LOW FREQUENCY ELECTRIC FIELD RADIATION LEVEL AROUND HIGH-VOLTAGE TRANSMISSION LINES AND IMPACT OF INCREASED VOLTAGE VALUES ON THE CORONA ONSET VOLTAGE GRADIENT

by

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In this article the summary of measurement and calculation values of low frequency electric field radiation around the high-voltage transmission lines and impact of the increased voltage values on the AC corona onset voltage gradient are presented. The measurements of the low frequency electric field radiation level were performed under the 400 kV transmission lines of horizontal configuration with standard and compact dimensions. In all cases analyzed in this article, the measurements are performed in the middle of the span, because at this point the conductors are closest to the ground. The analysis in this article has been initiated by the increased voltage values of long duration that have been registered in nodes of the 400 kV network in Bosnia and Herzegovina and the neighbouring countries during the last years. The calculation of the low frequency electric field radiation of the different configuration of the high-voltage transmission lines will be useful for determining the non-ionization radiation exposure levels of the general public in the future as well as to determine their impact on the AC corona onset voltage gradient.

Key words: non-ionization radiation, low frequency electric field, high voltage transmission line, AC corona, corona onset voltage gradient

INTRODUCTION

The low frequency (LF) electric fields radiation, generated from the high-voltage transmission lines is very important from the aspects of its influence on human beings and animal bodies, as well as its impact on surrounding objects and the environment. The high-voltage (HV) transmission lines are partially located in populated areas. In the general public, there is a socio-phenomena opinion about the negative influence of 'radiation' from different electric power objects, specifically the HV transmission lines. The exposure to LF electric field radiation may cause a well-defined biological response, ranging from the perception to the annoyance, through the surface electric-charge effects [1] as well as their impact on the surrounding objects (pipelines, telecommunication lines, *etc.*). In last couple of years several scientific articles have been published, in which the human dosimetry quantity for the LF electromagnetic field exposure was analyzed although the basic restrictions for human exposure to the time-varying LF electric field are well defined [1, 2]. The low frequency electric field radiation has an impact onto environment through the origin AC corona discharge. The formation of AC corona discharge due to the ionization of the air around the stranded conductor is caused by the increased values of power frequency voltage. The AC corona discharge has light effects, the electromagnetic interference (EMI), the audio noise (AN) and the ozone as well as the corona losses (CL). In the analyzed period (01.01.2010 up to 31.12.2017) the increased maximum values of voltage up to 439.95 kV (2017) were registered with the time duration in yearly percentage up to 71 % (2017). The registered increased voltage values are above the maximum permitted values of 420 kV.

It is well known that the value of the LF electric field radiation and the AC corona onset voltage gradient depends on the value of the applied voltage. This effect is especially emphasized for the HV objects (Power Plants – PP and Substations – SS) and transmission lines. In recent years, high voltage values in the 400 kV network of Bosnia and Herzegovina have been registered. This phenomenon is noticeable in all nodes of the 400 kV network in Bosnia and Herzegovina. Also, in some nodes of the 400 kV net-

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work, the maximum voltage values, as well as their duration, increase every year. This is caused by the construction of new production facilities and due to the domestic production of reactive energy with the contribution of interconnection transmission lines with neighbouring countries. Taking into account the tendency of increasing the voltage values and their duration during the year, it is very useful to know the values of the LF electric field radiation both due to the influence on human beings and from the aspect of the appearance of the AC corona discharge. The voltages above the permitted values adversely affect the insulation level of the equipment, the shortening of its lifetime, and at the same time increase power losses due to the AC corona. Using the measuring equipment and the mathematical model for the calculation of the LF electric field radiation it is possible to confirm the real values of electric field, including the measures for their mitigation.

THE MEASUREMENT OF THE LF ELECTRIC FIELD RADIATION

In this article, the horizontal arrangement of the stranded conductor of 400 kV transmission lines SS Sarajevo 10-SS Sarajevo 20 (standard dimensions) and SS Tuzla 4-SS Višegrad (compacted dimensions) and the single circuit with horizontal configuration are analyzed, fig. 1 [3, 4]. The stranded conductor of bundle, ACSR 2 485/63 mm^2 has the aluminum wire number equal to 54 while the steel wire number is 7. The diameter of the sub-conductor *d* is 30.42 mm and the diameter of the aluminum wire is 3.38 mm. The number of outer strand is 24 with bundle spacing equal to 400 mm.

