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Influence of environmental factors on corona voltage

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Abstract. The environmental conditions related to the air i.e. pressure, temperature, and humidity are relevant in the development of the corona effect in high voltage systems, affecting both corona onset voltage and the observed corona mode. This paper studies the influence of those environmental factors on the effective ionization coefficient and corona onset voltage, based on theoretical analysis, finite element modelling (FEM) and simulation results.

Key words. Corona effect, FEM, high voltage, relative density, humidity.

1. Introduction

The corona effect is an electrical phenomenon ubiquitously occurring in any high voltage system with gas insulation. Nowadays, high voltage implementations such as DC substations on offshore wind farms and long-distance transmission lines are arising renewed interest. These implementations are subjected to various environmental and operative conditions. Thus, the prevailing environmental conditions in the enclosure and related to the air i.e. pressure, temperature, and humidity are relevant in the development of the onset voltage and the observed corona mode. The present paper presents a theoretical analysis of the influence of environmental factors on corona voltage, based on finite element modelling (FEM) and simulation.

Several criteria have been developed over time for the prediction of corona effect, each with specific conditions that must be met8 for different corona features [1,2]. The corona prediction criteria of Townsend [3] and Pedersen [4] are under study for this paper. To properly define the criteria, it is required to know a possible discharge path and the reduced ionization coefficient α/p across it. In the case of gases with an electronegative molecule, like air, we use the effective ionization coefficient, $\bar{\alpha}$. VerPlanck defined the ionization coefficient piece wisely by dividing the electric field at intervals, based on the experimental data obtained by Townsend, Wheatley, Paavola, Masch and Sanders [5]. VerPlanck considered standard conditions. However, the effective ionization coefficient depends on relevant environmental factors, such as pressure, temperature and humidity [6,7]. And as a consequence, corona onset voltage also depends on environmental conditions. The present paper studies the impact of pressure, temperature and humidity on both the effective ionization coefficient and on corona voltages.

Section 2 introduces the corona prediction criteria used for the present study, i.e. Townsend's criterion and Pedersen's criterion. Section 3 explains the influence of pressure, temperature and humidity on the effective ionization coefficient. Then, the research is completed by Section 4, with the analysis of the impact of pressure, temperature and humidity on corona voltages based on FEM simulation results for a single set-up and same scenarios. Section 5 opens the discussion with reference to existing literature and predicted values. Finally, Section 6 presents main conclusions.

2. Corona prediction criteria

A. Townsend's criterion

The most simplified corona prediction criterion, in which it is assumed that the discharge occurs along a critical line and only considering the area of ionization around the electrode can be stated as indicated in (1).

$$\int_{x_0}^{x_f} \bar{\alpha}(x) \cdot dx = K \qquad (1)$$

where x_0 is the initial radius of ionization area, x_f is the final radius of ionization area, $\bar{\alpha}$ is the effective ionization coefficient and x the distance to the electrode. The constant K in (1) may have different values depending on the structure considered. The accepted values for K are usually 9.2 for Townsend's criterion.

B. Pedersen's criterion

Alternatives to the prediction model along the same lines, but not considering a fixed value of K in the case of a non-uniform field have been suggested by Pedersen [4]. In this case, instead of assuming a constant K, a function of pressure and electrode separation, (x, p), is considered as shown in (2). As for Townsend's criterion, the voltage at

which both sides of the equation coincide is defined as corona voltage.

$$\ln[\bar{\alpha}(x_0)] + \int_{x_0}^{x_f} \bar{\alpha}(x) \cdot dx = g(x,p) \qquad (2)$$

where the function $g(x, p)$ is determined considering breakdown conditions under a uniform electric field. Instead of a defined value of we need to compute (x, p) at each position x, as indicated in (3).

$$g(x,p) = \bar{\alpha}(x) + \ln[\bar{\alpha}(x_0)] \qquad (3)$$

3. Analysis of the effective ionization coefficient

A. Influence of pressure and temperature

VerPlanck studied the relation between α and the electric field in function of relative density δ, which is a correction factor for air density depending on pressure and temperature. Peek introduced the use of this correction factor in [8]. At microscopic level, the average collision distance between the electrons and the neutral particles is affected by pressure and temperature.

