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51st Internationales Wissenschaftliches Kolloquium
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V. Javor, P. D. Rancic

One model for calculating the lightning generated electromagnetic field above real ground

INTRODUCTION

One model for numerical determining of electromagnetic field structure in frequency domain is proposed in this paper as the basis for modelling of electromagnetic field radiated during lightning discharge at the real ground. The following is adopted for the modelling procedure:

- lightning channel is modelled by a vertical monopole mast antenna;
- lightning return stroke current at the base of the channel, as an excitation, is modelled by a pulse $\delta-$generator of voltage U and frequency f; and
- the real ground is treated as homogeneous lossy half-space of known electrical parameters.

This model of the lightning discharge is used in order to include the influence of finite conductivity of the real ground. The structure of Lightning Electromagnetic Field (LEMF) in time domain can be obtained afterwards using Fast Fourier Transform (FFT). This kind of modelling is done because including real ground influence would be more complicated in calculations directly in time domain ([1], [2]).

A few steps are made in the procedure of obtaining general model. The first step is to adopt thin wire antenna model of lightning discharge channel. Then, for the chosen frequency $f \in [0.01 \div 10\,\mathrm{MHz}]$, the Unknown Current Distribution (UCD) along the antenna is determined. Because of the wide range of frequencies of interest, the total height of antenna is divided into segments for higher frequencies, while UCD-s of each segment satisfy conditions of current continuity at the ends/beginnings of segments and also current's first derivative continuity. The next step is to calculate electromagnetic field components in arbitrary field point in the air as the function of frequency, using definition relations.

UCD-s along the antenna are numerically determined using the Moments Method (MoM) for solving integral equations for the currents. System of integral equations of two potentials (SIE-TP) is used in this paper ([3]). Entire-domain polynomial approximation ([4]) is used for the UCD-s along the antenna segments with unknown complex current coefficients, which are determined by the Point Matching Method ([5]). Excitation is modelled by voltage $\delta-$generator located at the base of antenna, but all of the results in this paper are referred to the potential at the beginning of first segment V_{e1}, taken as $\mathrm{V}_{e1} = U + \mathrm{V}_{ground} = 1\mathrm{V}$.

The influence of finite ground conductivity is taken into account through Sommerfeld's integral kernel (SIK) in the relations for potentials (Hertz's vector potential and electrical scalar potential) and it is modelled in a new and simple way. This model of SIK gives solution of satisfactory accuracy in a certain range of distances from the antenna without limitations for ground electrical parameters values or antenna height. The model can be used in a wide range of electrical parameters ($\varepsilon_{r1} \in [0,81]$, $\sigma_1 \in [0,\infty]$, $\mu_1 = \mu_0$). This is particularly important for the higher frequencies ([6]).

The results in frequency domain are compared to the results from literature [4] and some to the results of available program packages for solving antenna problems above perfect ground [7].

The reliability of the results is analyzed in order to obtain field components in time domain using Fast Fourier Transform (FFT). That is going to be done in further investigations.

THEORETICAL BACKGROUND

The lightning current channel is approximated by vertical mast antenna above real ground, as illustrated in Fig. 1. The problem of lightning generated electromagnetic field can be solved if unknown current distribution along the antenna is determined. Antenna having total length h is divided into N segments, each of length l_k, such that $h = l_1 + l_2 + ... + l_N$. Thin wire approximation is used if radius $a << l_k$ and $a << \lambda_0$ (λ_0 – wavelength in the air). Antenna is excited in its base by $\delta-$generator of voltage U and frequency f.

Entire-domain polynomial approximation is used, so the unknown current distribution along the axis of the $k-$th segment is $\underline{I}_k(s_k') = \sum_{m=0}^{M_k} \underline{I}_{mk} (s_k'/l_k)^m$, $0 \le s_k' \le l_k$, $z_k' = z_{\mathrm{A}k} + s_k'$, $z_{\mathrm{A}k}$ – the beginning of the $k-$th segment, and $\underline{I}_{mk}$, $k = 1, 2, ..., N$, the unknown current complex coefficients.

Distributed impedance along the $k-$th segment is $\underline{Z}_k'(s_k') = \text{const}$, for $k = 1, 2, ..., N$. The upper half-space is air with electrical parameters ε_0, μ_0 and $\sigma_0 = 0$, and the lower half-space is ground, treated as linear, isotropic and homogeneous medium, with known parameters $\varepsilon_1 = \varepsilon_{r1}\varepsilon_0$, $\mu_1 = \mu_0$ and σ_1.

