



Calculation of the (I-V) characteristics of corona discharge in an electrode model with a rectangular to line configuration

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Abstract

This research compares the formulation of the current-voltage (I-V) characteristics of symmetric and asymmetric direct current CCP equipment in the case of corona discharges in the air. The electrode configuration model taken for the symmetric CCP case is the coaxial cylinder, and for the asymmetric CCP case, it is rectangular to the line. Both types of electrodes use a modified capacitance concept in the (I-V) characteristic calculations. This concept originates from a geometric approach solution of the size of active and passive electrodes, where there is a corona electric current multiplier factor (to conventional electric current quantities) as well as the nature of the corona discharge, which will collect at the sharp tip of the active electrode and passive electrode.

Keywords: CCP, asymmetric electrode model, (I-V) characteristics, corona discharge, modified capacitance

Introduction

There is no need to doubt the need for plasma technology to help with daily human activities, especially electronic equipment such as TVs, refrigerators, etc. Plasma technology is also used in the fields of health^[1], agriculture and biomedicine^[2], surface modification of polymer materials^[3], area coatings^[4], lens-shaped electrodes^[5], and dielectric barrier discharge^[6], etc. Plasma technology uses equipment similar to a capacitor called capacitively coupled plasma (CCP)^[7]. According to Stambouli *et al.*^[8], CCP equipment is divided into three categories: the electric asymmetric CCP, the direct current CCP, and the dual-frequency CCP.

For CCP equipment that uses the direct current (DC) model, the calculation of the plasma discharge's current-voltage (I-V) characteristics is very different from that of ordinary conventional electric currents. This can happen because plasma discharge is caused by various physical events, such as electrodynamics^[9], electric wind^[10], and so on. Of course, the best solution for the (I-V) characteristics, in this case, is to use a physical properties solution using quantum, electrical, and magnetic properties (usually using the concept of Maxwell's equations); as found by Zheng *et al.*^[11] & Wardaya *et al.*^[12], even though the resulting solution is only suitable for the initial corona discharge curve.

However, there is a (I-V) characteristic model using a fairly simple formulation through a geometric approach to the dimensions of the electrode. This formulation occurs in the direct current CCP model with a symmetrical arrangement of the active electrode to the passive electrode, namely in the case of a coaxial cylindrical electrode with the inner and outer cylinders, respectively, being the active and passive electrodes, which are radially symmetrical cylinder systems. This characteristic equation is expressed through equation^[13],

$$i = \frac{I}{l} = \frac{10^6}{l} \frac{4b_0 C_{CC}}{\sigma R^2} V(V - V_i), \quad (1)$$

where I is corona current (A), i is corona current/length (A/m), and σ is the density of the air relative to standard

conditions (250C, 76 cm Hg) in the range of $0.1 < \sigma < 35$. The constant b_0 is the mobility of air ions (O_2) at $\sigma = 1$. The quantities R and l are the radii of the outer cylinder and the length of the Coaxial Cylinders, respectively. The C_{CC} quantity is a capacitance formulation of a cylindrical coaxial electrode shape^[14] that is,

$$C_{CC} = \frac{2\pi\epsilon l}{\ln(R/r)}, \quad (2)$$

where r is the radii of the inner cylinder (thin wire). The striking thing about characteristic equation (1) is the appearance of the capacitance value of the coaxial cylinder, which is expressed in equation (2), as well as the appearance of an electric current multiplier factor of 10^6 . This multiplier factor is the comparative value of the plasma discharge electric current (which is very large) to that of ordinary conventional electric current.

The characteristic equation model (1) can be applied to direct current CCP with the active electrode having a shape that is not symmetrical to the passive electrode, which is referred to as electric asymmetric CCP, but with certain differences in formulation. This difference arises because, according to experimental results by Dobranszky *et al.*^[15], the plasma discharge will be seen collecting only at the sharper ends of the active electrode compared to the less sharp part of the active electrode, which is the condition of the electric asymmetric CCP model. The correction to equation (1)'s formulation, which is applied to the case of electric asymmetric CCP, appears in the formulation of the concepts of capacitance and electric current multiplier factor. According to research results by Wardaya *et al.*^[16-17], for the case of electric asymmetric CCP, an electric current multiplier factor of k is inserted in the capacitance calculation from the sharp, active electrode calculation section, which is called the modified capacitance equation.

The rectangular to line electrode configuration model

We present an example of the modified capacitance model of the garis-trapesium terbalik electrode model to illustrate

the capacitance calculation of the electric asymmetric CCP model in air. The illustration of the capacitance model is shown in Figure 1.

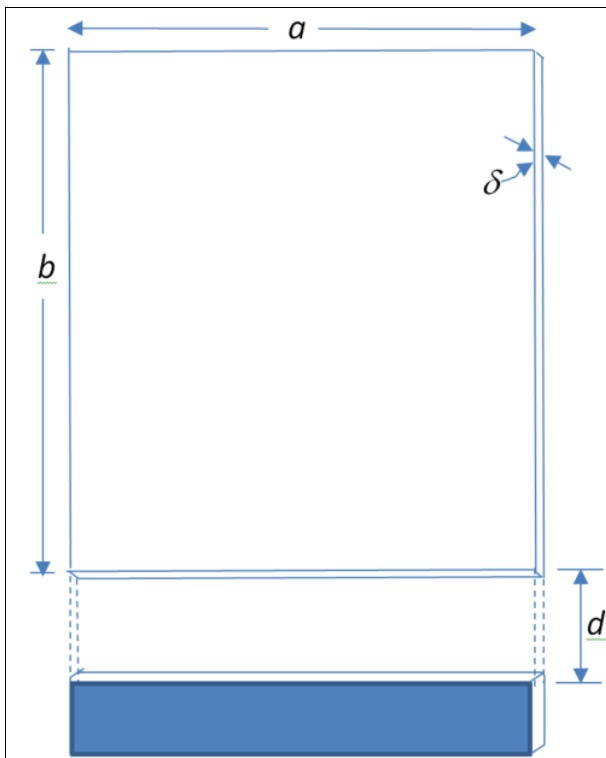


Fig 1: Illustration of an electrode model with a rectangular to line configuration