Contrastingly, under humidity conditions H_20 molecules are present in air. Thus, the study of new ion creation reactions is not streamlined and cannot be carried out by simplified models.

B. Influence of humidity

For the present work, Abdel-Salam's research on the ionization and attachment coefficients depending on relative humidity HR has been reviewed [7]. Our approach has involved computing the effective ionization coefficient within the range of reduced electric fields defined by Abdel-Salam. Then, it has been compared to the effective ionization coefficient calculated by VerPlanck, computed under identical temperature and pressure conditions but without factoring in the humidity. Subsequently, we have incorporated Abdel-Salam's calculations with an adjusted humidity level RH of 70% to observe the variations in the predicted effective ionization coefficient.

The effective ionization coefficient, calculated for an electric field ranging from 15 kV/cm to 50 kV/cm, is depicted as follows in Fig. **1**. It is observed that the coefficient values obtained using Abdel-Salam's results at 0% RH are marginally higher than those calculated by VerPlanck at standard conditions.

With increased humidity (RH = 70%), the difference in the effective ionization coefficient becomes more pronounced with the electric field (153.7 1/cm for Abdel-Salam vs. 135.5 1/cm for VerPlanck to an electric field of 50 kV/cm) and the electric field threshold also increases to 28.5 kV/cm.

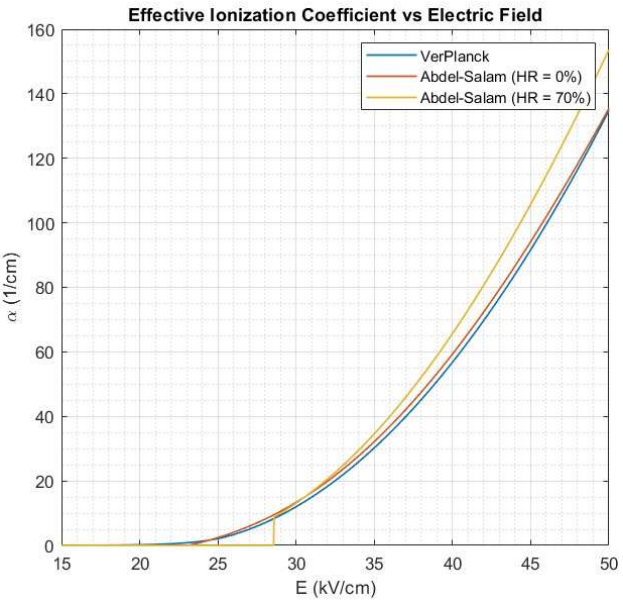

Fig. 1. Comparison between different effective ionization coefficients by authors and RH

4. Analysis of corona onset voltage

A. Set-up and methodology

Corona onset voltages have been calculated for the set-up shown in Fig. 2, for all environmental factors under study i.e. pressure, temperature and humidity. It is a sphere-plane configuration, with a radius of 7 mm.

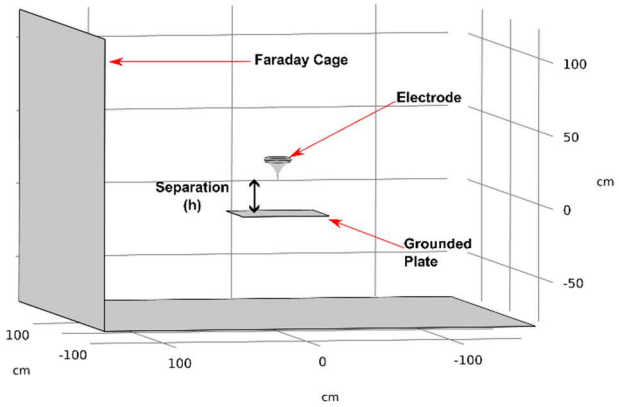

Fig. 2. Set-up for the study

We have chosen FEM as the mathematical tool to solve the electric field between the electrode and the plane. The electric field has been calculated for a given starting voltage and evaluated along the critical line to determine the maximum field value, and to obtain the effective ionization coefficient at discrete intervals along the line. The process has been repeated iteratively, by raising the voltage each time, until the conditions for the criterion have been met.