Complex conductivity is defined as $\underline{\sigma}_i = \sigma_i + \mathrm{j}\omega\varepsilon_i$, for $\omega = 2\pi f$, and complex propagation constant as $\underline{\gamma}_i = \alpha_i + \mathrm{j}\beta_i = \sqrt{\mathrm{j}\omega\varepsilon_i \underline{\sigma}_i}$, for i=0, 1. The refraction index is $\underline{n}_{10} = \underline{\gamma}_1 / \underline{\gamma}_0 = \sqrt{\underline{\varepsilon}_{r1}} = \sqrt{\varepsilon_{r1} - \mathrm{j}60\sigma_1\lambda_0}$.

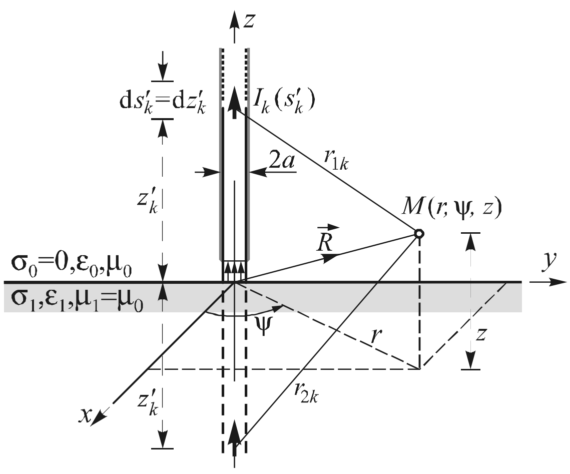

Fig. 1 Antenna model of lightning channel current and geometry of the problem

The system of integral equations of two potentials (SIE-TP) can be used for solving different antenna and grounding problems. Using general formulation of the SIE-TP different excitation models can be included and also distributed or coating impedances of the antenna. The SIE-TP can be written for any wire structure in the presence of inhomogeneous medium if:

- excitation of wire structure is harmonic generator;
- inhomogeneity can be modelled with a finite number of homogeneous domains;
- it is possible to determine the total tangential component of Hertz's vector and electrical scalar potential at the surface of the $n-$th conductor in the domain where the $n-$th conductor of the wire structure is positioned.

The SIE-TP can be written in the following implicit form

$$\underline{\gamma}_0 \int_{s=0}^{s_n} \varphi_0(s)\,\mathrm{ch}\left[\underline{\gamma}_0(s_n - s)\right]\mathrm{d}s + \underline{\gamma}_0^{\,2} \int_{s=0}^{s_n} \Pi_{z0}(s)\,\mathrm{sh}\left[\underline{\gamma}_0(s_n - s)\right]\mathrm{d}s +$$

$$+ \int_{s=0}^{s=s_n} \underline{Z}_n{}' \underline{I}_n(s)\,\mathrm{sh}\left[\underline{\gamma}_0(s_n - s)\right]\mathrm{d}s = \underline{V}_{en}\,\mathrm{sh}\left(\underline{\gamma}_0 s_n\right) + \int_{s=0}^{s=s_n} \left(\underline{\vec{E}}_{exn} \cdot \hat{s}_n\right)\mathrm{sh}\left[\underline{\gamma}_0(s_n - s)\right]\mathrm{d}s, \tag{1}$$

$$\varphi_0(s_n) + \underline{\gamma}_0 \int_{s=0}^{s_n} \varphi_0(s)\,\mathrm{sh}\left[\underline{\gamma}_0(s_n - s)\right]\mathrm{d}s + \underline{\gamma}_0^{\,2} \int_{s=0}^{s_n} \Pi_{z0}(s)\,\mathrm{ch}\left[\underline{\gamma}_0(s_n - s)\right]\mathrm{d}s +$$

$$+ \int_{s=0}^{s=s_n} \underline{Z}_n{}' \underline{I}_n(s)\,\mathrm{ch}\left[\underline{\gamma}_0(s_n - s)\right]\mathrm{d}s = \underline{V}_{en}\,\mathrm{ch}\left(\underline{\gamma}_0 s_n\right) + \int_{s=0}^{s=s_n} \left(\underline{\vec{E}}_{exn} \cdot \hat{s}_n\right)\mathrm{ch}\left[\underline{\gamma}_0(s_n - s)\right]\mathrm{d}s, \tag{2}$$

where: $\varphi_0(s)$ and $\Pi_{z0}(s)$ are electrical scalar potential and the resulting tangential component of Hertz's vector potential calculated at the surface of the $n-$th segment, respectively, $\underline{V}_{en}$ – the unknown integration constant, i.e. potential at the beginning of the $n-$th segment, $\vec{E}_{exn}$ – external electric field, and s_n – local coordinate along the generatrice of the $n-$th segment and $0 \le s \le s_n \le l_n$, for $n = 1, 2, ..., N$.

