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# Impact of Daily Variations of Atmospheric Conditions on the AC Corona Onset Electric Field

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**Abstract.** The electric power network in Bosnia and Herzegovina on the 400 kV voltage level built up in the 70's of the last century, has an important role for the electric energy exchange. Its parts are more than 40 years old. The paper investigates the impact of daily variations of the atmospheric conditions on the AC corona onset electric field. The AC corona onset electric field on overhead transmission lines is affected by a several factors. Besides the conductor dimensions, the atmospheric conditions have the largest impact on the value of the relative air density as well as the surface conductor roughness. The relative air density is a function of the ambient temperature and pressure. Ambient temperature at any given location is subject to daily and seasonal variations. The ambient pressure is not subject to large daily variations. The sag of the overhead transmission lines increases by an increase of the conductor temperature due to the electric load and specific atmospheric conditions. Increased voltages increase the value of the electric field and can presents risks for the exposure of human beings. Also, high voltages in the network cause high power losses due to the AC corona.

**Keywords:** electric field; overhead transmission lines (OHTL); AC corona onset electric field; atmospheric conditions

**Vpliv dnevnih sprememb atmosferskih razmer na velikost električne poljske jakosti za AC-korono**

Visokonapetostno omrežje (400 kV) v Bosni in Hercegovini, zgrajeno v 70. letih prejšnjega stoletja, ima pomembno vlogo pri prenosu in dobavi električne energije. V prispevku analiziramo dnevni vpliv sprememb v ozračju (temperatura, zračni tlak, gostota zraka) na električno poljsko (AC), pri kateri se začne pojavljati korona. Povešanje nadzemnih električnih vodov narašča s temperaturo v vodu zaradi električne obremenitve in trenutnih razmer v ozračju. Povečanje napetosti poveča vrednost električne poljske jakosti in lahko pomeni tveganje za izpostavljenost ljudi. Visoke napetosti v prenosnem omrežju tudi povečujejo izgube zaradi AC-korone.

## 1 INTRODUCTION

The corona occurrence on the overhead transmission lines (OHTL) is affected by the physical state of the atmospheric and OHTL conditions:

- Corona is formed by ionization of the air surrounding the conductors. It is affected by the atmospheric conditions (temperature, pressure and humidity),
- The corona effect depends on the conductor shape (size and roughness),
- Spacing between the conductors affects the electric stresses at the conductor surface,
- The value of the line voltage greatly affects corona.

Electric load and environmental daily variations affect the OHTL conductor temperature. As a consequence, the OHTL sags change during seasonal and daily environmental variations, which affects the conductor height above the ground level, the value of the electric field on the conductor surfaces and in their immediate vicinity as well as the AC corona onset electric field. For OHTL, the ground clearance of the conductors is one of the important parameters and a safety margin has to be maintained throughout the OHTL operational life. To assure the OHTL safety, regular measurements of these values should be taken. A high temperature due to climate changes decreases the OHTL efficiency. An extreme weather condition would increase the probability of the OHTL failure rate. A temperature rise results in a thunder storm and may cause the lightning to strike into OHTL. It's known that a temperature rise of 20 C° increases the network losses by 0.04% [1]. Due to the conductor weight, OHTL intrinsically tend to sag. The initial sag increases with an increment of the ambient temperature. An increase in the OHTL length produces a large and potentially hazardous increase in the sag. OHTL sagging poses an electrocution hazard to humans and vehicles, can interrupt the power supply and may cause a huge destruction and expensive forest and bush fires. Every

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year, electrocution causes a number of deaths [1]. Electric and magnetic fields, generated by the electrical equipment, are very important in terms of their impact on humans and other living organisms, as well as on surrounding objects. In the public, there is a general negative opinion about the OHTL emission impact [2].

From October 2004 onwards, after reconnection of Bosnia and Herzegovina (B&H) electric power network (EPN) with the European Network of Transmission System Operators for Electricity (ENTSO-E), long-duration power frequency overvoltages have been recorded, especially in the small load regime. The IEC 60038 [3] defines a nominal and the highest voltages which are in analyzed cases 400 kV and 420 kV. The Independent System Operator of B&H operates the network in accordance with ENTSO-E, Grid Code [4] and IEC 60038. The voltage control within permissible values contributes to an optimal EPN operation and reduces the transmission system losses. The greatest impacting factor on the power frequency ovevoltages are load of the 400 kV OHTL below the natural capacity, as well as very limited opportunities for the excessive reactive power compensation. The voltages above the permissible values adversely affect the equipment insulation and at the same time increase power losses due to AC corona [5]. Daily reductions of the conductor heights above ground level increase the value of the electric field on the conductor surfaces. This increases the losses due to AC corona.

