Ion flow simulations of HVDC conductors under rainy conditions

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Abstract

During the last years, more and more renewable power generation units have been connected to the European power grid, creating demands for higher transport capacity as well as longer transport distances. Plans for the construction of HVDC and hybrid HVAC/HVDC corridors in Europe lead to an increased interest in the corona behaviour of direct current overhead lines. Within the scope of this paper, simulations and measurements are conducted to analyse the accuracy of the used simulation tool for rainy conditions, which is constituting an important study case since corona intensity is significantly increased during periods of precipitation. Especially, charge generation at the conductor surface and its influence on total corona current as well as on the ion current distribution at ground level under rainy conditions are investigated. As a result, the idea that a single onset field strength can describe the entire V-I characteristic of an overhead line under rainy conditions is challenged. It is shown that a field dependent correction factor for the onset field strength can improve the accuracy of simulations considerably. Additionally, in order to improve the simulated current distribution at ground level, a method to inversely calculate charge generation profiles is introduced.

1 Introduction

In the past decade, due to a significant increase of installed wind and solar power generation units, the demand for transport capacity in the European energy grid increased considerably [1]. For this reason, HVDC corridors are planned to be introduced into the grid of mainland Europe in the near future. Additionally, conversions of single alternating current systems on multi-circuit towers into direct current systems are discussed as a cost effective method to improve transport capacity [2].

Still, before HVAC and HVDC lines can be operated in close proximity on the same tower, the influence of coupling effects has to be investigated. Constant ion currents caused by coronaing DC poles are of major interest due to their implications on the HVAC systems as well as public concerns [3]. In order to comply with technical requirements and regulations, accurate simulations of ion current distributions are inevitable for the planning of hybrid lines. Rainy weather, besides frost, constitutes the worst case in terms of total corona losses and ground level ion current density [4] and therefore deserves in-depth investigation.

Simulating the ion flow problem means solving coupled differential equations that describe the problem. The modelling of complex geometries like polluted conductor surfaces or rain drops is not feasible since it considerably increases already significant computational costs. Instead, simplified models are used and conditions like conductor type, pollution or rain are not taken into account by geometrical changes modelling the occurring field enhancements, but by modifying the corona inception criterion of the simplified model in such a way that the simulation behaves similar to the actual geometry.

This is accomplished by using empirical surface roughness factors that reduce the onset field strength for the investigated arrangement [5]. In existing approaches for overhead-lines, constant factors are used that do not take into account time or voltage dependent changes of the conductor surface [6, 7, 8]. While this may be sufficient for stranded conductors or surface pollution, investigations show that rain drops deform under the influence of high electric fields and significantly change form as well as drip-off behaviour depending on the applied voltage, which influences the discharge behaviour [9, 10].

For this reason, simulations and measurements are conducted to investigate if a constant onset field strength is suitable to represent the V-I corona characteristic of HVDC conductors in rain. Motivated by observed deviations and the influence of rain drops on DC corona behaviour found in literature, improvements of the Iterative Method of Characteristics for these conditions are presented.

2 Laboratory Setup

Due to a lack of data for corona behaviour of HVDC lines under controlled rainy conditions, laboratory experiments with a scaled setup were conducted. Recorded quantities include both total corona currents as well as spatial distribution of ion currents at ground level.

A schematic drawing of the laboratory setup can be seen in figure [1]. It consists of a mounted overhead line, a DC source and a rain dispenser. Additionally, sensors to measure total
corona current, ion current distribution at ground level and applied voltage are used, of which only the Wilson probe array that measures the current distribution is indicated in this figure (placed in the centre below the line). The minimal distance between probe and conductor is referred to as \( h \). The total length of the mounted line is \( l_{\text{line}} = 6.8 \) m. However, the area that is exposed to rain and therefore relevant for the conducted measurements is considerably shorter (\( l_{\text{effective}} = 3.4 \) m). In the performed experiments a single 264-AL1/34-ST1A conductor with a diameter of 22.4 mm was used.