The measurements of the LF electric field radiation were performed in the middle of the span. At these points the highest values of the LF electric field radiation are expected, because the position of the transmission line is the nearest to the ground. The measurement of the LF electric field radiation under the 400 kV transmission lines with standard and compact dimensions were performed on 1 m above the ground with two different measuring instruments. One instrument is maintained in a fixed position for recording the time variations of electric field and the other instrument is moved under the transmission line for recording the space variation [5, 6]. The measured values of the LF electric field radiation under the HV transmission lines are given in fig. 2. The measurements of the LF electric field radiation values are performed during 22.06.2014. and 23.06.2014, respectively [3].

Some uncertainty during the measuring of the LF electric field radiation may be caused by the temporal variation of the measured field in relation to the time constant of the field meter as well as the variation of the height of conductor during the measurement [7-9].

THE CALCULATION MODEL AND RESULTS

The values of the LF electric field radiation on the surface of the stranded conductor and its immediate vicinity as well as at 1 meter above the ground under the transmission lines were investigated in many researches and scientific papers [3, 10-12]. For the calculation of the LF electric field radiation on the surface of the stranded conductor and its immediate vicinity, the charge simulation method (CSM) was used [3]. For the purpose of the calculation, the height of the conductors and the ground wires above the ground in the middle of the span were used. These heights are de-

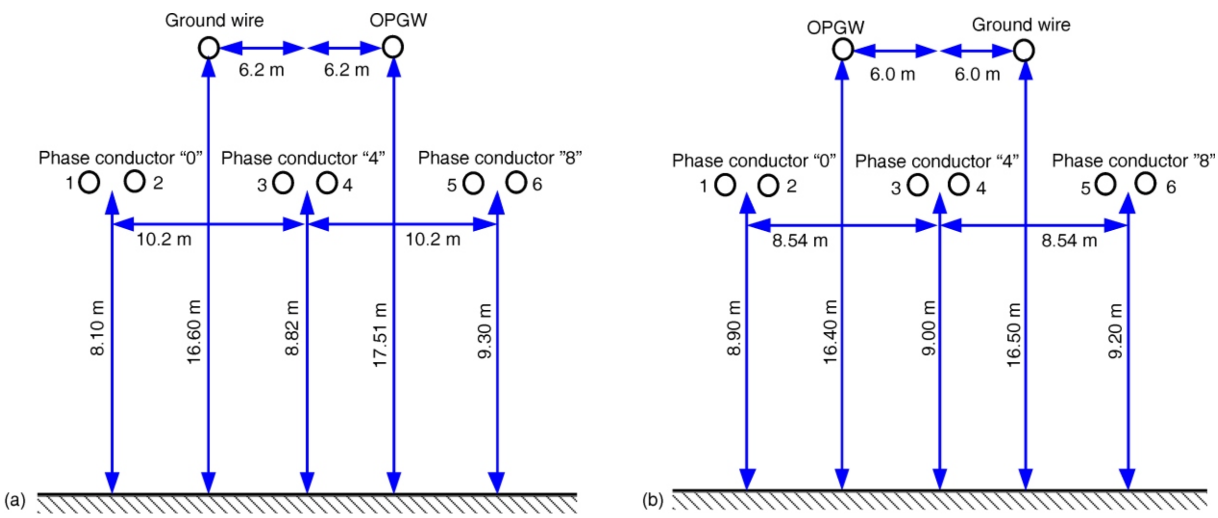

Figure 1. Three phase horizontal configuration of 400 kV transmission line with dimensions; (a) SS Sarajevo 10-SS Sarajevo 20, (b) SS Tuzla 4-SS Višegrad (OPGW – Optical ground wire, sub-conductors 1-6) [3, 4]

