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Modified Capacitance Model In The Corona Plasma Discharge.

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Abstract
This research calculates the modified capacitance of the electrode capacitively coupled plasma (*CCP*) model with a crown sharp-plane configuration. The *CCP* model is an electrode model similar to the principle of a capacitor in a conventional circuit but differs in the arrangement of the electrodes. In the case of a positive corona, the structure of the positions of the active electrodes is almost vertical in the air, and the part of the passive electrodes is lying horizontally under the active electrodes. The shape of the active electrode is sharp at the tip of the electrode, which will cause a high potential gradient in that area, resulting in a more significant plasma discharge in the pointed area than in the less sharp area. A current multiplier factor k is entered in the tapered region of calculating the capacitance model (modified capacitance) to anticipate the difference in the plasma flow. The modified capacitance model for calculating the corona discharge's current-voltage (*I-V*) characteristics has proven that geometric calculations of the electrodes can also be carried out without using a physical calculation model (Maxwell's equations).

Keywords : CCP, Corona discharge, crown sharp-plane configuration, current multiplier factor *k*, (*I-V*) characteristics

1. Introduction.

Plasma discharge-based electronic equipment technology has attracted much attention from the public and industry because it has several advantages that conventional electronic equipment does not have. One of these plasma equipment technologies is called capacitively coupled plasma (CCP) (Saikia et al., 2018), which has an electrode configuration like a capacitor in conventional electronic circuits.

Usually, the CCP model is composed of two electrodes in a mutually perpendicular position. In the case of a positive dc corona plasma discharge, the active electrode is in a vertical position. The lower end of the electrode has a sharp surface, and the passive electrode has a large enough surface area in a horizontal place below the active electrode (van Veldhuizen and Rutgers, 2001). This CCP equipment can produce a corona plasma discharge if the dc or ac voltage difference is applied between the two electrodes.

Corona discharge events are characterized by a substantial electric current compared to conventional electric currents. This difference is caused in the case of corona discharge; there are various physical events such as convective heat transfer (Robinson, 1970), electric wind (Robinson, 1962), electrostatic precipitation (Bush et al., 1979), etc. Most corona discharge events will emerge from the surface of the active electrode geometry, which is sharp towards the passive electrode below it because the surface of the pointed geometry will have a high potential gradient (van Veldhuizen and Rutgers, 2001).

Several journals have discussed the shape of the current-voltage (I-V) characteristics of various electrode/capacitor configuration models such as cylinder-wire-plate configuration (Dumitran et al., 2007), sub-millimeter electrode gap configuration (Tirumala et al., 2011), needle-to-plate configuration (Kanazawa et al., 2002), and the electro-hydrodynamics (EHD) model (Guan et al., 2018).

This research discusses one of the CCP models with a sharp crown-plane electrode configuration consisting of an active electrode in the form of a pointed crown and a passive electrode in the form of a plate wide enough in a horizontal position below the active electrode. The research focuses on calculating the capacitance value to be used in formulating the current-voltage characteristics in the case of a positive dc corona discharge.

2. Electrode Configuration

An overview of the CCP model with a sharp crown-plane electrode configuration can be seen in Figure 1,