The Hertz's vector potential in arbitrary field point in the air is $\vec{\Pi}_0(\vec{r}) = \Pi_{z0}\hat{z}$, and calculated at the surface of the $n-$th segment it can be expressed as

$$\Pi_{z0}(s_n) = \frac{1}{4\pi\underline{\sigma}_0} \sum_{k=1}^{N} \int_{s_k'=0}^{l_k} I_k(s_k')\left[K_0(r_{1k}) + S_{00}{}^{v}(r_{2k})\right]\mathrm{d}s_k', \tag{3}$$

and electrical scalar potential, $\varphi_0(\vec{r}) = -\mathrm{div}\vec{\Pi}_0 = -\partial\Pi_{z0}/\partial z$, as

$$\varphi_0(s_n) = \frac{1}{4\pi\underline{\sigma}_0} \sum_{k=1}^{N} \int_{s_k'=0}^{l_k} I_k(s_k') \frac{\partial}{\partial s_k'}\left[K_0(r_{1k}) - S_{00}{}^{v}(r_{2k})\right]\mathrm{d}s_k', \tag{4}$$

where: r_{1k}, r_{2k} – the distances from the current element and its image to the matching point, respectively; $K_0(r_{1k}) = \exp(-\underline{\gamma}_0 r_{1k})/r_{1k}$ – the standard form of the potential kernel of the current element and $S_{00}{}^{v}(r_{2k})$ – the Sommerfeld's integral, i.e. semi-infinite integral with a very complex integrand,

$$S_{00}{}^{v}(r_{2k}) = \int_{\alpha=0}^{\infty} \tilde{R}_{z10}(\alpha)\,\tilde{K}_0(\alpha, r_{2k})\,\mathrm{d}\alpha, \tag{5}$$

where: $\tilde{R}_{z10}(\alpha) = \tilde{R}_{z10}(u_0) = (\underline{n}_{10}{}^2 u_0 - u_1)/(\underline{n}_{10}{}^2 u_0 + u_1)$ – the spectral reflection coefficient (SRC), $u_0 = \sqrt{\alpha^2 + \underline{\gamma}_0^{\,2}}$, $u_1 = \sqrt{\alpha^2 + \underline{\gamma}_1^{\,2}} = \sqrt{u_0^{\,2} + \underline{\gamma}_0^{\,2}(\underline{n}_{10}{}^2 - 1)}$ and $\tilde{K}_0(\alpha, r_{2k})$ – the spectral form of the standard potential kernel from the image in flat mirror,

$$K_0(r_{2k}) = \int_{\alpha=0}^{\infty} \tilde{K}_0(\alpha, r_{2k})\mathrm{d}\alpha = \int_{\alpha=0}^{\infty} \frac{\exp[-u_0(z+z_k')]}{u_0} \alpha J_0(\alpha r)\mathrm{d}\alpha = \exp(-\underline{\gamma}_0 r_{2k})/r_{2k}, \qquad (6)$$

where: $r_{1k} = [r^2 + (z - z_k')^2]^{1/2}$, $r_{2k} = [r^2 + (z + z_k')^2]^{1/2}$, and $J_0(\alpha r)$ – the Bessel's function of the first kind and zero order.

Simple new approximative model for the SRC is used in this paper, as in [6]. The SRC approximation is expressed as

$$\tilde{R}_{z10}(u_0) \cong B + A(\underline{\gamma}_0 / u_0), \qquad (7)$$

where A and B are the unknown constants that can be obtained matching (7) in points $u_0 = \underline{\gamma}_0$ and $u_0 \to \infty$. The following values are obtained for these constants:

$$B = \tilde{R}_{z10}(u_0 \to \infty) = (\underline{n}_{10}^{\ 2} - 1)\big/(\underline{n}_{10}^{\ 2} + 1) \qquad (8)$$

and

$$A = (\underline{n}_{10} - 1)\big/(\underline{n}_{10} + 1) - B. \qquad (9)$$

Substituting (7) in (5), approximate solution of the Sommerfeld's integral is obtained

$$S_{00}^{\ v}(r_{2k}) \cong BK_0(r_{2k}) + A\underline{\gamma}_0 L(r_{2k}), \qquad (10)$$

where $L(r_{2k})$ is the new integral kernel, calculated as in [6].

In this paper SRC is approximated by coefficient B and better approximation of SRC using also coefficient A and consequently both terms of expression (10) is going to be used in further investigations.