The Wilson probe array that is used is specially designed to withstand rainy conditions. It consists of 13 probes with the dimensions 0.14 m by 1 m that are surrounded by a grounded guarding ring. As illustrated in figure 2, they are oriented in order to record the lateral ion current profile 1 m to the left and to the right of the centre.

Fig. 1: Schematic drawing of the experimental setup.

As illustrated, the overhead line is fixed to two toroids at both ends. These are used to produce a more homogeneous field at the end of the line and to suppress undesired corona activity at its edges. The insulators connected to both toroids are wall-mounted with a system of ropes, which makes it possible to adjust the conductor height continuously.

With each measurement, both total ion current and ion current density at ground level below the mid of the conductor are recorded. The Wilson probe array that is used is specially designed to withstand rainy conditions. It consists of 13 probes with the dimensions 0.14 m by 1 m that are surrounded by a grounded guarding ring. As illustrated in figure 2, they are oriented in order to record the lateral ion current profile 1 m to the left and to the right of the centre.

Fig. 2: Photography of the experimental setup.

With this arrangement, measurements were carried out under steady state rainy conditions. In order to determine the onset voltage and current-voltage relation, tests were conducted using step-profile voltages. This was done since the pulsating character of the discharges makes averaging over a certain period of time necessary. Otherwise judging if an observed pulse is an individual event or part of a series marking corona inception is not possible. Hence, voltage ramps are not suitable.

For a more accurate determination of the ion current density distribution at ground level, additional measurements at constant voltage are conducted. Each measurement is performed at four different conductor heights starting at 1.2 m (\( h_1 \)) down to 0.6 m (\( h_4 \)) with a regular spacing of 0.2 m.

3 Simulation

In this paper, the method chosen to simulate the ion flow problem is the so called Iterative Method of Characteristics (IMoC) \[6\]. Its basic concept is to switch between solving electric field distribution and ion flow equations iteratively. For the first problem the finite element method (FEM) is used, while the latter one is solved by the Method of Characteristics (MoC).

Similar to other methods \[8\], IMoC is based on a number of simplifications and assumptions in order to reduce the complexity of the mathematical structure of the problem. The geometry of the simulated arrangement is modelled in form of a 2D cross section, perpendicular to the longitudinal axis of the conductors and at the point of highest sag. Towers are not taken into account and the conductor cross sections are modelled by perfect circles. A schematic of the used 2D model is illustrated in figure 3. Besides a ground plane, it consists of safety fences placed on both sides of the arrangement and an idealized conductor. The whole arrangement is surrounded by a bounding box (B).

Fig. 3: Schematic drawing of the used simulation model.

The exact dimensions of the model are listed in table 1.

<table>
<thead>
<tr>
<th>( h )</th>
<th>( h_f )</th>
<th>( d_{ff} )</th>
<th>( d_{fr} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6 - 1.2 m</td>
<td>2.15 m</td>
<td>3.62 m</td>
<td>2.55 m</td>
</tr>
</tbody>
</table>

Table 1: Dimensions of the used simulation model.

Besides a definition of conductor and ground potentials, serving as boundary conditions for Poissons equation, it is necessary to calculate the charge density at the conductor surface,
since it is used as a boundary condition to solve the transport problem. Below the so called onset field strength, no ionization takes place at the conductor, therefore the charge density is equal to zero. For higher field strengths, corona activity of the conductor creates a space charge that shields the conductor and homogenizes the electric field distribution near the conductor surface. For the calculation of the space charge density on the conductor surface, it is assumed that charge generation remains at a level high enough that the resulting space charge limits the electric field to the onset field strength. This often referred to as the Kapzow assumption and frequently used in ion flow simulations [11, 12].

