltage is that through these models is not possible to predict standing wave pattern presented in [1]. Therefore, TL model proposed in [7], instead of a lumped voltage source at the bottom of the secondary, features a distributed voltage along the line and better describes of the Tesla secondary. Discussion on some TL aspects of Tesla's propagation-through-Earth theory is available in [7].

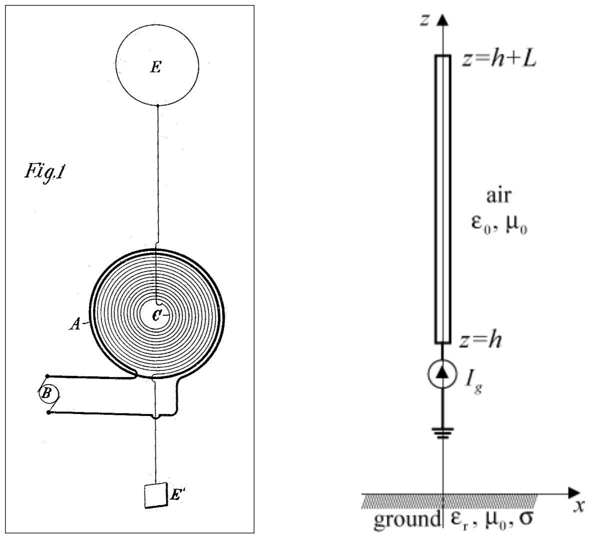
This paper is an extension of our previous study of Tesla's transmitter by using the wire antenna theory [18], [19]. Contrary to the implementation of *transmission line models*, the approach presented in [18] and [19] treats the radiating part of Tesla's transmitter (secondary) via *monopole antenna model*. While models presented in [18] and [19] are restricted to free-space antenna representations and formulations based on Hertz and magnetic vector potentials this work accounts for the ground effects. The formulation is based on the homogeneous Pocklington integro-differential equation.

The Pocklington equation is numerically solved by means of the Galerkin Bubnov variant of the Indirect Boundary Element Method (GB-IBEM) and the current distribution along the equivalent monopole antenna is obtained, providing the field assessment.

2. VERTICAL MONOPOLE ABOVE A LOSSY GROUND: INTEGRAL EQUATION FORMULATION

Figures 1a and 1b show Tesla's transmitter represented by an equivalent perfectly conducting (PEC) vertical monopole antenna of length L and radius a, located vertically at a height h=25m above a finitely conducting ground is considered. The wire dimensions (L=65m, a=10cm) are in accordance to thin wire approximation [20] and the current along the wire can be assumed to be z-directed only.

The vertical monopole is driven by an ideal current source I_g, representing the current induced in the secondary input due to the oscillations in the primary of the transformer being part of the Tesla's transmitter



a) Tesla's transmitter: electric scheme *b) Equivalent monopole antenna above ground*

Figure 1 - Representation of Tesla's Transmitter via vertical monopole above a lossy ground

2.1 Integral Equation for Current along the Vertical Monopole

The key point in the mathematical model is to assess the current distribution induced along the vertical monopole due to a time-harmonic excitation. This current distribution is governed by the homogeneous Pocklington integro-differential equation which can be derived by expressing the electric field in terms of the magnetic vector potential and by satisfying the continuity conditions for the tangential field components at the antenna surface.

Starting from Maxwell equations the total electric field can be expressed, as follows:

$$\vec{E} = \frac{1}{j\omega\mu\varepsilon_0}\nabla\left(\nabla\vec{A}\right) - j\omega\vec{A} \tag{1}$$

Due to rotational symmetry the radiated electric field is independent of azimuth variable Φ and the resulting field components are:

$$E_\rho = \frac{1}{j\omega\mu\varepsilon_0}\frac{\partial^2 A_z}{\partial\rho\partial z} \tag{2}$$

$$E_z = \frac{1}{j\omega\mu\varepsilon_0}\frac{\partial^2 A_z}{\partial z^2} - j\omega A_z \tag{3}$$

The z-component of the magnetic vector component can be expressed by the following particular integral [20]:

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$$A_z = \frac{\mu}{4\pi}\int_h^{h+L} g(x,z,z')I(z')dz' \quad (4)$$

where $I(z')$ is the unknown current distribution along the vertical monopole, while $g(x,z,z')$ is the total Green function given by:

$$g(x,z,z') = g_0(x,z,z') + R_{TM}\, g_i(x,z,z') \quad (5)$$

where free space Green function is of the form:

$$g_0(x,z,z') = \frac{e^{-jkR}}{R} \quad (6)$$

the Green function arising from the image theory is given by:

$$g_i(x,z,z') = \frac{e^{-jkR^*}}{R^*} \quad (7)$$

where R is the distance from the source point on the vertical monopole in the air to the arbitrary observation point in air, while R^* is the distance from the source point on the image wire to the arbitrary observation point in free space.
R_{TM} is the reflection coefficient for transfer magnetic (TM) polarization.

$$R_{TM} = \frac{\underline{n}-\sqrt{\underline{n}}}{\underline{n}+\sqrt{\underline{n}}} \quad (8)$$

and $\underline{n}$ is given by:

$$\underline{n} = \frac{\varepsilon_{eff}}{\varepsilon_0} \quad (9)$$

The total tangential electric field on the PEC wire surface vanishes and the interface condition can be written, as follows:

$$E_z^{exc}(a,z) + E_z^{sct}(a,z) = 0 \quad (10)$$

where E_z^{exc} denotes the excitation function and E_z^{sct} is the related scattered field.
Combining equations (3) to (10) yields the Pocklington integro-differential equation for the single wire above a lossy ground:

$$E_z^{exc} = -\frac{1}{j4\pi\omega\varepsilon_0}\int_h^{h+L}\left[\frac{\partial^2}{\partial z^2}+k^2\right]g(z,z')I(z')dz' \quad (11)$$

Finally, in the analysis of Tesla's transmitter, the excitation function cannot be expressed in the form of electric field, as the equivalent antenna is neither illuminated by the plane wave, nor driven by the voltage generator.

Consequently, the left-hand side of the equation (11) vanishes and the integro-differential equation (11) becomes homogeneous:

$$-\frac{1}{j4\pi\omega\varepsilon_0}\int_h^{h+L}\left[\frac{\partial^2}{\partial z^2}+k^2\right]g(z,z')I(z')dz' = 0 \quad (12)$$

The vertical monopole antenna is excited by an ideal current generator with one terminal connected to the antenna and the other one grounded in the remote point. This type of excitation can be included into the integral equation scheme through the forced boundary condition applied at the down end of the wire:

$$I(0) = I_g \quad (13)$$

where I_g denotes the actual current generator.
Integral equation (12) contains the quasi-singular kernel due to the presence of differential operator [20]. This problem can be overcome by implementing the weak formulation of the problem and Galerkin-Bubnov indirect Boundary Element Method (GB-IBEM) [20].
Solving the homogeneous Pocklington equation the current distribution along the vertical monopole is obtained.

2.2 Electric Field Formulas

The complete electromagnetic field irradiated by the equivalent monopole antenna can be assessed knowing the current distribution along the wire.

Inserting the vector potential particular integral (4) into (2) yields the radial field component:

$$E_\rho = \frac{1}{j4\pi\omega\varepsilon_0}\int_h^{h+L} I(z')\frac{\partial^2 g(z,z',\rho)}{\partial\rho\partial z}dz' \quad (14)$$

which can be rearranged performing the integration by parts:

$$E_\rho = \frac{1}{j4\pi\omega\varepsilon_0}\left[\begin{array}{l}\displaystyle\int_h^{h+L}\frac{\partial I(z')}{\partial z'}\frac{\partial g_0(z,z',\rho)}{\partial\rho}dz' - \\ \displaystyle -\int_h^{h+L}\frac{\partial I(z')}{\partial z'}R_{TM}\frac{\partial g_i(z,z',\rho)}{\partial\rho}dz'\end{array}\right] \quad (15)$$