NUMERICAL MODEL DESCRIPTION

Explicit form of the SIE-TP for UCD-s is obtained if (10) is substituted in (3) and (4), and then those in (1) and (2). The unknown integration constants V_{en}, $n = 1, 2, ..., N$, are: $\mathrm{V}_{e1} = U + \mathrm{V}_{ground} = 1\mathrm{V}$, and the rest ($N-1$) satisfy $N-1$ conditions for the potential continuity at the joints of the segments. The UCD-s along segments are approximated by polynomials, so there are $N_u = \sum_{k=1}^{N}(1+M_k)$ unknown current coefficients, which are determined as solution of algebraic equations system obtained by matching SIE-TP (1) in N_u points.

Input admitance Y_{ul} and input impedance Z_{ul}, referred to the potential of excitation point V_{e1}, are defined by the following relation

$$Y_{ul} = G_{ul} + jB_{ul} = 1/Z_{ul} = I_1(0^+)/V_{e1}. \qquad (11)$$

On the basis of this numerical model program package in FORTRAN is realized for the PC numerical calculations. In order to check the reliability of the model many numerical experiments are made, and some results are presented in the following paragraph.

NUMERICAL RESULTS

For the polynomial degree M_k of $k-$th segment current approximation it is usually enough to choose $2 \le M_k \le 4$ for the length $l_k \le 0.50\lambda_0$. In the case of a very long antenna, according to the wave-length, as for the approximation of lightning channel current, the antenna should be divided into segments of length $l_k \le 0.50\lambda_0$, and the conditions $a << l_k$ and $a << \lambda_0$ should also be satisfied.

The results for the input admittance of monopole antenna having total length $h = \lambda_0/4$ or $\lambda_0/2$ and radius $a = 0.007022\lambda_0$, above perfectly conducting ground, for different number of antenna segments N=1, 2 and 3, are presented in Table 1. The results are in good agreement with the results from [4].

Table 1. Input admittance of monopole antenna above perfectly conducting ground for lengths $h = \lambda_0/4$ and $\lambda_0/2$; radius $a = 0.007022\lambda_0$; number of segments N=1, 2 and 3.

$Y_{ul} = G_{ul} + \mathrm{j}B_{ul}$ (mS)						
	$h = 0.25\lambda_0$			$h = 0.50\lambda_0$		
	M=2	M=3	M=4	M=2	M=3	M=4
N=1	18.31-j7.14	18.32-j7.11	17.61-j6.61	1.96+j3.08	1.93+j3.16	1.94+j3.33
N=2, $l_k = h/N$; k=1,2	18.20-j7.43	17.56-j6.89	17.16-j6.52	1.92+j3.10	1.95+j3.30	1.96+j3.60
N=3, $l_k = h/N$; k=1,2,3	17.82-j6.91	17.66-j6.75	17.07-j6.07	1.93+j3.27	1.96+j3.56	1.97+j3.97
Popovic [4]	18.32-j7.14	18.32-j7.10	17.62-j6.62	1.96+j3.08	1.92+j3.16	1.94+j3.34
Mack (measured)	17.80-j6.92			2.04+j3.36		

The influence of the distributed resistance R' along the lightning channel on the input admitance/impedance of equivalent antenna is presented in Table 2. It can be noticed that the influence on the current distribution and consequently on the input admittance/impedance is not so great for the values of $R' < 10\Omega/\mathrm{m}$. The results are compared to the results of program package AWAS [7].

Table 2. Input admittance and impedance of monopole antenna above perfectly conducting ground for length $h = \lambda_0/2$, radius $a = 0.007022\lambda_0$, different resistance R' per antenna unit length and polynomial degree M=3 per segment, compared to AWAS [7].

$h = 0.50\lambda_0$, $a = 0.007022\lambda_0$						
	$Y_{ul} = G_{ul} + \mathrm{j}B_{ul}$ (mS)			$Z_{ul} = R_{ul} + \mathrm{j}X_{ul}$ (Ω)		
	AWAS [7] $M=3, N=1$	M=3 $N=1$	$M_k=3,\ k=1,2$ $N=2$	AWAS [7] $M=3, N=1$	M=3 $N=1$	$M_k=3,\ k=1,2$ $N=2$
$R'=0$	2.048+j3.244	1.9268+j3.1723	1.9483+j3.3181	139.2-j220.5	139.866-j230.280	131.590-j224.113
$R'=0.01\Omega/\mathrm{m}$	2.048+j3.244	1.9268+j3.1723	1.9483+j3.3181	139.2-j220.5	139.866-j230.276	131.590-j224.109
$R'=0.1\Omega/\mathrm{m}$	2.048+j3.244	1.9273+j3.1725	1.9487+j3.3184	139.2-j220.4	139.867-j230.240	131.591-j224.076
$R'=1\Omega/\mathrm{m}$	2.052+j3.246	1.9318+j3.1747	1.9531+j3.3206	139.2-j220.2	139.879-j229.876	131.605-j223.748
$R'=10\Omega/\mathrm{m}$	2.088+j3.264	1.9768+j3.1962	1.9963+j3.3424	139.1-j217.4	139.966-j226.307	131.710-j220.521
$R'=100\Omega/\mathrm{m}$	2.430+j3.438	2.3962+j3.3936	2.3979+j3.5443	137.1-j194.0	138.845-j196.636	130.949-j193.550
$R'=200\Omega/\mathrm{m}$	2.756+j3.598	2.7963+j3.5699	2.7786+j3.7276	134.2-j175.2	135.984-j173.604	128.549-j172.449

