DETERMINATION OF CRITICAL ATMOSPHERIC ELECTRIC FIELD AROUND FRANKLIN'S LIGHTNING PROTECTION ROD THAT LEADS TO BREAK-DOWN

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SUMMARY

In this paper atmospheric electric field distribution is determined in the vicinity of the Franklin's lightning protection rod top which is modeled by half-spherical ending. Special emphasis is given to determination of critical atmospheric electric field that leads to break-down at the top of the rod. For the values of external atmospheric electric field that overcome critical value at the rod top, the corona occurs, so linear analysis is not valid any more. In this paper the first Laplace equation for potential is solved, for Franklin lightning protection rod approximated with one half of the prolate rotational ellipsoid in homogeneous earth atmospheric electric field, and the equation itself is solved in the coordinate system of prolate rotational ellipsoid. For that case, electric field along z-axis is determined and especially at the top of the rod. As numerical methods, method of subsections and finite element method are used and the comparison of these two methods is given.

Keywords: *Metod of Segments (MS), Finite Element Method (FEM), Laplace equation, Perfect conductive materials (PEC), Charge Simulation method (CSM),Point Matching Method (PMM)*

1. INTRODUCTION

Lightning discharge has impressed people since ancient times. Almost no other natural phenomenon has influenced people more than magnificent lightning and thunder. Thunderstorms were expected with fear, as they brought lightning with fire, killing and devastation. In the beginning, man has feared and characterized them as not natural. Fear and devastation made people looking for lightning protection in caves and other natural shelters. With development of science and techniques men have understood the phenomenon and the lightning protection became necessary. That protection concerns people, industrial objects with flammable substances, residencies etc. Atmospheric discharge have been studied for a long time and explained with different and some even opposite theories. First theories, from XVII century, explained the lightning discharge phenomenon so that higher cloud falls to the lower, compresses the air and such develops heath, followed with light and blast. At the beginning of XVIII century atmospheric discharge was explained chemically as burning of sulphurous and fat vapours from the earth surface. In the middle of XVIII century the electrical nature of lightning was discovered. Benjamin Franklin noticed many similarities between lightning discharge and electrical sparkle. His experiments were carried out with dragon as a toy. Experiments carried out in that time showed that conductive sphere with metal needle can not be charged up to high voltages (edge effect) which later led to development of lightning rod as protection from lightning discharge. In the middle of XIX century Maxwell proposed lightning protection using Faraday's cage. Recently, this idea is used for protection of lines and cities. There are also other ways of protection.

Typical value of atmospheric electric field, during nice summer day in our region is about 150 V/m, while during thunderstorm this value varies from 5 to 10 kV/m. In plane regions, usually positive charge is on the top of the cloud, while on the bottom of the cloud is negative. That negative cloud's charge induces positive charge on the earth's surface, making thus capacitor that discharges under some circumstances, as lightning. It is well known that 90% of discharges are negative, while at high mountains, there are also positive discharges. Having that in mind, it is supposed in this paper that electric field is vertical and upwards [1-5].

2. PROLATE ROTATIONAL ELLIPSOID COORDINATE SYSTEM

Let the Franklin's rod be modelled with half of perfectly conducting prolate rotational ellipsoid and let it be in the earth's atmospheric electric field as in Fig. 1. Between orthogonal coordinates, x, y, z and coordinates, u, v, w of prolate rotational ellipsoid, there are relations:

$$\begin{aligned} x &= c\,\mathrm{sh}(u)\sin(v)\cos(w), \\ y &= c\,\mathrm{sh}(u)\sin(v)\sin(w), \\ z &= c\,\mathrm{ch}(u)\cos(v). \end{aligned} \tag{1}$$

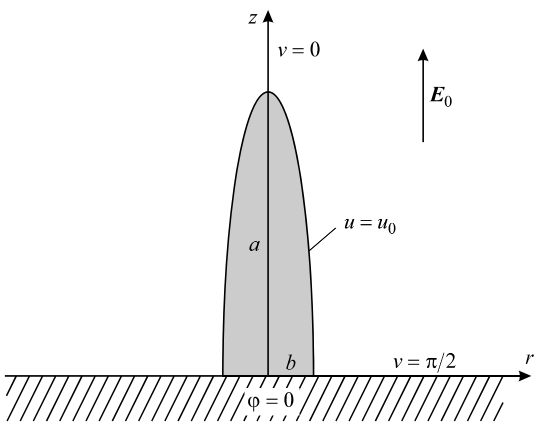


Fig. 1 Lightning protection rod model.