COMSOL Multiphysics R 5.6 has been used for the FEM for all the cases under analysis. The codes related to each corona prediction criterion have been programmed in MATLAB 2020 with the additional integration module in COMSOL Multiphysics.

For this analysis, we have included two electrode separations (h separation in Fig. 2), the largest and the smallest, to illustrate the effects under these varied conditions and assume a maximum relative humidity in the testing. Table I shows the separation between electrodes in centimetre under consideration, and according to each criterion.

Table I .- Scenarios considered

CRITERION	Applied Voltage	Electrode Separation	Electrode Separation
TOWSEND	DC -	33.7 cm	1.2 cm
PEDERSEN	DC +	38.7 cm	6.0 cm

B. Simulation results for pressure

Pressure conditions have been varied, with the maximum pressure set at 1050.6 hPa and the minimum pressure at 640 hPa, while the standard pressure remained at 1013.25 hPa. For all calculations, temperature has been fixed to 25 ºC. The effective ionization coefficients have been calculated according to VerPlanck and the reference pressure set to 1013.25 hPa.

The outcomes for the negative corona (Trichel Pulses) are presented in Table II and for the positive corona (Streamer) in Table III. When comparing the results for both criteria under varying atmospheric pressure, an inverse relationship is observed. Ionization potential tends to favour low-pressure environments, as evident in the breakdown inception voltage calculated using Paschen's Law for higher pd factors. However, this trend is only consistent with Townsend's criteria concerning the negative corona effect.

Table II .- Inception voltage from criteria results for DC- comparing the effect of pressure and different electrode separations (h)

PRESSURE	h=33.7 cm	h=1.2 cm
640 hPa	26.56 kV	12.64 kV
1013.25 hPa	39.9 kV	17.5 kV
1050.6 hPa	38.9 kV	17.9 kV

Table III .- Inception voltage from criteria results for DC+ comparing the effect of pressure and different electrode separations (h)

PRESSURE	h=38.7 cm	h=6 cm
640 hPa	43.87 kV	31.33 kV
1013.25 hPa	43.4	30.8
1050.6 hPa	40.48 kV	28.8 kV

C. Simulation results for temperature

To encompass extreme laboratory conditions, both maximum and minimum temperatures have been selected. These values are -32 °C and 47.6 °C, respectively, with a standard temperature set at 25 °C. For all calculations, pressure has been fixed to 1013.25 hPa. The effective ionization coefficients have been calculated according to VerPlanck and the reference temperature set to 25 ºC, as indicated in That are the values for standard conditions at what the ionization coefficient was measured experimentally.

The outcomes for the negative corona (Trichel Pulses) are presented in Table IV and for the positive corona (Streamer) in Table V. Townsend's criterion exhibits a consistent trend with pressure variations, while Pedersen's criterion lacks clarity regarding the trend. Within this range, the influence of temperature appears to be less significant compared to pressure on the streamer inception voltage.

Table IV .- Inception voltage from criteria results for DC- comparing the effect of temperature and different electrode separations (h)

TEMPERATURE	h=33.7 cm	h=1.2 cm
-32 ºC	46.67 kV	21.01 kV
25 ºC	39.9 kV	17.5 kV
47.6 ºC	37.46 kV	16.83 kV

Table V .- Inception voltage from criteria results for DC+ comparing the effect of temperature and different electrode separations (h)

TEMPERATURE	h=38.7 cm	h=6 cm
-32 ºC	36.34 kV	26 kV
25 ºC	43.4	30.8
47.6 ºC	41.28 kV	29.49 kV

D. Simulation results for humidity

We have applied both one negative corona prediction criterion (Townsend's, which relies on a constant integral limit) and one positive corona criterion (Pedersen's, based on comparing two functions for inception voltage), as outlined in the paper, to assess:

1. The impact on corona inception voltage prediction is due to adopting a new effective ionization coefficient (Abdel-Salam at RH=0% and VerPlanck).
2. The influence of humidity on corona inception voltage considering Abdel-Salam at RH=0% and RH=70%.