The results for input resistance and reactance for $h = \lambda_0/2$ and $h = \lambda_0/4$ monopole having radius $a = 0.007022\lambda_0$, above real ground, for different values of ε_{r1}, versus $\sigma_1\lambda_0$, for M=3 as the current approximation polynomial degree, are presented in Figs. 2 and 3.

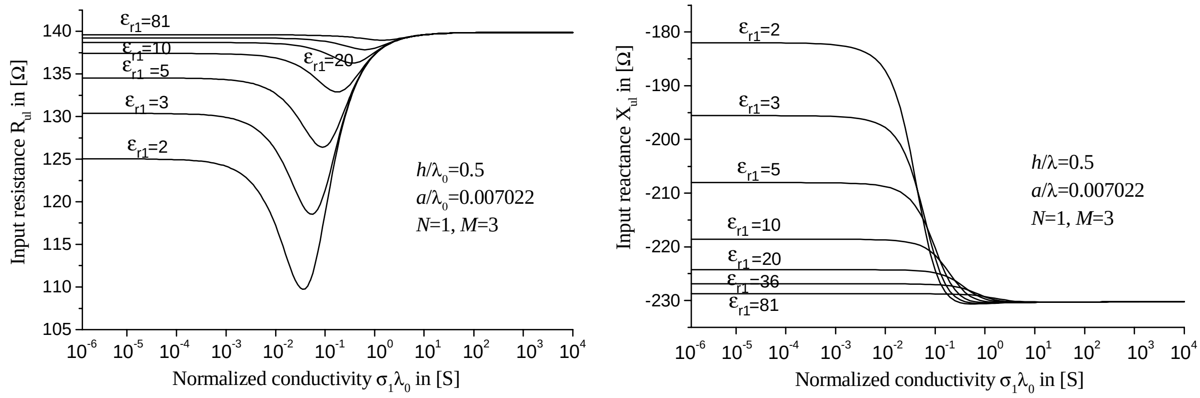

Fig. 2 Input resistance and reactance for $h = \lambda_0/2$ and different ε_{r1} versus $\sigma_1\lambda_0$.

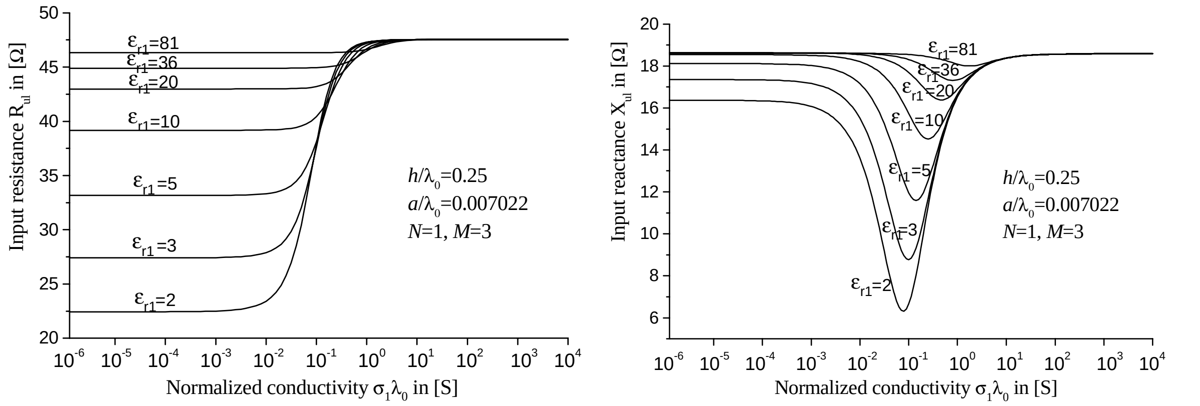

Fig. 3 Input resistance and reactance for $h = \lambda_0/4$ and different ε_{r1} versus $\sigma_1\lambda_0$.