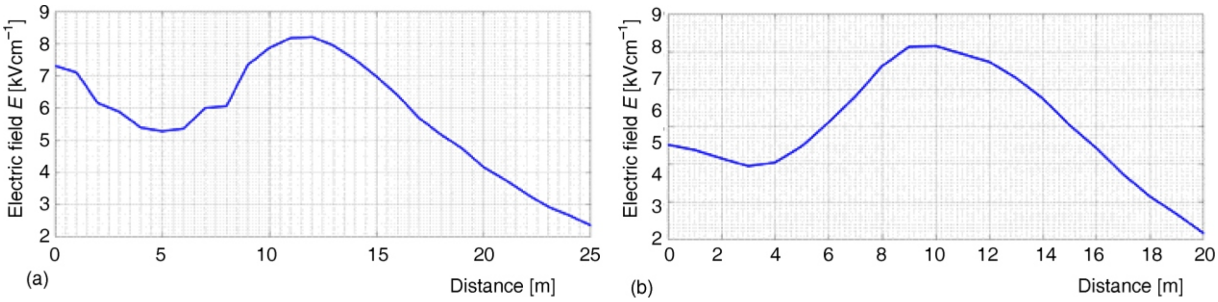

Figure 2. The measured LF electric field radiation at 1 m above the ground under the HV transmission line conductor; (a) SS Sarajevo 10-SS Sarajevo 20 (June 22, 2014), (b) SS Tuzla 4-SS Višegrad (June 23, 2014)

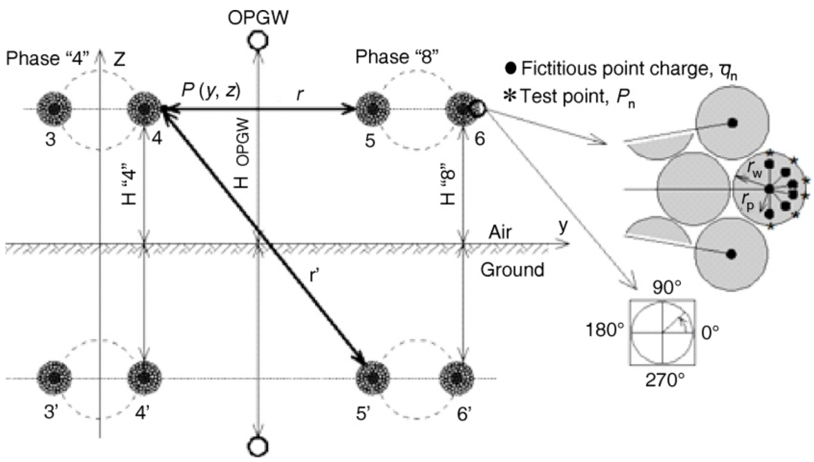

Figure 3. The central and the outer phases of three phase horizontal arrangement for the twin-bundle cylindrical stranded conductor and the charge representation [3] *(OPGW – Optical ground wire)*

termined by the measurements using a laser telemeter. The voltage values correspond to the voltage values at the time when the measurements of the LF electric field radiation were taken. The distributed charge of stranded conductor is modeled by the *n* fictitious point charges $\overline{q}_n$ in each outer stranded wire of the sub-conductor of bundle and placed uniformly in the semicircle within each wire with radius $r_p = 0.75\, r_w$, fig. 3. The fictitious point charges are placed outside the region where the field solution is desired. The test points, P_n, are placed on the surface of the wire. The influence of the soil surface is taken into account by using the reflection coefficient whose value is approximately equal to –1 [13].

The used mathematical model for calculating the value of the LF electric field radiation on the surface of stranded conductor and their immediate vicinity is given in [3]. This mathematical model was also used in [3] to calculate the LF electric field radiation under the transmission line at the height 1 meter above the ground. For the verification of the presented mathematical model, the results of the measurement values of LF electric field radiation under the high-voltage transmission lines SS Sarajevo 10-SS Sarajevo 20 and SS Tuzla 4-SS Višegrad were used [3]. The comparison of the measured and calculated values of the LF electric field radiation by the adopted mathematical model showed a good agreement because the difference does not exceed 1.4 %, thus confirming the credibility of the developed mathematical model [14].

The distribution of the calculated LF electric field radiation around the surface of the sub-conductor "6", phase "8" (a), and the LF electric field radiation distribution in immediate vicinity of the tip of the outer strand (b) for the transmission line SS Sarajevo 10-SS Sarajevo 20 and SS Tuzla 4-SS Višegrad are shown in figs. 4-5, respectively.