Cylindrical coordinates r, z, can be calculated as $r = c\,\mathrm{sh}(u)\sin(v)$ and $z = c\,\mathrm{ch}(u)\cos(v)$, so, for $z \geq 0$

$$\mathrm{ch}(u) = \sqrt{\frac{r^2 + z^2 + c^2 + \sqrt{\left(r^2 + z^2 - c^2\right)^2 + 4r^2c^2}}{2c^2}}, \quad (2)$$

$$\mathrm{sh}(u) = \sqrt{\frac{r^2 + z^2 - c^2 + \sqrt{\left(r^2 + z^2 - c^2\right)^2 + 4r^2c^2}}{2c^2}}, \quad (3)$$

$$\cos(v) = \sqrt{\frac{r^2 + z^2 + c^2 - \sqrt{\left(r^2 + z^2 - c^2\right)^2 + 4r^2c^2}}{2c^2}}, \quad (4)$$

$$\sin(v) = \sqrt{\frac{c^2 - r^2 - z^2 + \sqrt{\left(r^2 + z^2 - c^2\right)^2 + 4r^2c^2}}{2c^2}}. \quad (5)$$

At large distances from the origin, where these equations become $2r \approx c\,\mathrm{e}^u \sin(v)$ and $2z \approx c\,\mathrm{e}^u \cos(v)$, so that $R = \sqrt{r^2 + z^2} \approx \dfrac{c\,\mathrm{e}^u}{2}$, coordinate surfaces in coordinate system of prolate rotational ellipsoid (Fig. 2) are:

a) Confocal prolate rotational ellipsoids which are described by equation

$$\frac{x^2 + y^2}{c^2\,\mathrm{sh}^2(u)} + \frac{z^2}{c^2\,\mathrm{ch}^2(u)} = 1,\ 0 \leq u < \infty \quad (6)$$

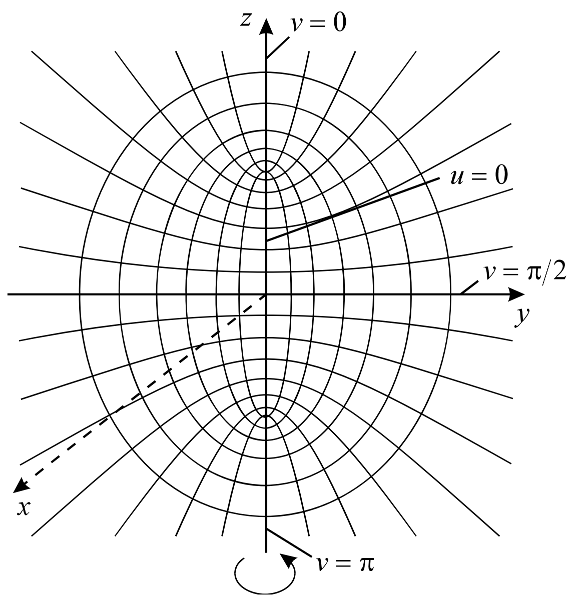


Fig. 2 Prolate rotational ellipsoid coordinate system.

(Half-axes of these ellipsoids are: $a = c\,\mathrm{ch}(u) \geq b = c\,\mathrm{sh}(u), c^2 = a^2 - b^2$. For $u = 0$ all these ellipsoids degenerate to lines $x = y = 0$, $-c \leq z \leq c$, and when u becomes great, to spherical surface of radius $cu^2/2$, with a centre in the coordinate origin.);

b) Confocal two-brand rotational hyperboloids with equation

$$\frac{z^2}{c^2\cos^2(v)} - \frac{x^2 + y^2}{c^2\sin^2(v)} = 1,\ 0 \leq v \leq \pi \quad (7)$$