## 2 Background of the Problem

In the B&H EPN in the last few years, increased values in the power frequency overvoltages of the long duration have been registered. Thus typically happen during the night and mostly at a minimum load regime..

In the observed period (2013 – 2017), most lines were loaded bellow the natural transmission power that is 550 MW in the 400 kV network. This generates a significant capacitance load. Generation of the reactive power, low reactive power losses and low active power load, gives rise to the occurrence of the power frequency overvoltages. In addition to the domestic generation of the capacitive power charge, the B&H interconnection grid with the neighboring countries regularly exports 80-100 MVAr of the reactive power. This raises the voltage values in the 400 kV above the set limit value (420 kV) [6-8].

Fig. 1 shows a diagram of the duration time in % of the voltage values for the substation (SS) Sarajevo 10 from the highest to the lowest voltage values in the observed period.

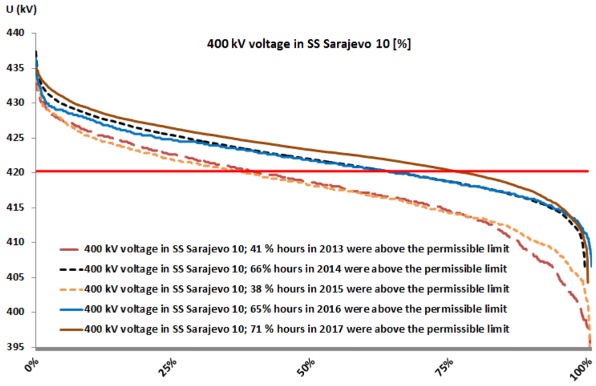


Figure 1. Diagram of the duration of the 400 kV voltages at SS Sarajevo 10 during the period 2013 – 2017 [6].

In 2017, the overvoltages at the SS Sarajevo 10 were almost 77 % of the time above the set permissible voltage value by the Grid Code [4]. These overvoltages are detrimental for the equipment insulation and have negative impact on the power quality. At the same time, the increased power frequency overvoltages increase the power losses due to AC corona. This makes it necessary to analyze of the impact of atmospheric conditions on the AC corona onset electric field and increase in the voltage values on the electric field on the surface of twin-bundled central and outer stranded sub-conductors.

## 3 A Mathematical Model

To know whether an AC corona will appear on the OHTL, it is necessary to determine the value of the electric field strength on the conductor surfaces. For this task various analytical and numerical methods can be applied. In this paper to calculate of the electric field strength, a charge simulation method (CSM) is used. The used mathematical model is developed with the following assumptions:

- each conductor is treated as equipotential (phase and ground conductors),
- each conductor is represented by a certain number of point charges,
- all conductors are perfectly parallel with the ground surface and are treated as infinite,
- ground is treated as a perfect conducting medium,
- complex image theory is applied.

Each conductor of the system is represented by fictitious point charges placed inside the conductor in order to avoid singularity points. The number of point charges per conductor and their position is shown in Fig. 2. By applying the complex image theory, additional point charges are introduced in the problem. They are placed in the ground at depth equal to the conductor heights, as shown in Fig 2. Theirs impact on the electric field strength of an arbitrary point is attenuated by a complex reflection coefficient which depends on the electric properties of the air and ground. Being assumed that the ground can be treated as a perfect conducting medium, the value of this complex reflection coefficient is -1 [9, 10]. Also, by assuming the conductors to be parallel with the ground surface and treated as infinite, the problem can be treated as a 2-D problem, i.e. the longitudinal component of the phasor of the electric field vector can be neglected [11]. The above listed assumptions introduce errors in the mathematical model, but in most cases these errors can be neglected [10].