THE CORONA ONSET CRITERION

For the stranded conductor of the HV transmission lines, the determination of the conditions in which the AC corona onset criterion is based on the article by Yamazaki and Olsen [15]. The AC corona onset criterion take into account the distribution of the LF electric field radiation around the conductor surface and its immediate vicinity. Also, in the process of applying the AC corona onset criterion, it is necessary to take into account the characteristics of the transmission line, *i. e.*, the arrangement and the size of the stranded conductor as well as the atmospheric condition of the air around the conductor. For sub-conductor of the bundle, fig. 3 assumes the creation of $K(d)$ free electrons at the local position, $s = r_1 + d$, where r_1 is a surface of the conductor and d is the boundary where the ionization coefficient α equals the attachment coeffi-

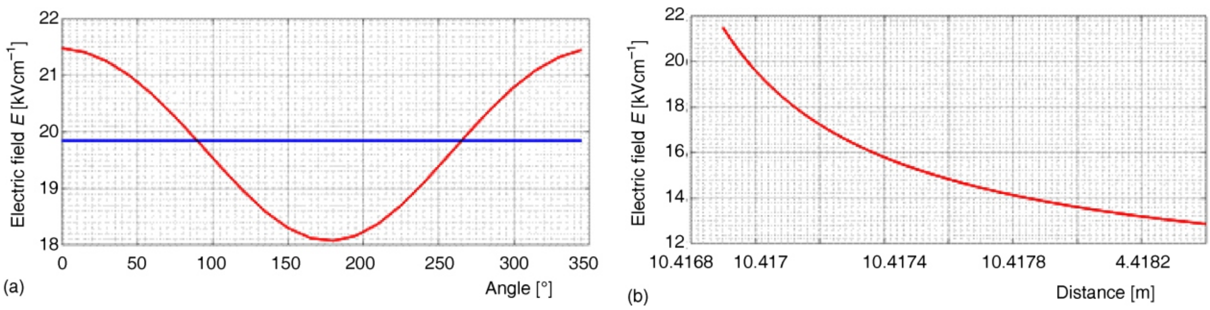

Figure 4. The transmission line SS Sarajevo 10 – SS Sarajevo 20; (a) the distribution of the LF electric field radiation around the surface of sub-conductor '6' of outer phase '8', (b) the distribution of the value of the LF electric field radiation near the tip of the outer strand of the sub-conductor '6' of outer phase '8'

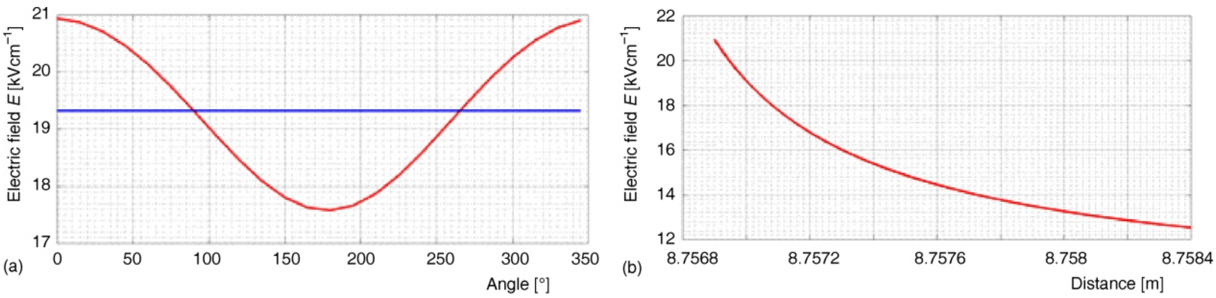

Figure 5. The transmission line SS Tuzla 4 – SS Višegrad; (a) the distribution of the LF electric field radiation around the surface of the sub-conductor '6' of outer phase '8', (b) the distribution of the value of the LF electric field radiation near the tip of the outer strand of the sub-conductor '6' of outer phase '8'

cient η, *i. e.*, no ionization can take place. When the electron obtains a sufficient kinetic energy, it collides with an air molecule and causes an initial electron avalanche [16, 17]. In the ionization region, the collision ionization coefficient α is greater than the electron attachment coefficient η. At the ionization boundary, $\alpha = \eta$, and the ionization process cease. In non-uniform field gap, the onset of a self-sustained discharge can be written as [15]

$$K(d) \quad \exp \int_{r_1}^{r_1 \ d} (\alpha \quad \eta)\mathrm{d}s \qquad (1)$$