The axial z-component of the electric field is defined by equation (3) and (4), i.e. by the following expression:

$$E_z = -\frac{1}{j4\pi\omega\varepsilon_0}\int_h^{h+L}\left[\frac{\partial^2}{\partial z^2}+k^2\right]g(z,z',\rho)I(z')dz' \quad (16)$$

Performing the integration by parts (16) becomes:

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$$E_z = -\frac{1}{j4\pi\omega\varepsilon_0}\left[\begin{array}{l}\int\limits_h^{h+L}\frac{\partial I(z')}{\partial z'}\frac{\partial g_0(z,z',\rho)}{\partial z}dz' - \\ -\int\limits_h^{h+L}\frac{\partial I(z')}{\partial z'}R_{TM}\frac{\partial g_i(z,z',\rho)}{\partial z}dz' + \\ +k^2\int\limits_h^{h+L}I(z')g(z,z',\rho)dz'\end{array}\right] \quad (17)$$

The integrals in equations (15) and (17) contain quasi-singular kernel due to the presence of differential operator [20]. This quasi-singularity can be efficiently treated by the boundary element/finite differences approach [20].
It is worth noting that the model presented so far can be farther upgraded by taking into account the influence of the earth via the rigorous Sommerfeld integral approach instead of the simplified Fresnel reflection coefficient.

3. COMPUTATIONAL EXAMPLE

The electromagnetic radiation from the vertical monopole antenna representing the Telsa's transmitter is studied for the operating frequency f=150kHz. The antenna is energized by the unit current excitation, i.e.:

$$I_g = 1e^{j0} \quad (18)$$

Figure 2 shows the spatial current distribution along the vertical monopole antenna, while the related tangential electric field component radiated by the monopole for three different scenarios; wire in free space, wire above a PEC ground and wire above a imperfectly conducting half-space is shown in Fig 3. The current induced along the vertical monopole shows linear behavior and falls to zero at the free end of monopole satisfying the edge condition proposed by the thin wire approximation [20].

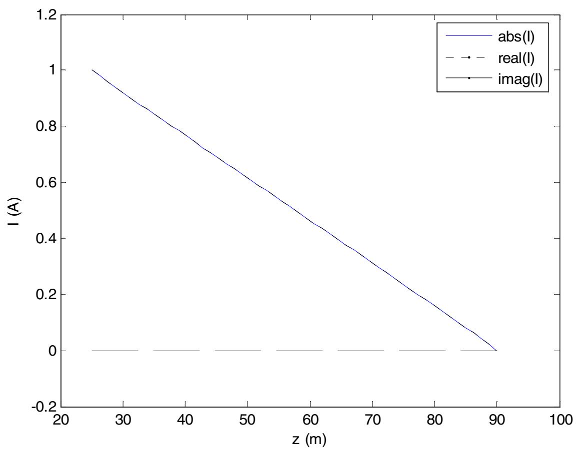
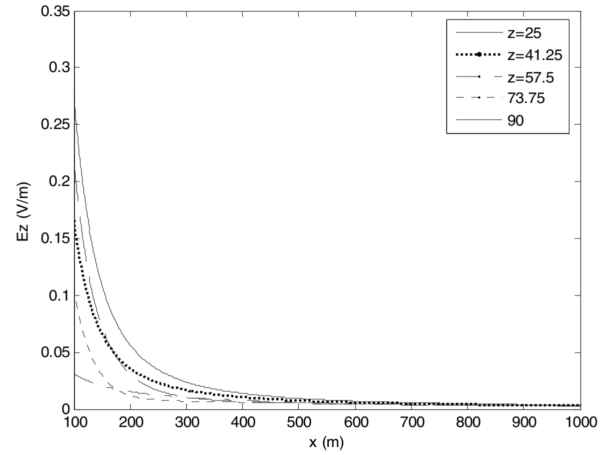
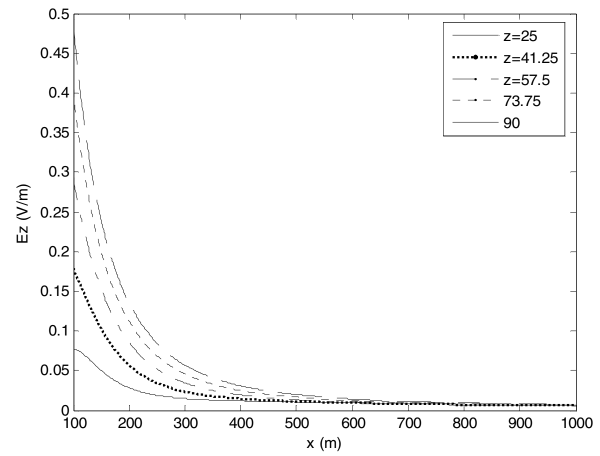