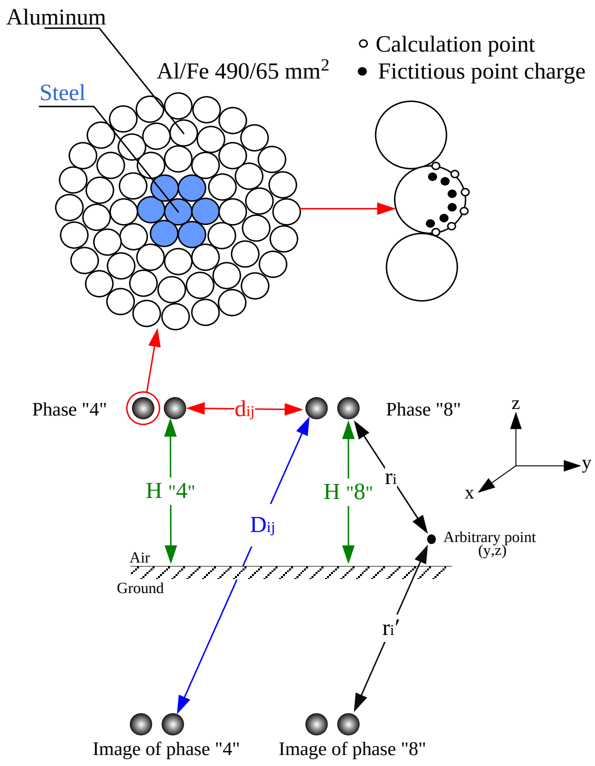


Figure 2. Central and outer phase of a three phase horizontal arrangement of a twin-bundle cylindrical stranded conductor and point charge representation.

The electric field strength vector in an arbitrary point can be calculated by using the following equation:

$$\underline{\vec{E}}(y,z)=\underline{E}_y(y,z)\vec{a}_y+\underline{E}_z(y,z)\vec{a}_z=\sum_{i=1}^{n}\overline{q}_i\left(f_y\vec{a}_y+f_z\vec{a}_z\right) \tag{1}$$

where $\underline{\vec{E}}(y,z)$ is the phasor of the electric field strength vector, $\underline{E}_y(y,z)$ and $\underline{E}_z(y,z)$ are the $y$ and $z$ phasor components of the electric field strength vector at the point with coordinates ($x$,$y$), $\vec{a}_y$ and $\vec{a}_z$ are the unit vectors at the $y$ and $z$ directions, $n$ is the total number of the point charges in the system, $\overline{q}_i$ is the phasor of the $i$-th point charge and $f_y$ and $f_z$ are the electric field strength coefficients.

The electric field strength coefficients are defined by the following equations [12]:

$$f_y=\frac{1}{2\cdot\pi\cdot\varepsilon_0}\left(\frac{y-y_i}{r_i^{\,2}}-\frac{y-y_i}{r_i'^{\,2}}\right) \tag{2}$$

$$f_z=\frac{1}{2\cdot\pi\cdot\varepsilon_0}\left(\frac{z-z_i}{r_i^{\,2}}-\frac{z+z_i}{r_i'^{\,2}}\right) \tag{3}$$

where $\varepsilon_0$ is the permittivity of the free space, ($y$,$z$) are the coordinates of an arbitrary point, ($y_i$,$z_i$) are the coordinates of the $i$ – th point charge, $r_i$ is the distance between the $i$ – th point charge and arbitrary point, and $r_i'$ is the distance between the image of the $i$ – th point charge and arbitrary point.

The unknown phasors of the point charges are calculated by using the following linear matrix equation [13]:

$$[P]\cdot\{\overline{q}\}=\{\overline{U}\} \tag{4}$$

where $\{\overline{U}\}$ is the vector matrix of the conductors line-to-ground voltages, $\{\overline{q}\}$ is the vector matrix of the unknown point charges phasors, $[P]$ is the matrix of the potential coefficients.