To fulfill this assumption, the amount of charges, generated at coronating conductors, needs to be sufficient to create the necessary space charge and compensate for ions drifting away from the conductor due to Coulomb forces. Hence, the selection of the onset field strength has a large influence on the corona losses and thus on ion current densities at ground level and ion current coupling between different conductors.

Because of high dependence of discharges on surface conditions under both dry and wet conditions an empirical approach is used to derive the point of corona inception for a certain setup. For smooth, cylindrical conductors the following formula is frequently used [13]:

\[ E_{\text{on}} = \delta E_0 (1 + \frac{K}{\sqrt{\delta \cdot r}}). \]  

Besides relative air density (\( \delta \)) and of the conductor radius (\( r \)) in centimetre, two constants are necessary to calculate \( E_{\text{on}} \). Summarizing different sources the following values apply:

<table>
<thead>
<tr>
<th>( K )</th>
<th>( E_0 ) (kV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>0.30</td>
</tr>
<tr>
<td>DC+</td>
<td>0.24</td>
</tr>
<tr>
<td>DC-</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Table 2: Average values to calculate corona onset with Peeks formula [14, 15, 9, 10].

Limitations of this formula become clear when it is used for power lines, since surface effects like pollution or defects come into place and stranded conductors are used. To adapt to those effects an improved version of Peeks formula can be used. The basic idea is that all surface changes lead to a constant field enhancement compared to a smooth, cylindrical conductor.

\[ E_{\text{on}} = m' \delta E_0 (1 + \frac{K}{\sqrt{\delta \cdot r}}). \]  

This is accounted for by the dimensionless factor \( m' \), which may vary between 1 (ideal cylindrical conductor) and 0. For stranded overhead lines this coefficient is reported to be between 0.75 and 0.85, while surface irregularities as well as weather conditions appear to influence it significantly (0.3 to 0.6 for rain, snow or ice) [5].

An experimental determination of the onset field strength usually is performed by measuring the onset voltage of a distinct setup. Since at this point the space charge density at the conductor surface is considered not to influence the electric field, a space charge free simulation can be used to determine the maximum value for the electric field that is considered to correspond to the onset field strength.

However, determining a distinct onset voltage is difficult, since different characteristics, like corona currents, light or sound emissions, can be used to detect the appearance of discharges, which may lead to different results [12, 16]. Within this paper, corona current based methods were chosen, using total corona current as well as ion current density at ground level to identify corona inception. Still, depending on the selected threshold, the calculated onset field strength can vary in a certain range.

To obtain a sufficient data set for the comparison, parameter variations regarding onset field strength, applied voltage and conductor height are performed.

### 4 Comparison of measured and simulated data

#### 4.1 Influence of the corona onset field strength

In order to compare the influence of the onset field strength on simulation results, the total ion current per unit length is illustrated as a function of the applied voltage for a number of selected measurements and corresponding simulations in figure 4. As expected, lower conductor positions cause higher ion currents and vice versa. Depending on the threshold, discharge inception can be determined between -20 kV and -40 kV for the lowest (0.6 m) and -30 kV to -50 kV for the highest conductor height (1.2 m). As a result, possible onset field strengths range from 5 kV/cm to 9 kV/cm for rainy conditions, values within this range are also found in literature [17].

Comparing measurement and simulation for a given height, considerable differences in the magnitude of the current become clear.

The ratio between measured and simulated values indicates that for voltages of -100 kV and below the relation between both stays almost constant, while at voltages closer to zero it is subject to considerable change. This supports the assumption that the corona behaviour of wet overhead lines is largely depending on the applied voltage and is subdivided into distinct phases that have individual characteristics.
Fig. 4: V-I curves of the used setup for simulation (SIM) and measurement (MSM) (l) as well as the factor between simulated and measured currents as a function of the applied voltage for different conductor heights (from \( h_1 = 1.2 \text{ m} \) to \( h_4 = 0.6 \text{ m} \) with 0.2 m spacing).