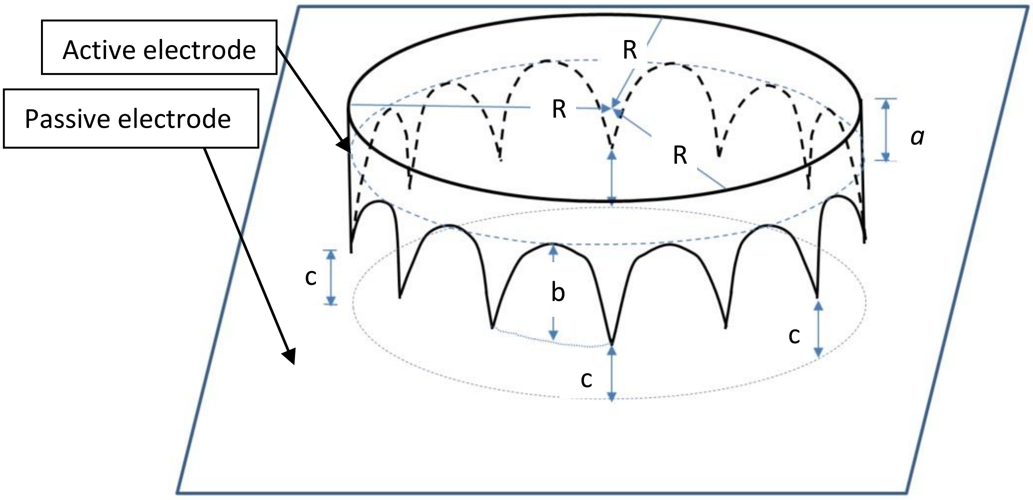

Figure 1. View of the electrode model with the sharp crown-plane configuration.

Before calculating the capacitance value from the model shown in Figure 1, we first look at the capacitance value with a rectangular active electrode curved with a flat plane curvature angle of $\Delta\phi$, and the distance from the center of curvature has a radius of curvature of ρ, as illustrated in Figure 2.

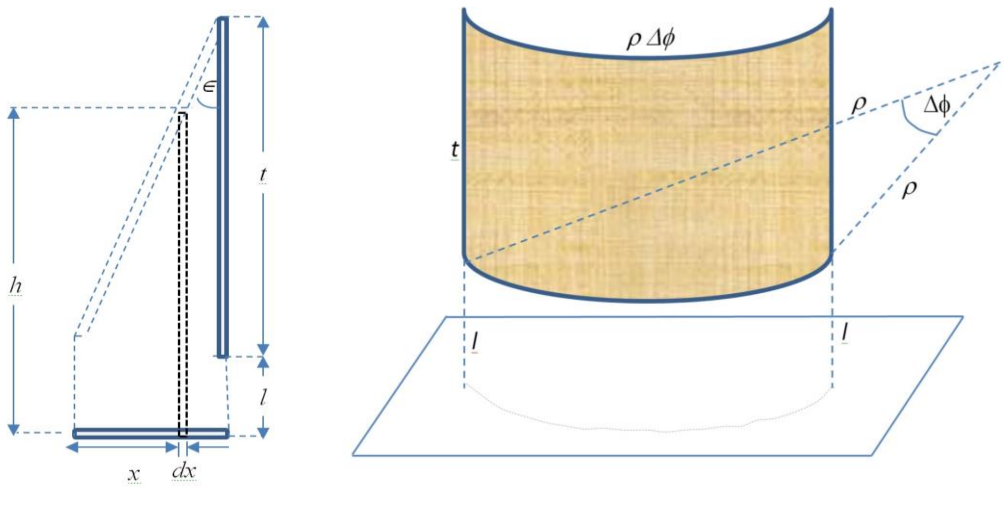

Figure 2. (a). A curved rectangular plate with an angle of curvature to the horizontal plane $\Delta\phi$, which is inclined, forms an angle $\in$ to the vertical plane (b). The rectangular plate is curved with an angle of curvature to the horizontal plane $\Delta\phi$ and in an upright position ($\in = 0^o$).

Figure 2(a) illustrates the viewpoint from the side of the two active and passive electrodes, where the active electrode (curved plate) is in two positions, namely a tilted position concerning the vertical plane (with an inclination angle of $\in$) and an upright position. Figure 2(b) is a front view for the case of the active electrode in the upright position ($\in = 0^o$). Through Figure 2, we can calculate the capacitance value in the case of the corona discharge.

3. Capacitance Value

The definition of the capacitance value of 2 parallel plates is written as (Neff Jr., 1991)

$$C = \varepsilon_0 A/h, \tag{1}$$

where C is the value of the capacitance, ε_0 is 8.854 × 10−12 F•m^{-1}, A is the area of the plate, and h is the distance between the active and passive electrodes. The capacitance element value in Figure 2.(a) can be calculated using the capacitance formula (1) at cylindrical coordinates, which is written as,

$$dC = \varepsilon_0 \frac{dA}{h} = \varepsilon_0 \frac{\rho d\phi\, dx}{(x\cot\in + l)} \quad ; \quad 0 < x < t\sin\in. \tag{2}$$