For OHTL consisting of the $n$ fictitious point charges placed inside of the conductors, the matrix elements of the potential coefficients are calculated by equation [14]:

$$p_{ij}=\frac{1}{2\cdot\pi\cdot\varepsilon_0}\cdot\ln\left(\frac{D_{ij}}{d_{ij}}\right) \tag{5}$$

The total r.m.s value of the electric field strength at an arbitrary point with coordinates ($y$,$z$) is calculated based on the value of individual components of the electric field strength vector, by using the following equation:

$$E_{rms}(y,z)=\sqrt{\left|\overline{E}_y(y,z)\right|^2+\left|\overline{E}_z(y,z)\right|^2} \tag{6}$$

When the electric field strength on the conductor surface exceeds the breakdown value (AC corona onset electric field value) of the air, a corona discharge takes place. To evaluate the r.m.s. values of the AC corona onset electric field on the conductor surface, $E_{20h}$, the Peek's equation is used [15]:

$$E_{20h}=\frac{29.8}{\sqrt{2}}m\delta_{20h}\left(1+\frac{0.301}{\sqrt{r\delta_{20h}}}\right)\left(kV_{rms}/cm\right) \tag{7}$$

where $m$ is the roughness coefficient which takes into account the surface conditions of the stranded conductor, $r$ is the radius of the stranded sub-conductor of twin bundle, $\delta_{20h}$ is the coefficient which takes into account air pressure $p$, temperature $t$ and relative humidity $h$ of the surrounding air. The standard reference atmospheric conditions are adopted, i.e. $p_0 = 101.3 \cdot 10^3$ Pa (1013 mbar, 760 mmHg), $t_0 = 20°$ C and absolute humidity $h_0 = 11$ g/m$^3$ [16]. The $\delta_{20h}$ coefficient can be determined by the following relation:

$$\delta_{20h} = \delta_{20} \cdot k_2 = \frac{p \cdot 293}{760 \cdot (273 + t)} \cdot k_2 \qquad (8)$$

where $k_2$ is the humidity correction factor and for AC voltage may be expressed according to IEC 60060-1 as in [17]:

$$k_2 = 1 + 0.01\left(\frac{h}{\delta_{20}} - 1\right) \qquad (9)$$

where $h$ is the absolute humidity and can be developed using the following equation:

$$h = \frac{6.11 \cdot R \cdot e^{\frac{17.6 \cdot t}{243 + t}}}{0.4615 \cdot (273 + t)} \qquad (10)$$

where $R$ is the relative humidity and $t$ is the ambient air temperature. Equation (9) applies for the condition 1 g/m$^3$ < $h/\delta_{20}$ < 15 g/m$^3$.

Roughness factor $m$ for an aged ACSR 2x490/65 mm$^2$ conductor is found by the following equation [18]:

$$m = 0.246 \cdot e^{-\frac{R_a}{11.53}} + 0.6074 = 0.72 \qquad (11)$$

where $R_a$ is the average roughness. For the aged conductors it is 8.93 µm.

## 4 Measurements

In Fig. 3 the 400 kV OHTL SS Sarajevo 10 – SS Sarajevo 20 is analysed. It is single-circuit horizontal configuration with the dimensions presented below. To investigate the effects of atmospheric conditions on the AC corona occurrence, measurements of the height of the inner and outer phase conductors (Fig. 4) and atmospheric conditions (temperature, pressure and humidity, Fig. 5. – 7.) were performed on August 3, 2014 (Case 1) and September 14, 2015 (Case 2), from 7 a.m. up to 2 p.m. at half-hour intervals [19].

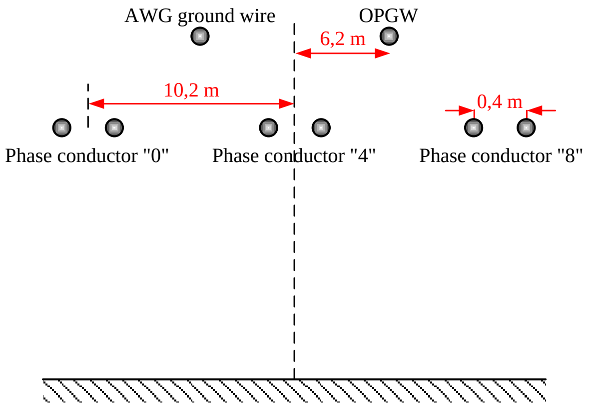


Figure 3. Dimensions of the observed 400 kV OHTL SS Sarajevo 10 – SS Sarajevo 20 at middle of span.

The heights at the middle of span between two towers Nos. 190 and 191, were measured.