In general, the deviation between simulation and measurement is similar for all conductor heights investigated. The simulation results illustrated in figure 4 are conducted with an onset field strength of 9 kV/cm, which corresponds to -52.9 kV at a conductor height of 1.2 m and -46.2 kV at 0.6 m. Since the ion currents tend to be too low, additional simulations with reduced onset field strength were performed. To exemplify its influence on simulation results, simulations corresponding to the upper and lower limit of the experimentally determined range (5 - 9 kV/cm) are depicted in figure 5. Besides the simulated voltage-current relations, two measurements are illustrated. The first was performed with a normal conductor under rainy conditions, the second, apart from having a slightly lower conductor height, contained an artificial surface defect, made from thin metal wire, mounted on the lower side of the conductor and was performed under dry conditions.

Comparing the shape of the simulated V-I characteristics with the one measured under rainy conditions shows that there is no constant deviation in magnitude considering the ion currents for neither of the used onset field strengths. At voltages slightly above corona inception, the rate of rise of the corona current is considerably higher in the simulation than in a corresponding measurement. This trend however reverses at roughly twice the inception voltage, as a result of which measured corona currents can be twice as high as simulated ones for electric field strengths which may occur in full scale tower arrangements. Similar observations were made for different conductor heights (ranging from 0.6 m to 1.2 m). The obvious differences in the shape of the curves make clear that simply selecting a different onset value will not be sufficient.

In contrast, with an attached surface defect, the shape of the V-I characteristic changes considerably. Over a broad range of voltages starting at corona inception, measured and simulated data show a good correspondence. Towards higher voltages, the slope of the measured current is even lower than in the simulation. As previously mentioned, the simulation model takes into account surface irregularities by using a lower onset field strength. The similarity between simulated results and the use of an artificial defect indicates that constant field enhancements can be modelled with this approach.

However, rain constitutes a different case. Optical observations during the measurements confirm that drop behaviour changes considerably over the investigated voltage range. While pendant drops have a round shape and the drip-off process seems not to be influenced significantly below corona onset, for voltages that are considerably higher than corona inception voltage both drop shape and drip-off behaviour are subject to significant change. Under these conditions a certain number of drops form Taylor cones \([13]\) that stay stable for several seconds before ejecting small water droplets. While this happens, an interaction between adjacent drops can be observed.

Concluding, significant field enhancements leading to corona inception are expected to appear only during the short moment of drip-off for low applied voltages, which is confirmed by observations with an UV scope. At higher voltages field enhancements in form of Taylor cones have a much more stable character. Light emissions of the discharges confirm that these cones are a major source of corona. Similar observations can be found in literature \([9, 10]\). This effect may explain the rather constant ratio between measured and simulated ion currents for higher applied voltages, while it is subject to large change around corona onset.
4.2 Current density distribution at ground level

As a second measure to compare with and to determine influences on the distribution of the ion current density at ground level, the Wilson probe array described in section 2 is used. Figure 6 depicts a comparison of simulated and measured values for different voltages, ranging from -90 kV (V1) to -180 kV (V4).

The overall relative deviation between simulation and measurement, as shown in the bar graph, becomes smaller for higher applied voltages, meaning that at higher corona levels, the simulation appears to be more accurate. This supports the hypothesis, that the used simulation model with a fixed onset field strength may be insufficient to describe conductors under rainy conditions over a broad voltage range.

Additional information about the performance of the simulation tool can be obtained when looking at the spatially resolved deviation. For lower voltage levels, the relative deviation is bell-shaped with a maximum in the center, directly below the conductor. When applying higher voltages, the course of the ratio is subject to a remarkable change, it becomes more and more constant. Besides the previously described deviation of the total corona current, this proves that the ion current distribution is also influenced by the applied voltage.

Since the calculated ion current distribution depends on the electric field on the surface of an idealized conductor, a bell-like deviation curve delivers further support for the assumption that in reality the water drops lead to a charge generation with a stronger focus on the lowest parts of the conductor than the simulation. As the form of the simulated ion current profiles stays the same for different applied voltages, the more constant deviation between simulation and measurement shows that for similar ion current distributions voltages considerably above corona inception are necessary.