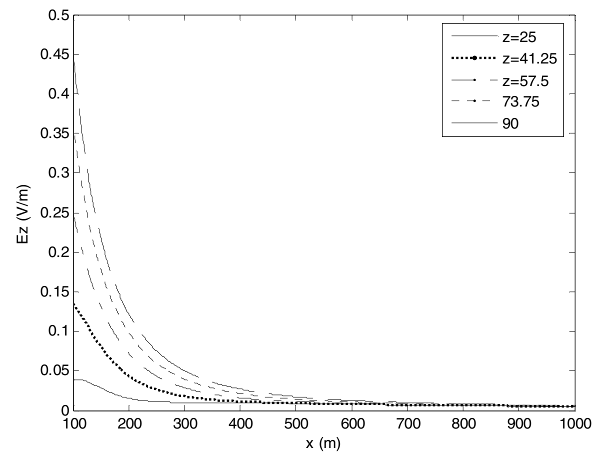
Figure 2 - Current distribution induced along the vertical monopole



a) Monopole in free space



b) Monopole above perfect ground



c) Monopole above imperfect ground

Figure 3 - Electric field at different heights for three different scenarios

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Analyzing all three scenarios from Fig 3 a rapid die-off for the z-component of the electric field, important for the antenna radiation, with distance is clearly visible.

These results further confirm the conclusion from the previous papers [18] and [19] that no significant (Hertzian) radiation occurs in the Tesla's transmitting system, i.e. no significant amount of electromagnetic energy is irradiated from the structure into the free space.

A very similar conclusion has been drawn in [7] in using the TL model has been used.

To a certain extent it is plausible to assume that Nikola Tesla, having designed his transmitter had obviously considered a propagation mechanism different from the one well-established by Heinrich Rudolph Hertz.

4. CONCLUSION

It was the very beginning of 20th century when great inventor Nikola Tesla, the scientist out of time, deeply believed he was heading to the development and design of communication and power wireless transmission using his *World System*. He never succeeded to get the sufficient financial support to work that out, and in spite of a number of proofs that he had made a significant contribution to the development of radio in its early phase the name of Nikola Tesla did not appear among six radio pioneers selected by the European Broadcasting Union in year 1996.

However, the spirit of his ideas continues to live on even through the work of researchers of today.

In this work a vertical monopole antenna model of the Tesla's transmitter has been developed. The radiating part of the Tesla's transmitter has been represented by an equivalent vertical monopole antenna above a real ground, excited by the ideal current source replacing the Tesla's transformer. The mathematical model is based on the frequency domain homogeneous Pocklington integro-differential equation. Solving the Pocklington equation numerically via the Galerkin Bubnov variant of the Indirect Boundary Element Method (GB-IBEM) current distribution along the vertical monopole is determined. Knowing the current distribution along the vertical monopole the radiated electric field is computed by integrating the induced current along the wire. Analyzing the obtained numerical results for the antenna current and related field it can be concluded that no significant radiation in Hertzian sense occurs in the Tesla's transmitting system. In other words, no significant amount of electromagnetic energy is irradiated from the transmitter into the free space.

This fact in some sense maybe fosters the assumption that Tesla considered some different propagation mechanism while having considered his transmitter. This work is a direct extension of the previous work on the subject that dealt with the simplified version of the monopole in free space by which the Tesla's transmitter was represented.

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