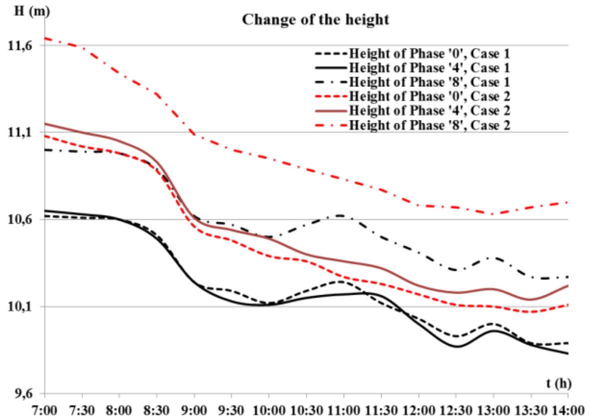


Figure 4. Measured heights of the inner and outer phase conductors [19].

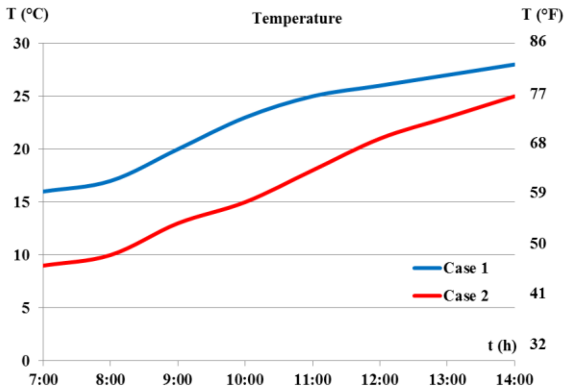


Figure 5. Measured air temperatures [19].

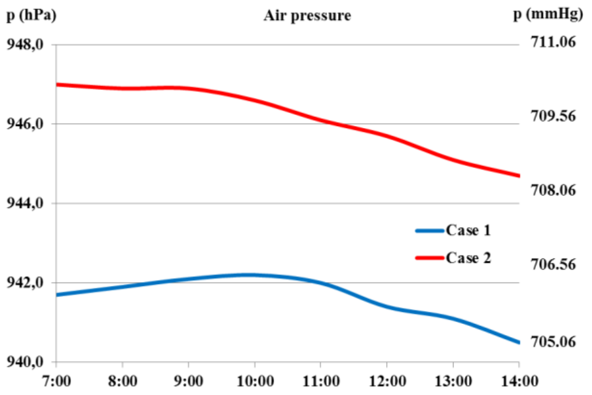


Figure 6. Measured air pressures [19].

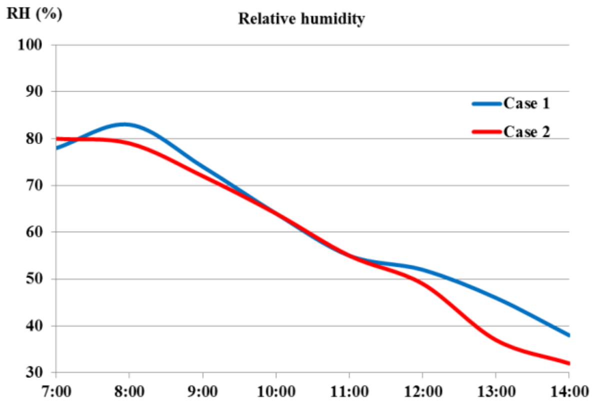


Figure 7. Measured relative humidities [19].

Figure 8. shows half-hourly voltage changes.

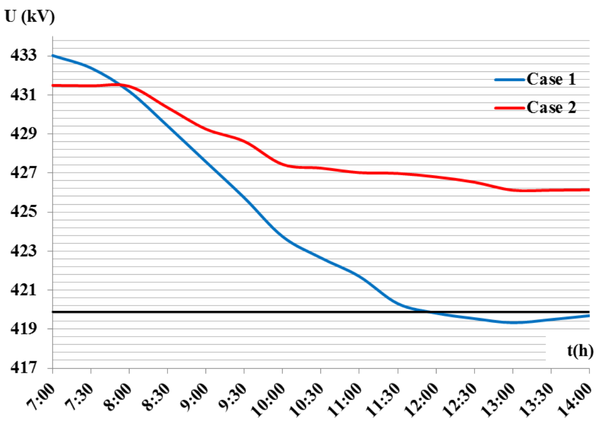


Figure 8. Voltage changes during measurements [19].