Figure 1 shows an active electrode as an upright rectangular plate with length a and width b thin plate thickness of δ . The passive electrode is an upright plate, and the distance between the two electrodes is d . Henceforth, this model is referred to as the rectangular to line electrode configuration model. If ΔA is the area of the active electrode facing downwards towards the passive electrode, then the amount of capacitance from the rectangular to line configuration model is defined as

$$C = \epsilon_0 \frac{\Delta A}{d} = \epsilon_0 \frac{a\delta}{d}, \tag{3}$$

where $\epsilon_0 = 8.854 \times 10^{-12} \text{ F}\cdot\text{m}^{-1}$. The capacitance values in eq. (1) apply if they occur in conventional electrical circuits that do not cause corona discharges. According to [15], a plasma discharge will occur if the tip of the active electrode is sharp enough so that a corona current will flow from the active electrode to the passive electrode. The multiplier factor for the corona current compared to conventional current is usually referred to as the k -shaped multiplier factor (because it is caused by the sharp shape of the active electrode), which is included in the capacitance formulation. What is the formulation for the electrode model depicted in Figure 1, which has equally sharp active and passive electrode shapes? This situation will produce additional effects besides the appearance of a corona current originating from the active electrode towards the passive electrode. This additional effect is the emergence of a reverse current from the passive electrode towards the active electrode again so that the corona current discharge event starts with the appearance of a corona current from the

active electrode towards the passive electrode (having a sign of positive current), followed by the corona current gradually decreasing and continuing with the appearance of a reverse current corona from the passive electrode to the active electrode (has a negative current sign). This situation causes the formulation of capacitance (3) to be modified by inserting a factor k and a positive and negative corona current change factor. For this event, a formulation of capacitance (3) as a function of voltage V is proposed, which is written as

$$C_{tot} = \epsilon_0 \frac{a\delta}{d} k \left(\frac{1 - \sin(0.1V\pi)}{1 - \cos(0.1V\pi)} \right), \tag{4}$$

where C_{tot} is a modified capacitance model that adds a factor k and a positive and negative corona current change factor as a function of voltage V . To calculate the (I-V) characteristics of the rectangular to line electrode configuration model, we can use formulation (1) adapted for the electric asymmetric CCP case,

$$I = \epsilon_0 k \frac{4a\delta b_0}{\sigma d^3} \left(\frac{1 - \sin(0.1V\pi)}{1 - \cos(0.1V\pi)} \right) V (V - V_i). \tag{5}$$

The difference that arises between the calculation of characteristics (I-V) from equation (1) for the CCP symmetric case and equation (5) for the CCP asymmetric case is

- The method of symmetrical multiplication of the electric current multiplier factor in the symmetric CCP case cannot be applied to the asymmetric CCP case because the corona electric current does not spread evenly to all parts of the active electrode tip but is only focused on the active electrode tip which has a sharp surface only.
- In the case of asymmetric CCP, the electric current multiplier factor k is inserted on the sharp part of the capacitance formulation's sharp electrode surface, referred to as the modified capacitance.
- For the case of the sharp active and passive electrodes, apart from the large corona discharge from the active electrode towards the passive electrode, it will also give rise to a reverse current from the passive electrode towards the active electrode, thus producing a positive corona current output (from the active electrode towards the passive electrode), and negative corona current (from the passive to the active electrode).
- The value of the multiplier factor k cannot be calculated using geometric concepts because it involves complex physical effects such as electrodynamic effects, electron winds, etc. The k value can only be calculated by a (I-V) characteristic graph program as a curve fitting effect, which physically shows the size of the corona discharge that occurs, or the large/small value of the discharge is determined by the considerable/small value of the k value.
- Equation (5) is the (I-V) characteristic form of the corona discharge in the asymmetric electrode model, which is adapted from equation (1) for the symmetric case, taking into account the existence of alternating corona discharges (positive and negative corona currents).

Discussion

The current-voltage (I-V) characteristics equation of corona discharge cases in symmetric and asymmetric CCP equipment can be calculated using physical methods (via Maxwell's equations) or geometric methods (electrode dimensions and modified capacitance). This study touches on the geometric approach to calculating the current-voltage (I-V) characteristics of the DC corona plasma discharge case in air. It adopts the geometric method used in the CCP symmetric case and applies it to the CCP asymmetry case with a plane-serrated knife electrode configuration model. In this study, the case of the active electrode position above the passive electrode was taken, and both were in an upright position in the air.

Conclusions

This research uses the rectangular-to-line configuration model to calculate plasma corona discharges' (I-V) characteristics. This calculation also uses a modified capacitance concept through a geometric approach. The physical or geometric approach method only calculates the approximate initial discharge curve from the (I-V) characteristic graph because the continuation curve of the (I-V) characteristic is quite difficult to predict due to the too complex physical problems in corona discharge events, which involve physical effects such as electrostatics, electron wind, quantum, etc. The use of a modified capacitance model by generating an electric current multiplier k as a fitting curve is a relatively simple approach to calculating the (I-V) characteristics of a corona discharge, compared to a solution approach based on physical effects, which requires the use of Maxwell's equations or quantum solutions. In the modified capacitance calculation, apart from the additional factor k , a factor that depends on the capacitance value of voltage V is also introduced to anticipate changes in the corona current value, which can be positive or negative.

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