The outcomes for the negative corona (Trichel Pulses) are presented in Table VI. As observed in the comparison, the corona inception voltage predicted using Abdel-Salam's coefficients is lower than that predicted by VerPlanck. Additionally, the differences arising from incorporating humidity into the calculations are less than 1% and are more significant at higher electrode distances than at lower ones.

Table VI .- Inception voltage from criteria results for DC- comparing the effect of humidity and different electrode separations (h)

	h=33.7 cm	h=1.2 cm
VERPLANCK STANDARD	39.9 kV	17.5 kV

ABDEL-SALAM AT RH=0%	37.2 kV	16.8 kV
ABDEL-SALAM AT RH=70%	37.4 kV	16.8 kV

For the positive corona (streamer), a similar trend is observed when employing Abdel-Salam's effective ionization coefficient as opposed to VerPlanck's as shown in Table VII. Nevertheless, in both scenarios—across varying electrode separations—humidity does not significantly affect the results.

Table VII .- Inception voltage from criteria results for DC+ comparing the effect of humidity and different electrode separations (h)

	h=38.7 cm	h=6 cm
VERPLANCK STANDARD	43.4 kV	30.8 kV
ABDEL-SALAM AT RH=0%	41.0 kV	29.3 kV
ABDEL-SALAM AT RH=70%	41.5 kV	29.8 kV

5. Discussion

Relative density relates both pressure and temperature. Therefore, based on simulation results for the scenarios described in Section 4, the relation between corona inception voltage and relative density has been plotted in Fig. 3 for negative corona. Fig. 4 shows the equivalent results for positive corona. Both figures are normalized against standard conditions. Thus, correction factors for pressure and temperature can be calculated, analogously to altitude correction factors introduced in standard IEEE 1829-2017 [9].

In Fig. 3, the relation can be linearly approximated to a first-degree equation for both electrode separations. The fit is not as straightforward for positive corona, as can be observed in Fig. 4.