## 5 Results and Discussion

The electric field strength on the surface of a stranded conductors and the AC corona onset electric field are calculated. The maximum electric field on the surface of a phase conductors, is calculated by using the presented mathematical model [20].

Figs. 9 and 10 shows results of the calculating the electric field on the surface of the central and outer phase and AC corona onset electric field of a stranded conductor for Case 1 and Case 2, respectively.

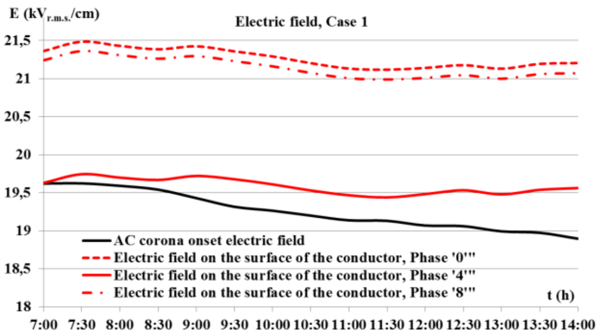


Figure 9. Electric field on the surface of the sub-conductor and AC corona onset electric field, Case 1.

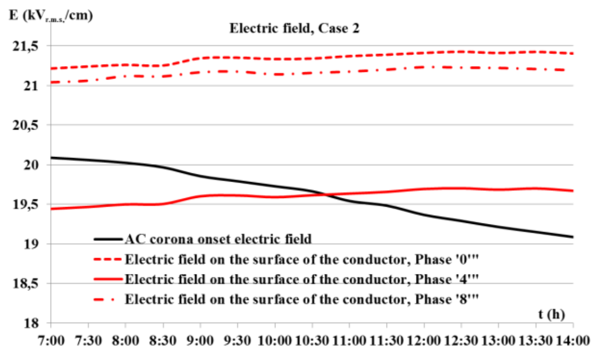


Figure 10. Electric field on the surface of the sub-conductors and AC corona onset electric field, Case 2.

The values of the electric field strength on the surface of the stranded conductors during the measuring period remain relatively constant, although the voltage values decrease and the conductor heights above the ground decreases too.

The value of the AC corona onset electric field ($E_{20h}$) in the whole measuring period (Case 1) from 7 a.m. up to 2 p.m. is less than the value of the electric field strength on the surface of the center and the outer phase conductors.

The value of the AC corona onset electric field ($E_{20h}$) in the whole measuring period (Case 2) from 7 a.m. up to 2 p.m. is less than the value of the electric field strength on the surface of the outer phase conductors. In the measuring period (Case 2) from 7 a.m. up to 10.45 a.m. the value of the AC corona onset electric field is greater than the value of the electric field strength on the surface of the center phase conductor. In measuring period from 10.45 a.m. up to 2 p.m. the value of the AC corona onset electric field is less than the value of the electric field strength on the surface of the center phase conductor.

## 6 Conclusion

Increased long duration overvoltages of power frequency occur in the 400 kV B&H electric power system. In analyzed part of 400 kV power system the highest overvoltages during 2017 are recorded in SS Sarajevo 10 (439.95 kV). Duration of power frequency non-permitted overvoltages (>420 kV) in 2017 was almost 77% of year. These overvoltages are harmful for the equipment insulation and have negative impact on power quality. At the same time, the increased power frequency overvoltages increase the power losses due to the AC corona.

The conductor heights above the ground level, atmospheric conditions and voltages are measured (Case 1 and Case 2). It is found that the atmospheric conditions affect the conductor heights above ground level as well as the AC corona onset electric field. The calculated value of the electric field strength (Case 1 and Case 2) on the outer phase conductors exceeds the value of the AC corona onset electric field and on the center phase conductor surface it is less than the value of the AC corona onset electric field in the measuring period from 7 a.m. up to 10.45 a.m. (Case 2). The value of the AC corona onset electric field in the measuring period from 10.45 a.m. up to 2 p.m. is less than the value of the electric field strength on the surface of center phase conductor (Case 1).

It is shown that the decrease of the atmospheric air pressure and increase of the air temperature during the measurement period decrease the relative density of the ambient air ($\delta_{20h}$) and in this way decreases the AC corona onset electric field. The decrease of the relative humidity does not importantly affect the decrease of the AC corona onset electric field, which is in accordance with the research carried out world-wide [21].

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