(When $v = 0$, i.e. $v = \pi$, these hyperboloids degenerate to half-lines $x = y = 0,\ z \geq c$, i.e. $x = y = 0,\ z \leq -c$, and when $v = \pi/2$ to the plane $z = 0$.); and

c) Half-planes that lean on $z-$axis

$$w = \arctan\left(\frac{y}{x}\right),\ 0 \leq w < 2\pi. \quad (8)$$

Lame's coefficients are:

$$h_u = h_v = c\sqrt{\mathrm{sh}^2(u) + \sin^2(v)} \ \text{ and } \ h_w = c\,\mathrm{sh}(u)\sin(v). \quad (9)$$

3. POTENTIAL AND ELECTRIC FIELD

If the rod is approximated by upper half of the prolate rotational ellipsoid, with half-axes a and b, $a \geq b$, of eccentricity $c = \sqrt{a^2 - b^2}$, then potential, φ, in the vicinity of the rod is a solution of the Laplace equation

$$\frac{1}{\mathrm{sh}(u)}\frac{\partial}{\partial u}\left[\mathrm{sh}(u)\frac{\partial\varphi}{\partial u}\right] + \frac{1}{\sin(v)}\frac{\partial}{\partial v}\left[\sin(v)\frac{\partial\varphi}{\partial v}\right] = 0 \quad (10)$$

which is equal to zero at its surface, and at great distances tends to the value of potential of excitation atmospheric electric field,

$$\lim_{u\to\infty}\varphi = -E_0\,z = -cE_0\,\mathrm{ch}(u)\cos(v). \quad (11)$$

So, the potential, φ, is obtained

$$\varphi = -cE_0\cos(v)\left[\mathrm{ch}(u) - \mathrm{ch}(u_0)\frac{Q_1}{Q_{10}}\right], \quad (12)$$

where the equation of the ellipsoid surface is

$$u = u_0 = \ln\left(\frac{a+b}{c}\right) = \frac{1}{2}\ln\frac{a+b}{a-b},$$
$$\mathrm{ch}(u_0) = \frac{a}{c},\ \mathrm{sh}(u_0) = \frac{b}{c}, \tag{13}$$

and with

$$Q_1 = Q_1[\mathrm{ch}(u)] = \frac{\mathrm{ch}(u)}{2}\ln\left[\frac{\mathrm{ch}(u)+1}{\mathrm{ch}(u)-1}\right] - 1, \tag{14}$$

is denoted Legendre function of the second kind, Fig. 3, which at the rod surface, is

$$Q_{10} = Q_1[\mathrm{ch}(u_0)] = \frac{a}{2c}\ln\left(\frac{a+c}{a-c}\right) - 1$$
$$= \frac{a}{c}\ln\left(\frac{a+c}{b}\right) - 1. \tag{15}$$

Besides,

$$\lim_{u\to 0} Q_1 \approx \ln\left(\frac{2}{u}\right) - 1\Big|_{u\to 0} \to \infty \text{ and}$$

$$\lim_{u\to\infty} Q_1 \approx \frac{1}{3\,\mathrm{ch}^2(u)}\Big|_{u\to\infty} \approx \frac{4}{3}\mathrm{e}^{-2u}\Big|_{u\to\infty}$$
$$= \frac{c^2}{3(r^2+z^2)}\Big|_{r^2+z^2\to\infty} \to 0. \tag{16}$$

In Fig. 4 equipotential surfaces in the vicinity of the rod, for different slimnesses are presented.
Electric field components are:

$$E_u = -\frac{\partial\varphi}{h_u \partial u} =$$
$$= E_0 \frac{\cos(v)}{\sqrt{\mathrm{sh}^2(u) + \sin^2(v)}}\left[\mathrm{sh}(u) - \frac{Q_1'}{Q_{10}}\mathrm{ch}(u_0)\right]$$

and

$$E_v = -\frac{\partial\varphi}{h_v \partial v} =$$
$$= E_0 \frac{\sin(v)}{\sqrt{\mathrm{sh}^2(u) + \sin^2(v)}}\left[\mathrm{ch}(u) - \frac{Q_1}{Q_{10}}\mathrm{ch}(u_0)\right], \tag{17}$$

where

$$Q_1' = \frac{\partial Q_1}{\partial(\mathrm{ch}(u))}\frac{\partial(\mathrm{ch}(u))}{\partial u} =$$
$$= \frac{\mathrm{sh}(u)}{2}\ln\left[\frac{\mathrm{ch}(u)+1}{\mathrm{ch}(u)-1}\right] - \frac{\mathrm{ch}(u)}{\mathrm{sh}(u)} \tag{18}$$

and

$$Q_{10}' = Q_1'(u = u_0) = \frac{b}{2c}\ln\left(\frac{a+c}{a-c}\right) - \frac{a}{b} =$$
$$= \frac{b}{c}\ln\left(\frac{a+c}{b}\right) - \frac{a}{b}. \tag{19}$$