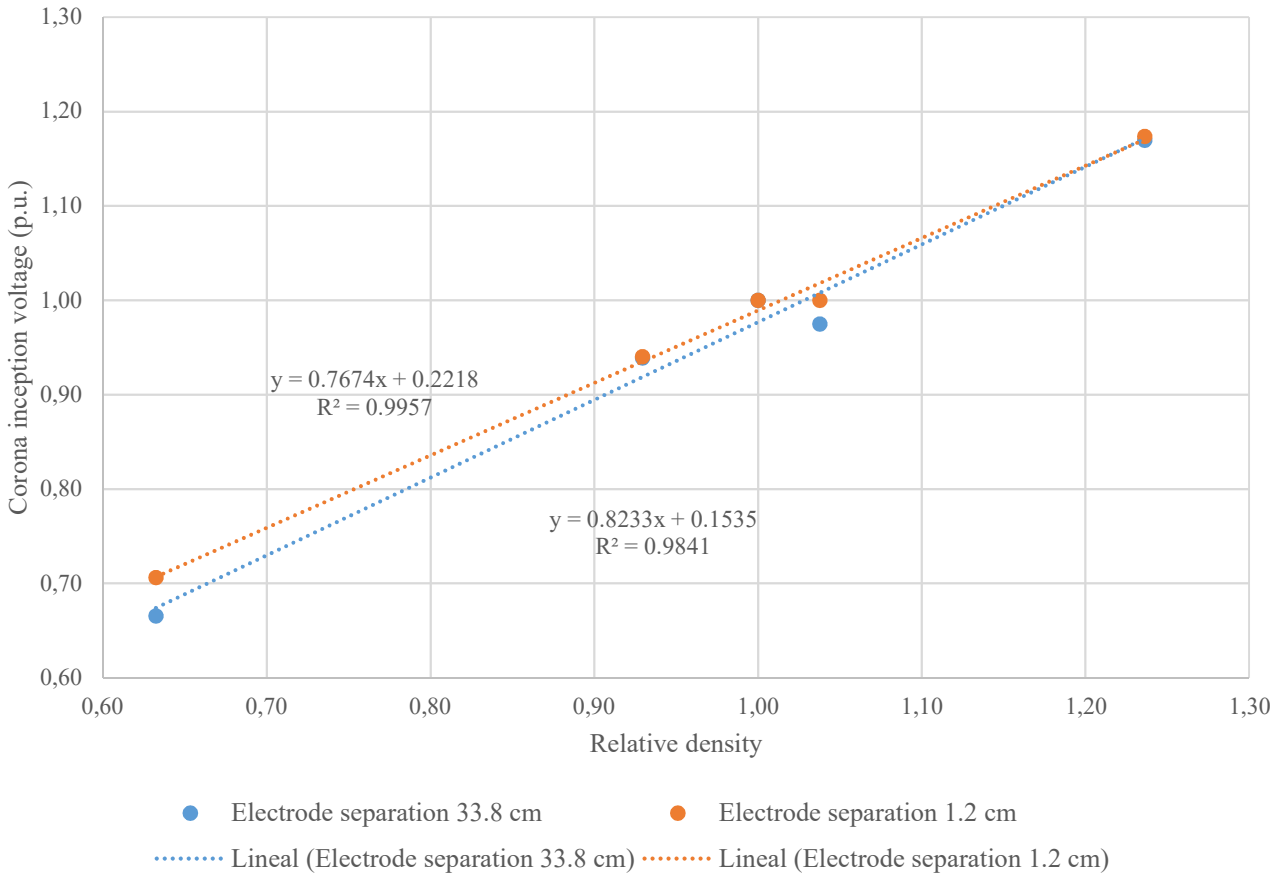

Fig. 3. Corona inception voltage for negative corona according to relative density

