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Calculation of the (I-V) Characteristics of Knife-Line Electrode Model in Air

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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 context of corona discharges in air. The electrode configuration model used for the symmetric CCP case is the coaxial cylinder, and for the asymmetric CCP case, it is the knife- line. Both types of electrodes use a modified capacitance concept in the (I-V) characteristic calculations. This concept originates from a geometric approach solution (electrode sizes), where there is a corona electric current multiplier factor (corona current multiplication factor compared to conventional electric current) as well as the nature of the corona discharge, which will collect at the sharp tip of the active electrode.

KEYWORDS: CCP, asymmetric electrode model, (I-V) characteristics, corona discharge, modified capacitance, knife-line.

I. 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 (Kim, & Kim, 2021), agriculture and biomedicine (Stryczewska, & Boiko, 2022), surface modification of polymer materials (Vidaurre, et al. 2002), area coatings (Anders, 2005), lens-shaped electrodes (Schmidt, et al. 2004), and dielectric barrier discharge (Bouremel, et al. 2013), etc. Plasma technology uses equipment similar to a capacitor called capacitively coupled plasma (CCP) (Saikia, et al. 2018). According to Stambouli et al. (2017), 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 (Guan, et al. 2018), electric wind (Robinson, et al. 1961), 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. (2015) & Wardaya et al. (2019), 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 (Robinson, et al. 1967),

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

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 < σ < 35. The constant b_0 is the mobility of air ions (O_2) at σ = 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 (Halliday, et al. 2013) that is,

$$C_{CC} = \frac{2\pi\varepsilon l}{\ln\left(R/r\right)}, \qquad (2)$$

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.

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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. (2008), 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. (2020, 2022, 2022A and 2022B), 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.

II. KNIFE-LINE CONFIGURATION MODEL.

We present an example of the modified capacitance model of the knife-line electrode model to illustrate the capacitance calculation of the electric asymmetric CCP model in the air-The illustration of the capacitance model in Figure 1 is

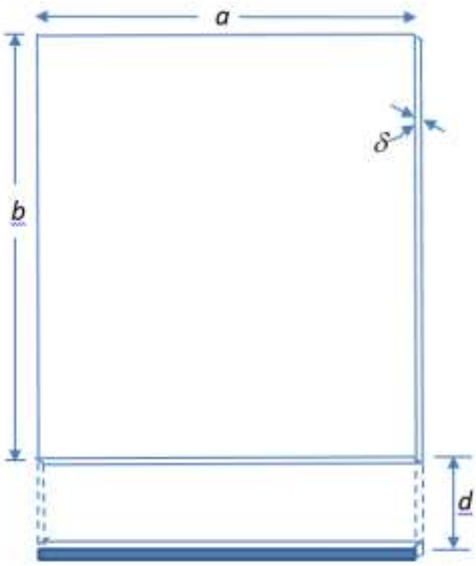

Figure 1. Sketch of the knife-line electrode configuration model.

The knife-line electrode configuration model consists of an active electrode in the form of a rectangular plate measuring a x b, with a thin plate thickness of δ. Passive electrodes are thin line-shaped plates. Its position is horizontal and located a distance d below the active electrode plate. According to research results by Wardaya et al. (2020, 2022A), the knife-line configuration model with an active electrode plate area of $a \times b$, which is a distance of d from the passive electrode, will have a capacitance value of

$$C = \varepsilon_0 \frac{\Delta A}{d} = \varepsilon_0 \frac{a\delta}{d} \ . \qquad (3)$$

For the knife-line electrode configuration model, as presented in Figure 1, both the active and passive electrode plates have sharp and flat surfaces, resulting in evenly distributed corona currents, as shown in Figure 1 above. Based on the reference from equation (3) and by entering an electric current multiplier factor of k on the part of the plate that emits a large corona current, the modified capacitance (because there is an additional factor k) of the line knife electrode configuration model is,

$$C = \varepsilon_0 k \frac{a\delta}{d} \ . \qquad (4)$$

To calculate the (I-V) characteristics of the knife-line electrode configuration model, we can use formulation (1) adapted for the electric asymmetric CCP case,

$$I = k\frac{4b_0}{\sigma}\left[\varepsilon_0 \frac{a\delta}{d^3}\right]V\left(V - V_i\right). \qquad (5)$$

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

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a. The method of symmetrical multiplication of electric current multipliers in the symmetric CCP case cannot be applied in the asymmetric CCP case because the corona electric current does not spread evenly to all parts of the active electrode tip but only focuses on the active electrode tip, which has a sharp surface. In this case, because both active and passive electrode surfaces are equally sharp, the plasma flow will flow uniformly from the active electrode to the passive electrode.
b. In the case of asymmetric CCP, the electric current multiplier factor k is introduced on the sharp part of the sharp electrode surface of the capacitance formulation, which is referred to as the modified capacitance. In this case, because all active and passive electrode surfaces are equally sharp, the k factor is directly multiplied as part of the capacitance formulation.
c. The value of the multiplier factor k cannot be calculated using geometric concepts because it involves complex physical effects, such as electrodynamic effects and electron winds. The k value can only be calculated using a characteristic graph (I-V) program, which employs curve fitting to physically show the size of the crown discharge that occurs. Alternatively, the size of the discharge value is determined by the size of the k value.
d. The radius of the outer cylinder R of the passive electrode in the symmetric CCP case in equation (1) can be replaced by the distance between the two electrodes in the asymmetric CCP case.

III. DISCUSSION

The current-voltage (I-V) characteristics equation for corona discharge cases in symmetric and asymmetric CCP equipment can be calculated using either physical methods (via Maxwell's equations) or geometric methods (based on electrode dimensions and modified capacitance). This study explores the geometric approach to calculating the current-voltage (I-V) characteristics of the DC corona plasma discharge in air. It employs the geometric method used in the CCP symmetric case and applies it to the CCP asymmetry case, utilizing a knife-line electrode configuration model. The position of the active electrode is vertical, and the position of the passive electrode is also vertical below the active electrode.

IV. CONCLUSIONS

This research uses a knife-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 electrodynamics, electron wind, quantum, etc. The use of a modified capacitance model, which generates 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 that require the use of Maxwell's equations or quantum solutions.

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