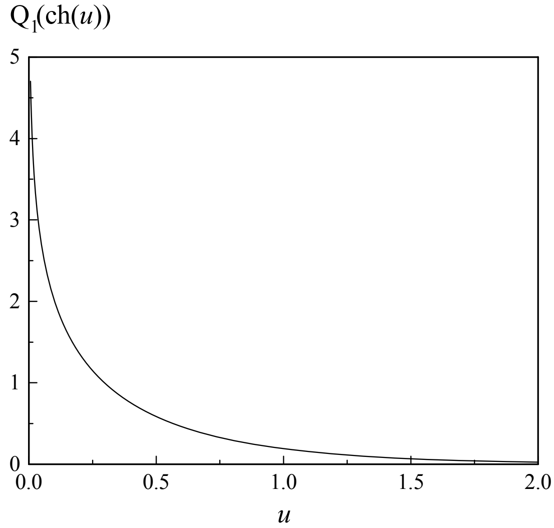
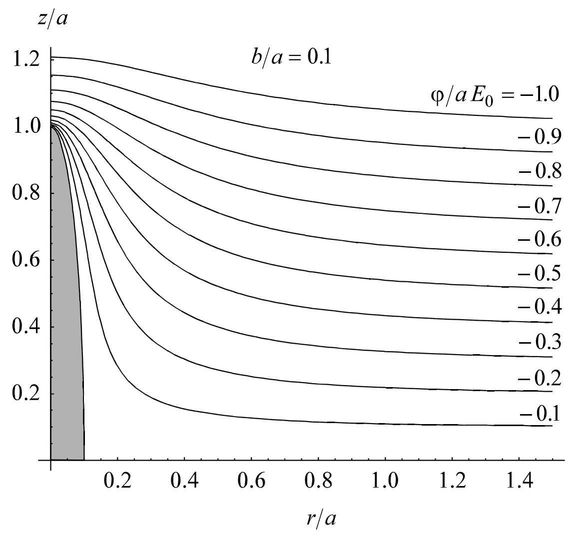
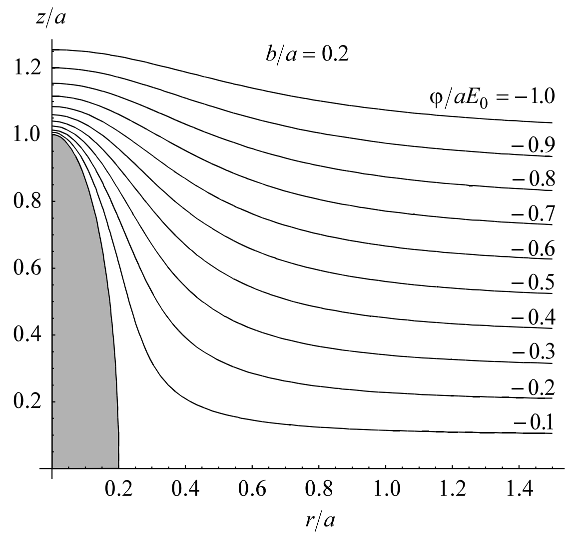


Fig. 3 Legendre function of the second kind.



a)



b)

Fig. 4 Equipotentials in the vicinity of rods for different slimness.