The capacitance value from equation (2) for figure 2. (a) can be written as,

$$C_A = \varepsilon_0 \rho \int d\phi \int_{z=0}^{t\sin\in} \frac{dx}{(x\cot\in + l)} = \varepsilon_0 \rho\, \Delta\phi \int_{z=0}^{t\sin\in} \frac{dx}{(x\cot\in + l)}. \tag{3}$$

Figure 2. (b) is the active electrode plate from Figure 2.(a) is in a position perpendicular to the vertical plane ($\in = 0^o$) and has an angle of curvature of the plate with a horizontal plane of $\Delta\phi = \pi/12$. The capacitance value obtained from Figure 2.(b) is

$$C_B = \lim_{\in\to 0} \lim_{\Delta\phi \to \frac{1}{12}\pi} \varepsilon_0 \rho\, \Delta\phi \int_{z=0}^{t\sin\in} \frac{dx}{(x\cot\in + l)} = \frac{\pi}{12} \varepsilon_0 \rho \ln\left|\frac{t}{l} + 1\right|. \tag{4}$$

The active electrode in Figure (1) consists of a circular plate with a horizontal circular radius of R and a plate height of $z = a$, and a circular plate (has a horizontal radius of R), which includes 12 symmetrical arcs of ½ circle vertical radius b with the cutting edge downward. For the circular plate section with a height $z = a$, we can use equation (3) to calculate it based on the data $t = a$, $l = b + c$, $\rho = R$, dan $\Delta\phi = 2\pi$, resulting in a capacitance value of

$$C_1 = \varepsilon_0 2\pi R \ln\left|\frac{a}{b+c} + 1\right| = \varepsilon_0 2\pi R \ln\left|\frac{a+b+c}{b+c}\right|. \tag{5}$$

Now examine 1 part of the sharp arc (semicircle with radius b) from the figure (1). Using the help of figure (3), it turns out that the curve has a symmetrical property of ¼ part of the circle (with a sharp electrode tip) on the left side of the u-axis to the right of the u-axis. The depiction of the ¼ part of the circle to the right of the u-axis can be seen in Figure (3) below,

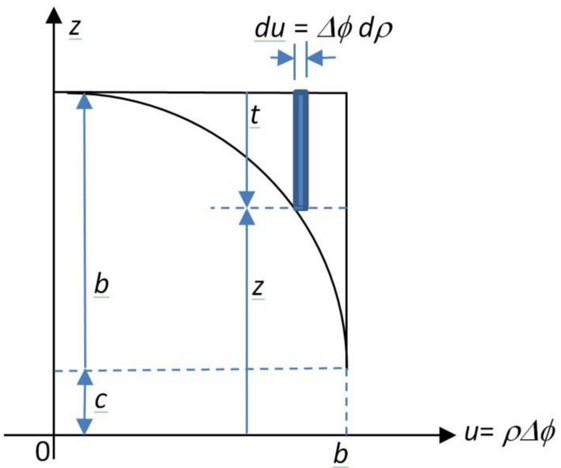

Figure (3). Illustration of a ¼ circle of an active electrode model in a semicircle with a vertical radius of b that is pointed downwards. The figure is 1/24 part of the circular curved electrode of radius b (at the active electrode) in Figure 1.

Figure (3) relates the equation of a circle with $\Delta\phi = \pi/12$ and the variable $u = \rho\Delta\phi = \rho(\pi/12)$ through the following equation,

$$\left(\tfrac{\pi}{12}\rho\right)^2 + \left(z-c\right)^2 = b^2 \;\; ; \;\; b = \tfrac{1}{12}\pi R \;\; ; \;\; t = c + b - z. \qquad (6)$$

From equation (6), we obtain the value of the circumference element of the tube circle $d\rho$ concerning the z-axis as,

$$d\rho = 6\frac{d\left[b^2-\left(z-c\right)^2\right]}{\pi\sqrt{b^2-\left(z-c\right)^2}}. \qquad (7)$$