This term is used as the *AC corona onset criterion*. The LF electric field radiation, for which the condition $\alpha = \eta$ is satisfied, is defined as the AC corona onset voltage gradient. The coefficients α and η are functions of the value of the LF electric field ($\mathrm{kVcm^{-1}}$), the temperature (t), the pressure (p) and the relative humidity of the air (h). The expression for α and η in the atmospheric air given by Sarma and Janischeskyj [18], was used for the AC corona onset voltage gradient [4]. On the basis of the experimental data for the ionization coefficient $\alpha/\delta = f(E/\delta)$ and the attachment coefficient $\eta/\delta = f(E/\delta)$ [18] and the calculated maximum values of the LF electric field radiation on the surface of the stranded conductor and its immediate vicinity, it is possible to determine the AC corona onset voltage gradient, fig. 6.

The highest value of the AC corona onset voltage gradient is 28.4924 $\mathrm{kV_{max}cm^{-1}}$, *i. e.*, 20.1477 $\mathrm{kV_{r.m.s.}cm^{-1}}$ for 400 kV transmission line SS Sarajevo 10-SS Sarajevo 20 and 28.4923 $\mathrm{kV_{max}cm^{-1}}$, *i. e.*, 20.1471 $\mathrm{kV_{r.m.s.}cm^{-1}}$ for 400 kV transmission line SS Tuzla 4-SS Višegrad.

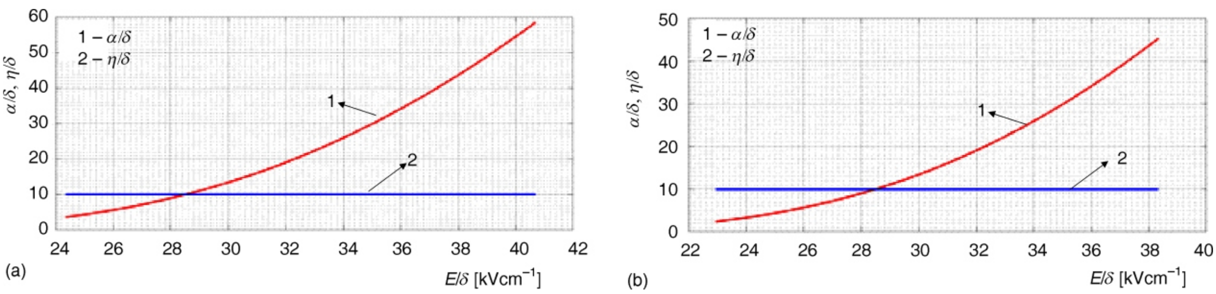

Figure 6. The ionization α/δ and the attachment η/δ coefficients as the function of E/δ on the surface of the stranded conductor and its immediate vicinity; (a) SS Sarajevo 10-SS Sarajevo 20, (b) SS Tuzla 4-SS Višegrad

Table 1. The comparison between the values using the mathematical model and the Peek's equation

400 kV transmission line	Voltage level [kV]	AC corona onset voltage gradient using mathematical model [$kV_{r.m.s.}cm^{-1}$]	AC corona onset voltage gradient using Peek equation [$kV_{r.m.s.}cm^{-1}$]	Difference [%]
SS Sarajevo 10 – SS Sarajevo 20	422.97 kV_{max} 244.21 $kV_{r.m.s.}$	20.1477	19.6 (δ_{20} = 0.914)	2.718
SS Tuzla 4 – SS Višegrad	417.20 kV_{max} 240.80 $kV_{r.m.s.}$	20.1471	19.7356 (δ_{20} = 0.941)	2.042