At $z-$axis is $r=0$, $v=0$, $\mathrm{ch}(u)=z/c$ and electric field has only axial component,

$$E_z = E_0\left[1-\frac{Q_1'}{Q_{10}}\frac{\mathrm{ch}(u_0)}{\mathrm{sh}(u)}\right]= \\ = E_0\left\{1-\frac{\mathrm{ch}(u_0)}{Q_{10}}\left[\frac{1}{2}\ln\left(\frac{z+c}{z-c}\right)-\frac{zc}{z^2-c^2}\right]\right\},\ z\geq a. \quad (20)$$

If $\xi = z/a$, then this field can be presented as

$$E_z = E_0\left\{\frac{1}{2\sqrt{1-\beta^2}}\ln\left(\frac{1+\sqrt{1-\beta^2}}{\xi+\sqrt{1-\beta^2}}\times\frac{\xi-\sqrt{1-\beta^2}}{1-\sqrt{1-\beta^2}}\right)+ \\ +\frac{\xi(1-\xi)+1-\beta^2}{\xi^2+\beta^2-1}\right\}\bigg/\left\{\frac{1}{2\sqrt{1-\beta^2}}\ln\left(\frac{1+\sqrt{1-\beta^2}}{1-\sqrt{1-\beta^2}}\right)-1\right\}, \quad (21)$$

for $\beta = b/a$.

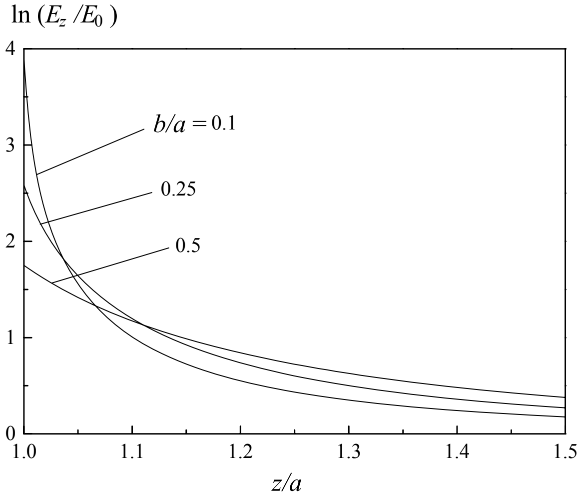


Fig. 5 Electric field along rod axis for different slimnesses.

The field is greatest at the rod top, for $z=a$, where the following expression is satisfied

$$E_s = E_z(z=a) = E_0\frac{c^2}{b^2\left(\frac{a}{2c}\ln\left(\frac{a+c}{a-c}\right)-1\right)}= \\ = E_0\frac{1-\beta^2}{\beta^2\left(\frac{1}{2\sqrt{1-\beta^2}}\ln\left(\frac{1+\sqrt{1-\beta^2}}{1-\sqrt{1-\beta^2}}\right)-1\right)}. \quad (22)$$

4. FRANKLIN'S ROD WITH HALF-SPHERICAL ENDING

Critical excitation atmospheric field, E_0, which leads to the beginning of break-down at the point A at the rod top (Fig. 6a and 6b), using method of segments, FEM and CSM combined with PMM in the potential rod points [6,7,8,12], is determined in this chapter. For half-spherical ending at the rod top, it is necessary to put one point charge at the centre of half sphere which adequately models the top of the rod, and the rod is segmented into a certain number of segments, Fig. 7.