To calculate the value of the dC capacitance element from the Figure (3), you can use the formulation on the far right side of equation (4), but of course, by changing the notation C_B to dC and the notation ρ to $d\rho$ (which values in equation (7)), as well as by changing the variable l to z, which results in the capacitance element equation as,

$$dC = \frac{\pi}{12}\varepsilon_0 \ln\left|c+b\right| \, d\rho - \varepsilon_0 \ln\left|z\right| d\left[b^2-\left(z-c\right)^2\right]^{1/2}. \qquad (8)$$

The solution of the capacitance value from equation (8), with the help of Gradshteyn and Ryzhik (2007), will produce the capacitance equation of the electrode arrangement in Figure (3) as

$$C = \frac{\pi}{12}R\varepsilon_0 \ln\left|c+b\right| - \varepsilon_0 b \ln\left|\,c\,\right| + \varepsilon_0 b - \left(\frac{\pi}{2}\right)\varepsilon_0 c + \left(\frac{\pi}{2}\right)\varepsilon_0\sqrt{c^2-b^2} - \varepsilon_0\sqrt{c^2-b^2}\sin^{-1}\left(\frac{b}{c}\right). \qquad (9)$$

Equation (9) is a capacitance value in conventional electronic circuits without involving a corona discharge event. For the case of corona discharge, equation (9) needs to add the multiplication factor of the corona current, which is entered manually in the integration result of the pointed form of the active electrode area in the modified capacitance formulation. This factor is the k current multiplier number (Wardaya et al., 2022). According to the calculation of the (I-V) characteristic graph of the corona discharge, the k value is the curve fit value.

According to physical reasoning, the greater the k value, the greater the plasma flow. The greater the plasma flow is characterized by, the sharper the shape of the active electrode (Dobranszky et al., 2008), so the value of k is also sometimes referred to as the form sharpness factor of the active electrode (Wardaya et al., 2022) in the case of a positive corona discharge.

The magnitude of the capacitance value at the sharp part of the active electrode in Figure 1 can be derived from equation (9) by providing a multiplier factor of 24 (the number of multiples of the curve from the figure (1) to the figure (3)) and entering the factor k in the sharp integration area of the active electrode, which gives the following equation,

$$C_2 = \varepsilon_0 k\left\{2\pi R\ln\left|c+b\right| - 24b\ln\left|\,c\,\right| + 24b - 24\sqrt{c^2-b^2}\sin^{-1}\left(\frac{b}{c}\right)\right\} + 12\pi\varepsilon_0\sqrt{c^2-b^2} - 12\pi\varepsilon_0 c. \qquad (10)$$

The total capacitance value in the electrode arrangement in Figure (1) for the sharp crown-plane electrode configuration model is the sum of the capacitance values originating from the curved circular plate with a plate width of a and the capacitance value of the active electrode with a sharp surface with a radius of curvature equal to b, is

$$\begin{aligned} C_{tot} = C_1 + C_2 &= \varepsilon_0 2\pi R \ln\left|\frac{a+b+c}{b+c}\right| + 12\pi\varepsilon_0\sqrt{c^2-b^2} - 12\pi\varepsilon_0 c \\ &\quad + \varepsilon_0 k\left\{2\pi R\ln\left|c+b\right| - 24b\ln\left|\,c\,\right| + 24b - 24\sqrt{c^2-b^2}\sin^{-1}\left(\frac{b}{c}\right)\right\}. \end{aligned} \qquad (11)$$

4. Electric Current Formulation

The total value of the electric current that comes out of the electrode system with a sharp crown-plane configuration for the case of corona plasma discharge through the concept of electrode geometric calculations is (Wardaya et al., 2022)

$$I=-\frac{dQ}{dt}=-\frac{\mu_0\left(V-V_i\right)^2\left(C_{tot}\right)^3}{\left(2\pi R\delta+12\delta^2\right)^2\varepsilon_0^{\ 2}},\tag{12}$$

where $\mu_0 = 4\pi \times 10^{-7}$ Hm^{-1}, δ is the thickness of the electrode plate and $(2\pi R\delta + 12\delta^2)$ is the Gaussian area. Equation (12) is the value of the electric current as a function of the voltage of the corona plasma discharge model with a sharp crown-plane configuration consisting of two electrodes in mutually perpendicular positions, with the active electrode having a sharp crown shape and the passive electrode having a rectangular shape.