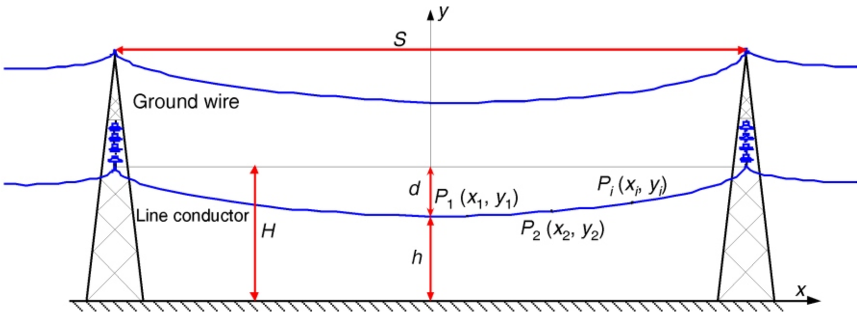

Figure 7. The longitudinal profile of 400 kV transmission line

In order to verify the obtained values of the AC corona onset voltage gradient using the developed mathematical model, the comparison is carried out with the effective values of the AC corona onset voltage gradient obtained from the widely used Peek's equation, [19]

$$E_0 \quad \frac{29.8}{\sqrt{2}} m\delta_{20} \quad 1 \quad \frac{0.301}{\sqrt{r\delta_{20}}} \quad [\mathrm{kV_{eff}cm}^{\ 1}] \tag{2}$$

where m is the roughness coefficient which takes into account the conductor surface condition ($m = 0.79$), r – the radius of the stranded conductor in cm (r = 1.57 cm), δ – the coefficient which takes into account the air pressure p and the temperature t of the surrounding air by equal

$$\delta_{20} \quad \frac{p(273 \quad t_0)}{p_0(273 \quad t)} \tag{3}$$

where p_0 is the reference air pressure 760 mmHg and t_0 is the reference air temperature 20 °C [20].

The comparison between the values of the AC corona onset voltage gradient using the mathematical model and the values using Peek's equation are given in tab. 1.

THE IMPACT OF THE CONDUCTOR'S HEIGHT ONTO THE VALUE OF THE LF ELECTRIC FIELD

For the calculation of the dependence of the LF electric field radiation on the surface of the stranded conductor and its immediate vicinity from the conductor's height, the sag calculation for the supports at equal levels as simple one are used, fig. 7. The position of the points $P_i(x_i, y_i)$ is determined from the exact catenary, eq. [21]

Table 2. The dimensions of the single-circuit horizontal configuration of the conductor

400 kV transmission line	H (m)	h (m)	d (m)	S (m)
SS Sarajevo 10-SS Sarajevo 20	23	9.3	13.7	420
SS Tuzla 4-SS Višegrad	22	9.2	12.8	323

$$y \quad h \quad \frac{4d}{S^2} \; x^2 \tag{4}$$

where h is the height of the conductor at the middle of the span, d – the sag and S – the length of the span of the analyzed the HV transmission line.

The dimensions of a single-circuit horizontal configuration of the conductor are given in tab. 2.

The height of the conductor and the ground wires to the ground increased from the middle of the span toward the towers. The co-ordinates of the points $P_i(x_i, y_i)$ are determined by using eq. (4).

The variation of the ELF electric field radiation on surface of the stranded conductor and the AC corona onset voltage gradient with the conductor height along the catenary is given in fig. 8.

The highest values of the LF electric field radiation on the surface of the stranded conductor are at the lowest point of catenary, $P_0(0, h)$, and the drop to the height of the conductors in which they become less than the values of the AC corona onset voltage gradient. For the 400 kV transmission line SS Sarajevo 10-SS Sarajevo 20, the distance x at which the value of the LF electric field radiation is less than the value of the AC corona onset voltage gradient is x = 94.32 m, *i. e.*, x = = 56.28 m for the 400 kV transmission line SS Tuzla 4-SS Višegrad, respectively. It can be concluded that for the voltage values that were at the time of measurement, the value of the LF electric field radiation on the surface of the stranded conductor on transmission line SS Sarajevo 10-SS Sarajevo 20 to 44.4 % of the span length were greater than the value of the AC corona onset voltage gradient, *i. e.*, 35 % for the transmission line