4.3 Inaccuracies of commonly used models

To explain the discrepancy between conducted measurements and obtained simulation results that occur under rainy conditions, a detailed understanding of the differences in discharge processes at dry and wet conductors is vital. Common simulation models are derived from dry conductors. To simplify the geometry, 2D cross sections are used and conductors are considered cylindrical [8, 6]. Below corona onset the maximum value for the electric field strength at the conductor surface is proportional to the applied voltage. Due to the inception of discharges and the resulting space charge, the field strength remains constant if the inception voltage is exceeded. In any case, the field strength is modelled time independent.

Stranded conductors as well as persistent surface changes like scratches lead to local field enhancements, where in fact the relation between applied voltage and maximal electric field value can be considered linear up to the point of corona inception, above which electric field values remain constant, as well as time independent in general. The same applies for surface changes that are constant for time frames which are significantly longer than the longest flight times of ions within a certain setup. While this may be true for pollution and surface degradation of overhead lines, it does not apply for drop formation processes under rainy conditions.

Figure 7 illustrates the difference between dry and wet conductors based on highly simplified schematic relations of the maximum electric field as well as the maximum space charge density at conductor surface as a function of the applied voltage for dry cylindrical (l), dry stranded (m) and wet cylindrical conductors (r).
Akazaki \cite{10}. Hence, the corona onset field strength is met at lower voltages, but in contrast to dry conductors at first only reached for the short moment of drip-off and only below the conductor at positions where drops are situated, which appears to have an influence on both distribution and magnitude of ion currents.

For significantly higher applied voltages, another corona regime applies. It is characterized by the appearance of drops forming sharp Taylor cones that last for several seconds. During this time, according to observations with a UV scope and in line with Hara et al. \cite{9,10}, the cones are sources of continuous discharges. Instabilities are caused by forces due to the electric field and result in the ejection of several small droplets. Afterwards the drop can form a Taylor cone again. While this behaviour is much more similar to a constant field enhancement than the corona regime for lower applied voltages, differences between the charge generation in simulation model and real conductor are quite possible. This effect may come into play even more when bundle conductors are taken into account since the maximum values for the electric field usually do not appear at the lowest part of each conductor, which may result in a shifted ion current profile. Furthermore, the influence of diffusion processes and an increasing ionization layer for high corona activity remain unclear.

### 5 Modifications of the simulation method

#### 5.1 Corona intensity

In the previous section the inaccuracy of the simulated corona intensity has been discussed. This is a result of using a highly simplified model in order to reduce computational effort. Rain drops do not constitute a constant field enhancement like scratches or pollution layers, but change with time and applied voltage.

To adapt for this character, a variable onset field strength value may be used. To derive a correction factor, a series of simulations was conducted and the V-I relations were compared with measured data. Every intersection of simulated and measured curves constitutes a point, where the chosen onset field strength leads to a correct corona current magnitude for a certain voltage. With this method, a relation between applied voltage and matching onset field strength can be derived. However, this relationship may only apply to the investigated setup. Compared to the voltage, the space charge free electric field strength constitutes a somewhat more general description of the corona intensity, since it takes into account the used geometry and hence is used for the description.

Conducting a simulation can hence be done by performing electrostatic simulations of the setup to determine the relation of applied voltage and maximum field strength at the conductor. Afterwards the maximum space-charge free field can be calculated for any applied voltage and a suitable onset field strength be determined for the simulation of the ion flow problem.