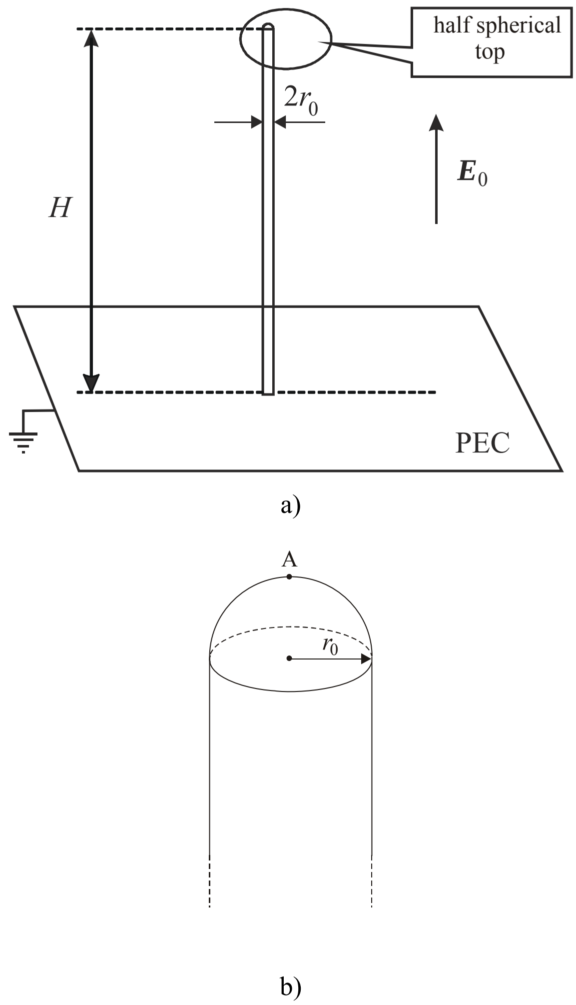


Fig. 6 Isolated Franklin's lightning protection rod.

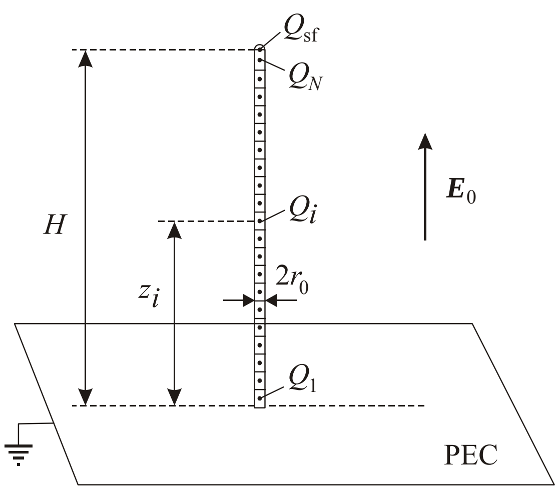


Fig. 7 Segmentation of the rod using method of segments.

Expression for potential is:

$$\varphi = -E_0 z + \sum_{i=1}^{N} \frac{Q_i}{4\pi\varepsilon_0} \left\{ \left(\frac{1}{\sqrt{r^2+(z-z_i)^2}} - \frac{1}{\sqrt{r^2+(z+z_i)^2}} \right) \right\} + \frac{Q_{sf}}{4\pi\varepsilon_0} \left(\frac{1}{\sqrt{r^2+(z-H)^2}} - \frac{1}{\sqrt{r^2+(z+H)^2}} \right), \quad (23)$$

where Q_i, Q_{sf} are unknown charges that have to be determined. As the break-down at rod top (point A) occurs for $E_{kr} = E_s = 3\,\mathrm{MV/m}$ (at normal atmospheric pressure and temperature about 27 ^{0}C), one equation more for electric field, at point A, has to be added to (23).

Matching potential (23) at N points at the rod surface and at point A at its top, as well as matching electric field (24) at the rod top (point A), the system of linear equations of order $(N+2)\times(N+2)$ is obtained, where Q_i^{k}, Q_{sf}^{k} and E_0^{k} are critical values

$$E_s = E_0 - \sum_{i=1}^{N} \frac{Q_i}{4\pi\varepsilon_0} \left\{ \left(\frac{1}{(H+r_0-z_i)^2} - \frac{1}{(H+r_0+z_i)^2} \right) \right\} - \frac{Q_{sf}}{4\pi\varepsilon_0} \left(\frac{1}{r_0^2} - \frac{1}{(2H+r_0)^2} \right). \quad (24)$$

of charge distribution along the rod, obtained under the action of critical excitation atmospheric electric field, E_0^{k}. It should be noticed that for $E_0 > E_0^{k}$ this analysis is not valid. In that case, around the top of the rod corona occurs with spacial charge and nonlinear effects, so further calculations become much more complicated. Obtained results, for E_0^{k}, will be presented in tables and commented in the conclusion.

Table I. Convergence of the results for E_0^{k} as the function of the number of segments.