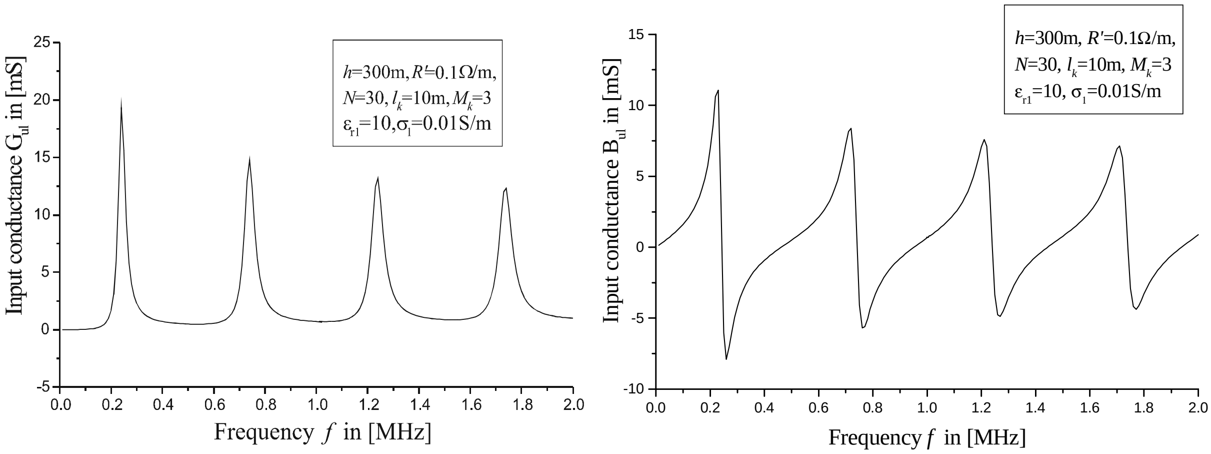

Fig. 4 Input conductance and susceptance for $h = 300\,\text{m},\ R' = 0.1\Omega/\text{m},\ N = 30,\ l_k = 10\,\text{m},\ M_k = 3,\ k = 1,...,N,$ for $\varepsilon_{r1} = 10$ and $\sigma_1 = 0.01\text{S/m}$, in the frequency range $0.01 \div 2\,\text{MHz}$.

The results for input conductance/susceptance for $h = 300\,\text{m},\ R' = 0.1\Omega/\text{m},\ N = 30,\ l_k = 10\,\text{m},\ M_k = 3,\ k = 1,...,N,$ for $\varepsilon_{r1} = 10$ and $\sigma_1 = 0.01\text{S/m}$, versus frequency, in the frequency range $0.01 \div 2\,\text{MHz}$ are presented in Fig. 4 and for input resistance/reactance in Fig. 5. Graphics are obtained for the frequency step $\Delta f = 10\,\text{kHz}$.

For antenna parameters $h = 300\,\text{m},\ a = 0.05\,\text{m},\ N$=30 segments, polynomial degree $M_k = 3,\ k = 1,...,30$ and $f = 3\,\text{MHz}$, the results for the real and imaginary part of current along the antenna versus z'/h are presented in Fig. 6 for ground parameters $\varepsilon_{r1} = 2$ and $\varepsilon_{r1} = 10,$ for $\sigma_1 = 10^{-1}\,\text{S/m}$ and $\sigma_1 = 10^{-5}\,\text{S/m}$.