For lower field strengths this equation indicates that corona onset \( E_{\text{Laplace}} = E_{\text{on}} \) happens at a field strength of about 10 kV/cm. While first discharges are observed at lower field strengths, this value may be suitable to model the onset of a significant ion current flow, depending on the selection of the threshold. The information that can be obtained by extrapolation of the curves towards higher field strengths however is limited. Since field strengths below 4 kV/cm in combination with high space charge densities lead to stability problems in the simulation tool, no statement can be made regarding a possible change of the course of the presented curves in this area. However, it is obvious that the linear trend cannot be extrapolated to arbitrarily high Laplace field strengths as a zero-crossing of \( E_{\text{con}} \).
is physically impossible. Anyhow, due to the high corona intensity at these voltages, simplifying assumptions like neglecting the ionization layer thickness may be invalid. Hence, it remains unclear if the simulation tool is suitable for this range.

5.2 Inverse calculation of the charge generation to optimize ion current distribution

The accuracy, with which the simulated ion generation at the conductor surface corresponds to the distribution on the laboratory setup, cannot be judged directly since it is not possible to measure it. However, the ion current density distribution at ground level, which is connected to the charge generation at the conductor surface via the electric field lines, is recorded in the measurements.

To perform a comparison, an inverse calculation of the charge generation is developed. Input data for this algorithm are both measured ion current density at ground level and simulated lines of the Poisson field. Assuming that the courses of simulated field lines mirror the actual field lines, a charge generation profile can be computed. As illustrated in figure 9, this is accomplished by tracing back the charges collected by the Wilson probe array to their point of origin at the conductor surface.

A comparison between the simulated ion current density at the conductor surface and the results of the inverse calculation of the charge generation for the described geometry is illustrated in figure 10. The ion current density is depicted as a function of the angle (θ) on a cross section of the conductor, where θ = 0° points towards ground. Inversely calculated profiles are displayed in blue colour (index: Inv) and simulated profiles in green (index: S). For a better comparison of the curve shape, a version of the simulated profile, normalized to correspond with the maximum current density of the inversely calculated profile is plotted in red (dotted line, index: SN).

The simulations and measurements are conducted for the geometry described in sections 2 and 3 (h = 1 m) for four different voltages above corona onset (-62 kV, -75 kV, -100 kV and -120 kV corresponding to the indices 1 to 4).

Fig. 10: Ion current densities at conductor surface from simulation and the inverse calculation algorithm for four different voltages (-62 kV, -75kV, -100kV and -120kV from upper left to lower right)

The presented generation profiles support the thesis that the charge generation on overhead lines is influenced by rain and depends on the applied voltage. Especially for voltages slightly above corona onset, the charge generation appears to be much more focused onto the lower parts of conductor, where the pendant drops are situated. In contrast, generation at the sides and presumably the top part of the conductor is lower compared to the simulation. However, it has to be noted that especially at the outer parts of the recorded ion current profile, which correspond to the upper sides of the conductor surface, signal amplitudes are very low. Therefore the influence of errors is increased in this area. Additionally, only parts of the profile can be calculated that have field lines connected to the Wilson probes. In the investigated cases, this is the case for angles between approximately 110 degree and 250 degree. 

Fig. 9: Principle of operation of the inverse calculation of the charge generation
As previously mentioned, a possible explanation for the observed behaviour is that at lower applied voltages the critical field strength is reached only due to field enhancements caused by drops. Since the drip-off process is concentrated onto the lowest part of the conductor and drops are elongated in the electric field, the resulting charge generation is much more inhomogeneous than at an idealized conductor.

For higher applied voltages, the shape of the generation profile changes. It becomes more round and similar to the simulation. This means that charge generation becomes more uniform at these voltages, however investigations with an UV scope show that visible discharges remain focused to the lower part of the conductor and are concentrated on Taylor cones. Possible reasons for this behaviour may be that intense charge generation takes place at the lowest part of the rain drop, below the actual conductor. This changes the space charge distribution compared to the simulation, which may influence the electric field and therefore the paths of ions. Hence, the charge generation may appear more homogeneous than it actually is. Additionally, Coulomb forces may play a more significant role for higher space charge densities and diffusion effects may have an influence. Also discharges with little to no light emission at the side of the conductor cannot be ruled out. The profiles obtained by inverse calculation can be used to estimate the charge generation profile at the conductor surface as a function of the applied voltage. As a proof of concept, this was integrated into the used simulation tool. Figure 11 depicts measured and simulated ion current densities at ground level for the given setup. Comparing the field dependent charge distribution (red line, J\text{SIM,circ}) with the developed empirical filters (green line, J\text{SIM,emp}) shows, that a much better correspondence with the measured ion current distribution can be obtained.

