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Calculation of the (I-V) Characteristics of Corona Discharge in an Asymmetrical Model from Active Electrodes to Passive Electrodes

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ABSTRACT: This research discusses the comparison of 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 is the plane-serrated knife. 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.

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),

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

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 (Halliday, et al. 2013) that is,

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

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. (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. PLANE-SERRATED KNIFE ELECTRODE CONFIGURATION MODEL.

We present an example of the modified capacitance model of the plane-serrated knife 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.

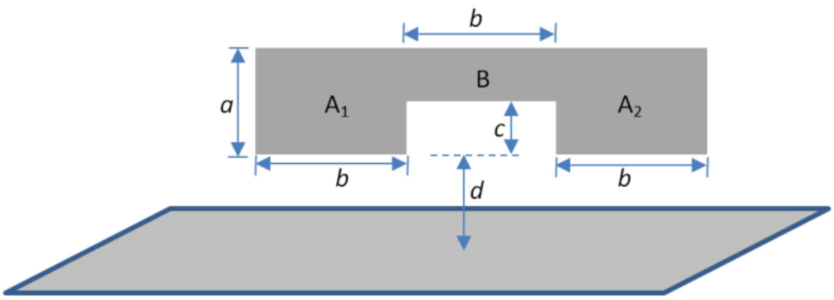

Figure 1. Sketch of the plane-serrated knife electrode configuration model.

The plane-serrated knife electrode configuration model consists of an active electrode in an upright position, consisting of three serrated rectangular plates: two plates, A_1 and A_2, of the same size, $a \times b$ and one plate *B* measuring $(a-c)\times b$. The passive electrode is a large rectangular plate that can accommodate all the corona electric current from the active electrode. This position is horizontally and located as far away as *d* below the plate A_1 or A_2. According to research results by Wardaya et al. (2020, 2022A), the plane knife 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

$$C_h = \varepsilon_0 b \ln\left|1 + \frac{a}{d}\right| . \quad (3)$$

For the plane-serrated knife electrode configuration model, as presented in Figure 1, the active electrode plates A_1 and A_2 will emit a fairly large corona current coming out of the two lower sharp edges of the active electrode plate towards the passive electrode. Meanwhile, plate *B* does not appear to emit corona current from the bottom surface of the active electrode to the passive electrode because the shape of the bottom surface of the active electrode is not sharp. Based on the reference from equation (3) and by inserting an electric current multiplier factor of *k* on the part of the plate that emits a large corona current, the amount of modified capacitance (because there is an additional factor *k*) of the plane-serrated knife electrode configuration model can be written as,

$$C_A = 2k\varepsilon_0 b \ln\left|1 + \frac{a}{d}\right| \quad \text{and} \quad C_B = \varepsilon_0 b \ln\left|1 + \frac{a-c}{c+d}\right| . \quad (4)$$

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C_A is the amount of capacitance originating from active electrode plates A_1 and A_2, which contain an electric current multiplier factor k. C_B is the amount of capacitance originating from active electrode plate B. To calculate the (I-V) characteristics of the serrated-plane electrode configuration model, we can use formulation (1) adapted for the electric asymmetric CCP case,

$$I = \frac{4b_0}{\sigma}\left[\frac{C_A}{d^2} + \frac{C_B}{\left(c+d\right)^2}\right]V\left(V - V_i\right). \tag{5}$$

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

a. 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.

b. 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.

c. 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.

d. The radius of the outer cylinder R of the passive electrode in the symmetric CCP case in equation (1) can be replaced as the distance between the two electrodes in the asymmetric CCP case.

III. 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. The position of the active electrode is vertical, and the position of the passive electrode is horizontally below the active electrode.

IV. CONCLUSIONS

This research uses a plane-serrated knife 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 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.

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