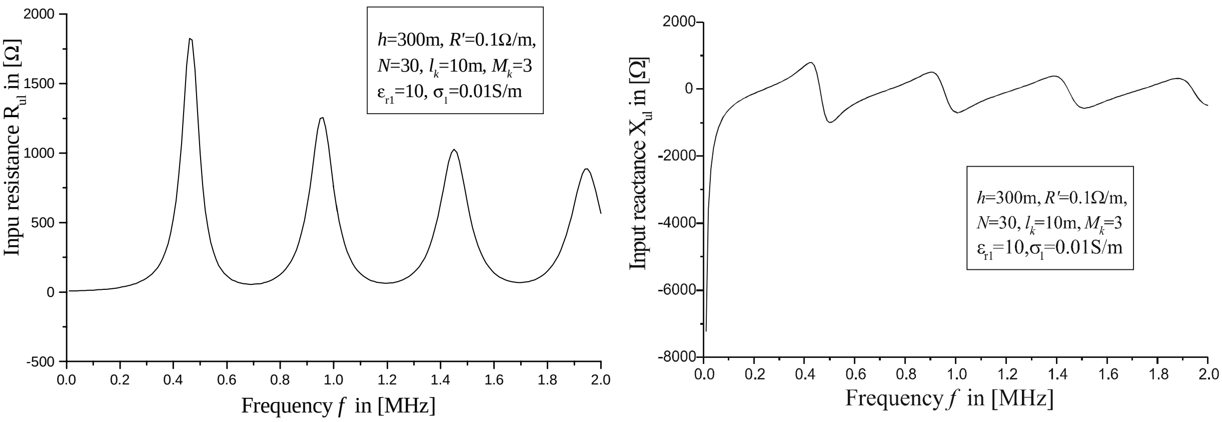

Fig. 5 Input resistance and reactance for $h = 300\,\mathrm{m}$, $R' = 0.1\Omega/\mathrm{m}$, $N = 30$, $l_k = 10\,\mathrm{m}$, $M_k = 3$, $k = 1,...,N$, for $\varepsilon_{r1} = 10$ and $\sigma_1 = 0.01\,\mathrm{S/m}$, in the frequency range $0.01 \div 2\,\mathrm{MHz}$.

Table 3. Input admittance and impedance of the mast antenna above real ground for $f = 3\,\mathrm{MHz}$, $h = 300\,\mathrm{m}$, $a = 0.05\,\mathrm{m}$, $R' = 0.01\Omega/\mathrm{m}$, M=3 per segment, $N = 10,20,30$ segments.

	$Y_{ul} = G_{ul} + \mathrm{j}B_{ul}$ (mS)			$Z_{ul} = R_{ul} + \mathrm{j}X_{ul}$ (Ω)		
	$M_k = 3$, $k = 1,...,N$ $N = 10$	$M_k = 3$, $k = 1,...,N$ $N = 20$	$M_k = 3$, $k = 1,...,N$ $N = 30$	$M_k = 3$, $k = 1,...,N$ $N = 10$	$M_k = 3$, $k = 1,...,N$ $N = 20$	$M_k = 3$, $k = 1,...,N$ $N = 30$
$\varepsilon_{r1} = 2$, $\sigma_1 = 10^{-5}$ S/m	1.46+j1.06	1.55+j1.13	1.61+j1.19	447.78-j327.05	420.88-j308.39	402.65-j297.52
$\varepsilon_{r1} = 2$, $\sigma_1 = 10^{-3}$ S/m	1.13+j1.03	1.13+j1.09	1.13+j1.14	485.19-j439.64	457.21-j440.75	439.27-j442.08
$\varepsilon_{r1} = 2$, $\sigma_1 = 10^{-1}$ S/m	1.14+j0.92	1.14+j0.95	1.14+j0.97	533.65-j430.77	518.68-j432.91	509.29-j434.25
$\varepsilon_{r1} = 10$, $\sigma_1 = 10^{-5}$ S/m	1.20+j0.94	1.22+j0.98	1.24+j1.01	516.03-j403.81	497.45-j398.77	485.25-j395.67
$\varepsilon_{r1} = 10$, $\sigma_1 = 10^{-3}$ S/m	1.17+j0.96	1.19+j1.01	1.19+j1.04	509.47-j417.99	488.86-j415.92	475.52-j414.87
$\varepsilon_{r1} = 10$, $\sigma_1 = 10^{-1}$ S/m	1.14+j0.92	1.14+j0.95	1.14+j0.97	533.64-j430.77	518.67-j432.90	509.28-j434.24

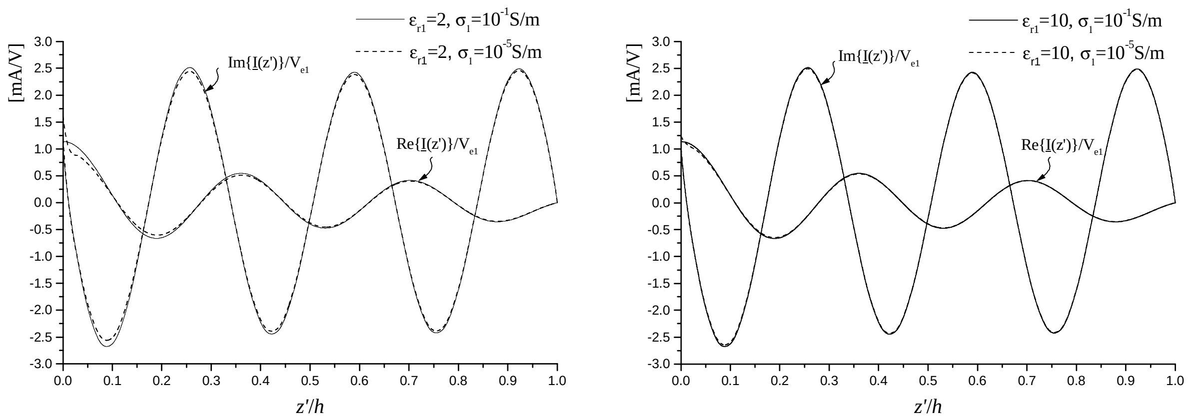

Fig. 6 Real and imaginary part of the current versus z'/h for $\sigma_1 = 10^{-1}\,\mathrm{S/m}$ and $10^{-5}\,\mathrm{S/m}$, $\varepsilon_{r1} = 2$ and 10; for $f = 3\,\mathrm{MHz}$, $h = 300\,\mathrm{m}$, $a = 0.05\,\mathrm{m}$, $R' = 0.1\Omega/\mathrm{m}$, $N = 30$ and $M_k = 3$, $k = 1,...,30$.