5. Discussion

The problem that often arises in calculating the current-voltage (*I-V*) characteristics of a corona discharge case is the curvature of the current curve as a function of voltage, which is different from that of conventional electric circuits. Usually, in the case of a corona discharge, the electric current is a function of the square of the measured voltage. The physical reasons for the curvature of the curve (*I-V*) are caused, for example, by the EHD flow, electric wind, etc. Apart from physical reasons, there are also geometric reasons based on the nature of the plasma flow, which gets more significant as it exits the surface of the active electrode, which is getting sharper (in the case of a positive plasma discharge). This property can occur because of the nature of the high potential gradient on the tapered electrode surface. This research emphasizes the sharp geometric nature of the electrode surface, using a modified capacitance concept (inserting a k factor into the capacitance calculation).

6. Conclusion

This study formulates modified capacitance values for the sharp crown-plane electrode configuration model. The capacitance formulation comes from the CCP model; namely, the position of the active electrode is vertical in the air, and the passive electrode is in a horizontal lying position under the active electrode so that the two electrodes are perpendicular to one another. Modified capacitance means calculating the capacitance by adding the plasma flow's multiplier factor k to the active electrode's sharp area.

References

1. Saikia P, Bhuyan H, Escalona M, Favre M, Wyndham E, Maze J, & Schulze J. (2018). Study of dual radio frequency capacitively coupled plasma: an analytical treatment matched to an experiment. *Plasma Sources Science and Technology*, *27* (1).
2. van Veldhuizen EM, & Rutgers WR. (2001). Corona Discharges : Fundamental and Diagnostics. *4th Frontiers in low temperature plasma diagnostics*, 40-49.
3. Robinson M. (1970). Convective Heat Transfer at The Surface of A Corona Electrode, *International Journal of Heat and Mass Transfer*, *13*(2) : 263-274.
4. Robinson M. (1962). A History of the Electric Wind, *American Journal of Physics*, 30: 366-372.
5. Bush JR, Feldman PL, & Robinson M. (1979). High Temperature, High Pressure Electrostatic Precipitation, *Journal of the Air Pollution Control Association*, *29*(4), 365-371
6. Dumitran LM, Dascalescu L, Notinger PV, & Atten P. (2007). Modelling of corona discharge in cylinder-wire-plate electrode configuration, *Journal of Electrostatics*, *65*, 758-763.
7. Tirumala R, Li Y, Pohlman DA, & Go DB. (2011). Corona discharges in sub-millimeter electrode gaps, *Journal of Electrostatics, 69*, 36-42.
8. Kanazawa S, Ito T, Shuto Y, Ohkubo T, Nomoto Y, & Mizeraczyk J. (2002). Chacarteristics of laser-induced streamer corona discharge in a needle-to-plate electrode system. *Journal of Electrostatics*, *55*, 343-350.
9. Guan Y, Vaddi RS, Aliseda A, Novosselov I. (2018). Analytical model of electrohydrodynamic flow in corona discharge. *Physics of Plasmas*, *25*: 083507. https://doi.org/10.1063/1.5029403.
10. Neff Jr. HP. Introduction Electromagnetics, John Wiley & Sons, Inc.: Canada; 1991.

11. Gradshteyn IS, & Ryzhik IM. Table of Integrals, Series, and Products. 7th ed. USA: Academic Press, Elsevier Inc; 2007
12. Wardaya AY, Muhlisin Z, Suseno JE, Munajib C, Hadi S, Sugito H, & Windarta J. (2022). Capacitance Calculation Model in Corona Discharge Case, *Mathematical Modelling of Engineering Problems, 9*(5): 1161-1171. doi: 10.18280/mmep.090501
13. Dobranszky J, Bernath A, & Marton, HZ. (2008). Characterisation of the plasma shape of the TIG welding arc, *International Journal of Microstructure and Materials Properties*, *3*(1): 126-140. doi: 10.1504/IJMMP.2008.016949.