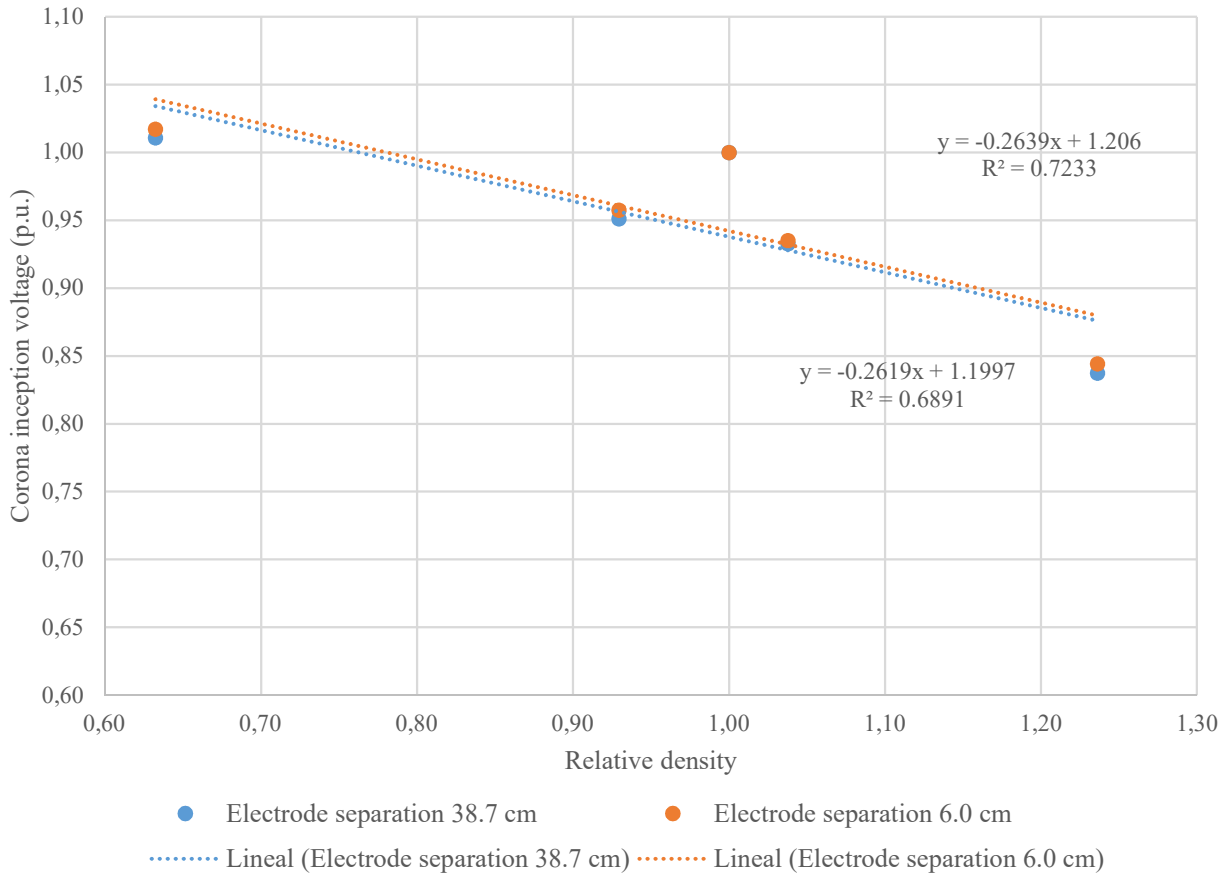

Fig. 4. Corona inception voltage for positive corona according to relative density

Meng, Shen, and Lu conducted a study on DC-positive corona in a rod-plane setup using a 4 mm diameter rod at temperatures between 20-30°C and relative humidity ranging from 20% to 90%. Their findings suggest that the streamer inception voltage remains consistent, as observed in Pedersen's criterion, while the corona glow inception voltage increases with humidity. Specifically, it rises by 5 kV when relative humidity increases from 40% to 90% RH **¡Error! No se encuentra el origen de la referencia.**. This issue is important to compare experimentally such criteria with was observed on laboratory, due both corona modes are positive and is easy to confuse each inception voltage.

Xu et al. investigated negative corona in a coaxial cylinder configuration, using brass inner electrodes of 0.5 mm, 0.3 mm, 0.25 mm radius and 1.2 m length and an outer electrode with a 10 cm radius. The experiments were conducted at a steady temperature of around 19°C and relative humidity varying from 10% to 90%. Their findings reveal that the inception voltage of negative corona decreases with increasing moisture, with the maximum inception voltage variation across the range being less than 1 kV **¡Error! No se encuentra el origen de la referencia.** as is seen in our results.

Based on these findings and the simulation results presented in Section 4, we have identified the following relevant points for our discussion respect relative humidity impact:

- Relative humidity does not impact the inception voltage for streamers in positive DC corona.
- Both positive glow and negative corona in DC voltage setups are influenced by relative humidity, leading to reduced inception voltage.
- The cited criteria fail to establish a criterion specifically related to positive glow, despite its significant susceptibility to relative humidity. It's crucial to consider this aspect in experimental comparisons of inception voltage to avoid misleading results.

6. Conclusions

The aim of the present paper is the analysis of the impact of pressure, temperature and humidity on both the effective ionization coefficient and on corona voltages. On one hand, literature on the topic has been reviewed. On the other hand, the influence of environmental factors on the effective ionization coefficient has been introduced, based on theoretical analysis and numerical results.

The results indicate that negative corona prediction aligns with the typical trend observed in laboratory testing at various altitudes. However, Pedersen's criterion for streamers exhibits limitations. Regarding humidity, both criteria predict slight differences in inception voltage for negative and positive corona. However, incorporating an

effective ionization coefficient a priori is necessary to account for this factor in calculations. Notably, only a few studies, such as Abdel-Salam's calculations, have considered this factor.

In contrast, pressure and temperature effects can be grouped using relative density. Nonetheless, further research is needed regarding positive streamers, supported by detailed models and experimental results, as a clear trend has not been observed in this study.

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