Realized model presents basis for calculating lightning electromagnetic field above real ground for the distances where the used approximation is good. The results for electric field components E_z and E_y, for frequency $f = 3\,\mathrm{MHz}$, $\lambda_0 = 100\,\mathrm{m}$, at the distances $r \le 2.5\lambda_0$ from antenna basis, at ground surface, for the antenna parameters $h = 300\,\mathrm{m}$, $a = 0.05\,\mathrm{m}$, number of segments $N = 20$, 30 and 50, polynomial degree $M_k = 3$, $k = 1,...,N$, for real ground parameters $\varepsilon_{r1} = 10$ and $\sigma_1 = 0.01\,\mathrm{S/m}$, are presented in Fig. 7. E_x component of the electric field at ground level is equal to zero.

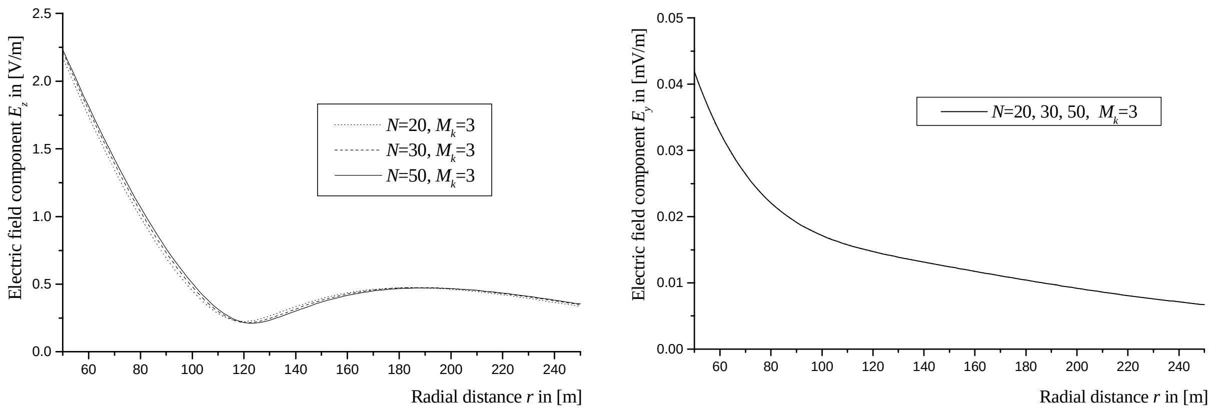

Fig. 7 Electric field components E_z and E_y at ground surface versus r, for $f = 3\,\mathrm{MHz}$, $h = 300\,\mathrm{m}$, $a = 0.05\,\mathrm{m}$, $N = 20, 30$ and 50, $M_k = 3$, $k = 1,...,N$, $\varepsilon_{r1} = 10$ and $\sigma_1 = 0.01\,\mathrm{S/m}$.

CONCLUSION

In this paper the analysis of vertical mast antenna above linear, isotropic and homogeneous ground for different number of antenna segments and different polynomial degree of the UCD approximation is presented. The SIE-TP for the UCD is numerically solved using the Point Matching Method. The validity of the output results (UCD and input impedance/admittance) of programs realized in Fortran is compared to the results from literature and other programs results ([4], [7]).

The results are presented for antenna length of several hundreds of metres and further calculations are aimed to longer antennas, for higher frequencies, i.e. to the lightning channel height values of $2600\mathrm{m}$ to $7000\mathrm{m}$, often used for lightning channel modelling. It should be noticed that for arbitrary height h the segmentation to N segments, needed for obtaining satisfactory results, depends on frequency and the segment length has to be $l_k \le \lambda_0/2$, for $k = 1,...,N,$ while satisfactory polynomial degree is then $M_k = 3$. Simple approximation of Sommerfeld's integral kernel is used in this paper. Coefficient that includes real ground influence can be used as $\tilde{R}_{z10}(u_0) \cong B$, but better results can be obtained for $\tilde{R}_{z10}(u_0) \cong B + A\underline{\gamma}_0 / u_0$ which is going to be investigated in further calculations.

This analysis is used for obtaining reliable model as the basis for calculating electromagnetic field radiated by a lightning discharge at real ground in time domain.

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