![Graph showing ion current density at ground level](image)

**Fig. 11:** Ion current density at ground level for measurement and simulation with field dependent (J\text{SIM,circ}) and empirical (J\text{SIM,emp}) charge generation filters, applied voltage: -62 kV, onset field strength: 9 kV/cm

In addition, the ion current density for the more inhomogeneous empirical profile is significantly closer to the measured one even without adjusting the onset field strength. This shows that adapting simulations to empirical charge generation profiles constitutes an option to improve accuracy for the ion current distribution at lower corona intensities.

However, as mentioned before, for higher applied voltages that mirror the conditions at full scale hybrid towers, this difference is much smaller and probably negligible.

### 6 Conclusion

The generation of ion currents on HVDC overhead lines is strongly influenced by weather conditions, rain constituting a worst case [4]. To compensate for this influence without changing the simple geometric structure of the used model, within which conductors are described with circular cross sections, the onset field strength is often reduced using a constant factor [5, 6].

Within investigations for this paper, this approach is challenged since both V-I characteristics for the total ion current as well as ion current distribution at ground level of simulations differ from conducted measurements. This fact is explained with the voltage dependent behaviour of pendant drops: At applied voltages that only slightly exceed corona inception, the drip-off behaviour is not significantly affected by electric fields. Optical observations confirm that discharges are concentrated on drops at the moment they detach from the conductor, resulting in an intermittent discharge process, since the critical field strength is only exceeded temporarily, resulting in lower ion currents compared to the simulation model. Additionally, measured ion current distributions at ground level differ from the simulated ones. Comparisons of charge generation at the conductor surface of simulation and measurement, using an inverse algorithm, indicate that in reality a stronger focus of the charge generation onto the lowest parts of the conductor exists. Due to the simplicity of the simulation model, this effect of the pendant water drops is not taken into account.

At higher applied voltages and therefore high corona intensity, the drip-off behaviour is completely changed by strong electric fields. Taylor cones develop at the lower parts of the conductor that remain stable for several seconds and, in contrast to the drip-off behaviour at lower applied voltages, only eject several small water droplets during short time intervals of instability. These cones are sources of the quasi-continuous discharges that are observed. The ratio between simulated and measured total corona currents becomes constant from about twice the onset voltage on and the shape of the measured ion current distribution at ground level becomes similar to the simulated one. This constant deviation between simulation and measurement is possibly caused by the rather constant field enhancements of the Taylor cones. Due to the observed differences between simulation and measurement, adjusting the simulation appears to be necessary in order to improve the predictive character of the simulation tool. However, it is not possible to find a single value for the onset field strength, with which the V-I characteristic or the ion current distribution can be described correctly.
over a significant voltage range.

In order to improve the accuracy of the simulation results for rainy conditions, a field dependent correction of the onset voltage is successfully introduced. For the given setup, a relation between space charge free field strength and onset field strength is presented that makes an accurate calculation of ion currents possible over a broad voltage range.

In addition, modifications of the charge generation at the conductor surface are performed, using charge distributions computed by an inverse algorithm described in chapter 5.2. While at higher applied voltages the measured ion current distribution matches quite well with the original simulation model, at lower voltages accuracy can be improved considerably.

Concluding, to obtain accurate simulation results for ion currents under worst-case conditions, rain effects have to be included in the used simulation tools. For this purpose, the presented approaches appear to be suitable, however more complex geometries may necessitate further adaptations.

References