$r_0/H = 3/600$			$r_0/H = 3/900$			$r_0/H = 3/1200$		
N	E_0^{k} [kV/m]	E_0^{k} (FEM)	N	E_0^{k} [kV/m]	E_0^{k} (FEM)	N	E_0^{k} [kV/m]	E_0^{k} (FEM)
50	21.717		50	14.110		50	10.216	
60	22.139		60	14.582		60	10.615	
70	22.383		70	14.938		70	10.947	
80	22.507		80	15.201		80	11.219	
90	22.553		90	15.391		90	11.440	
94	22.556		100	15.524		100	11.617	
100	22.547		110	15.613		110	11.757	
110	22.510		120	15.668		120	11.866	
120	22.453		130	15.698		130	11.949	
130	22.386		140	15.708		140	12.012	
140	22.312	22.549	142	15.709	15.701	150	12.058	12.123
150	22.237		150	15.705		160	12.089	
160	22.161		160	15.692		170	12.109	
170	22.088		170	15.671		180	12.121	
180	22.016		180	15.644		190	12.124	
190	21.948		190	15.614		191	12.125	
200	21.882		200	15.582		200	12.122	
-	-		-	-		210	12.116	
-	-		-	-		220	12.106	
-	-		-	-		230	12.093	
-	-		-	-		240	12.077	
-	-		-	-		250	12.061	

Using polynomial approximation for the charge per unit lenght along rod axis: $q'(z') = \sum_{m=1}^{M} A_m \left(\frac{z'}{H}\right)^m$, where A_m are unknown coefficients determined by matching integral equation for potential, i.e. solving the system of linear equations, very good results are obtained for E_0^{k} with $M = 3$ or 4. Of course, a better convergence of E_0^{k} is obtained regarding polynomial approximation degree, if polynomial approxiamtion of odd degree is used:

$$q'(z') = \sum_{m=1}^{M} A_m \left(\frac{z'}{H}\right)^{2m-1}, \quad (25)$$

what is logical, considering the nature of the problem.

It is also interesting to see what is obtained for E_0^{k} using equation (22) and taking into account $a = H + r_0$, $b = r_0$ and $E_{\mathrm{s}} = 3\,\mathrm{MV/m}$ (Table II).

Table II. Critical atmospheric electric field obtained according to (22).

E_0^{k} [kV/m]		
$r_0 / H = 3/600$	$r_0 / H = 3/900$	$r_0 / H = 3/1200$
0.371	0.179	0.106

As it can be seen from Table II, obtained values for E_0^{k} are much smaller than those obtained for the rod with half-spherical ending. Reasons should be found in the geometrical difference of the model, especially at the rod top. For given rod slimnesses, rotational ellipsoid that models the rod is more like a needle than in the case of half-spherical ending which drastically influences on results obtained for critical atmospheric electric field.

5. CONCLUSION

A theoretical derivation of expressions for electric field and potential distribution in the vicinity of an isolated Franklin's lightning protection rod installed at the earth surface is given in this paper. As a model, one half of rotational ellipsoid is used, placed in homogeneous atmospheric electric field. After that, especially Franklin's rod is examined, with the top of half-spherical shape. The authors of this paper have done calculations using different numerical methods and compared them. Obtained results have shown very good agreement for E_0^{k} using different methods. Very interesting results, obtained by method of segments, are given in Table I. When the number of segments increases, value of E_0^{k} also increases up to some maximal value, and after that decreases. It has been shown that, using FEM, the best values of E_0^{k} obtained using method of segments are those that give the maxima (in Table I framed values). The question is posed if there is an optimal number of segments which could in advance give reliable value for E_0^{k} without checking the convergence of the results as the function of segments number. Looking at the obtained results, for different slimnesses, authors noticed the rule which in their opinion presents original contribution. It turned out in sectioning of cylindrical structures (straight or curvilinear): an optimal number of segments is the number for which the length of cylindrical segment is equal to its thickness. Having this in mind, optimal segments number for all three slimnesses of the rod should be N=100, N=150 and N=200. Cylindrical structures with very high slimnesses require much more time for calculations.

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BIOGRAPHIES

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Saša S. ILIĆ was born in Niš, Serbia, on July 24, 1970. In 1990 he enrolled at the Faculty of Electronic Engineering, University of Niš, Serbia. He chose the electronics and telecommunications major and he received Dipl. Ing. degree in 1995 from the Faculty of Electronic Engineering of the University of Niš. From January 1998 up to now, he has engaged to the Department of Theoretical Electrical Engineering, at the Faculty of Electronic Engineering of the University of Niš. In 2001 he received M. Sc.-Dipl. Ing degree at the same Faculty. His researching areas are: lightning protection systems, low-frequency EM fields penetrated into human body and micro-strip transmission lines with isotropic, anisotropic and bianisotropic media.