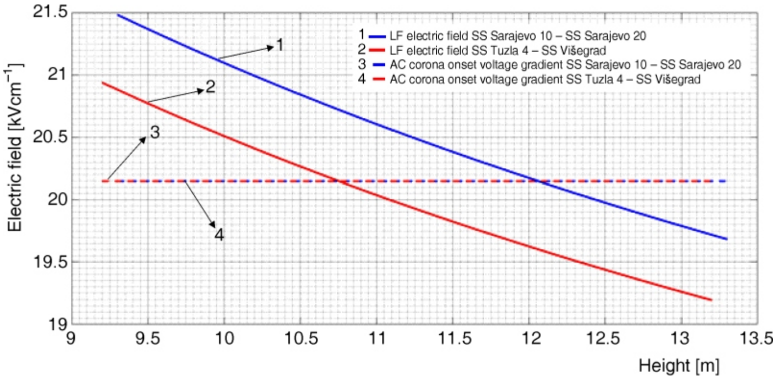

Figure 8. The LF electric field radiation on the surface of the stranded conductor and the AC corona onset voltage gradient as the function of the conductor height along the catenary

SS Tuzla 4-SS Višegrad, respectively. Reasons for these differences are:

– the voltage value during the analyzed period at the 400 kV transmission line SS Sarajevo 10-SS Sarajevo 20 (422.9 kV) was higher than at the 400 kV transmission line SS Tuzla 4-SS Sarajevo, Višegrad (416.7 kV),
– the LF electric field radiation on the surface of the stranded conductors at the 400 kV transmission line SS Sarajevo 10-SS Sarajevo 20 (standard dimensions) are higher than the LF electric field radiation at the 400 kV transmission line SS Tuzla 4-SS Višegrad (reduced dimensions) for the same voltage values and the same conductor's heights above the ground (normalized values) [22].

CONCLUSION

There are many parameters affecting the longitudinal distribution of the LF electric field radiation on the surface of the stranded conductors and their immediate vicinity along the sag of the transmission line: the conductor heights along the sag, the presence of the grounding wires, the presence of the towers, *etc*. In this article, the investigation of the impact of the heights of the stranded conductors along the sag of the typical 400 kV transmission lines with standard and compacted dimensions is presented.

On the analyzed transmission lines, the LF electric field radiation on the surface of the stranded conductor and its immediate vicinity is greater than the AC corona onset voltage gradient at 45 % of the length of the sag for transmission line SS Sarajevo 10-SS Sarajevo 20, or 35 % for the transmission line SS Tuzla 4-SS Višegrad, respectively.

AUTHORS' CONTRIBUTIONS

The main idea of applying th research about the impact of the conductor's heights onto the value of the LF electric field and all calculations was put forward by A. S. Čaršimamović. A. S. Čaršimamović and A. Z. Mujezinović have developed program code for the calculation of the electric field. A. S. Čaršimamović, A. Z. Mujezinović, Z. F. Bajramović, and I. M. Turković performed all experiments and analysis. M. P. Košarac participated in editing and revising of the manuscript. All authors discussed the results and commented on the manuscript.

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НИВО РАДИЈАЦИЈЕ НИСКОФРЕКВЕНТНИХ ЕЛЕКТРИЧНИХ ПОЉА ОКО ВИСОКОНАПОНСКИХ ПРЕНОСНИХ ЛИНИЈА И УТИЦАЈ ПОВЕЋАНОГ НАПОНА НА ГРАДИЈЕНТ НАПОНА ПОЧЕТКА КОРОНЕ

У раду је дат преглед вредности мерења и прорачун вредности радијације нискофреквентног поља око високонапонских преносних линија и утицај повишених вредности напона на напонски градијент почетка АС короне. Мерења нивоа радијације нискофеквентног електричног поља проведена су испод 400 kV преносних линија хоризонталне конфигурације са стандардним и компактизованим димензијама. У свим анализираним случајевима у овом раду мерења су извршена на средини распона, јер су у тим тачкама проводници најближи површини земље. Проведене анализе у овом раду настале су услед повишених вредности напона који су регистровани у чворовима 400 kV мреже у Босни и Херцеговини и суседним земљама, који дуго трају у последњих неколико година. Прорачун радијације нискофреквентних електричних поља различитих конфигурација високонапонских преносних линија користиће се за одређивање нивоа излагања нејонизујуће радијације опште популације у будућности, као и одређивања њиховог утицаја на напонски градијент почетка АС короне.

Кључне речи: нејонизујуће зрачење, нискофреквентно електрично поље, високонапонска преносна линија, АС корона, напонски градијент почетка короне