Current Voltage Analysis of High Voltage Plasma Discharge

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Abstract. Nowadays plasma technology can be used in various types of sectors in everyday life. The development of research on plasma technology provides many benefits in every sector, like industrial for material processing, environment for waste treatment, etc. This research aims to see the current-voltage impact on plasma discharge using Inverter Boost Kit 15 kV as the source of plasma, to find the energy needed to produce plasma and the distance of electrodes when the plasma occurs. Sensors of current and voltage were installed simultaneously on each side to measure the values during plasma discharges. Mathematical calculations were also performed to determine the electric charge and capacitance values of plasma. As the result based on the secondary current value, the discharge type of plasma is corona discharge, because the values reach the order of microampere. The capacitance value temperature value increase when batteries supply higher current to the electric motor, while voltage is decreasing. The capacitance value affected when the discharge gap change. The average discharge gap value is 5 mm, and when the discharge gap increase, the capacitance value will decrease.

1. Introduction
Plasma technology nowadays is a very needed technology because of its benefits in various types, like industrial, health, etc in everyday life. Plasma is the fourth state of matter, which can occur when the temperature or energy of a gas is raised to allow the ionized gas atoms to make the gas release its electrons which normally surround the nucleus [1]. The term plasma was first coined in 1928 and was defined as an "approximately electrically neutral collection of ions and electrons which may or may not contain a background neutral gas, and which is capable of responding to electric and magnetic fields" [2]. Analysis of plasma technology requires an accurate measurement system. This is because, based on the amount of current and voltage at the time of the plasma, it can be analyzed the type of plasma produced, as well as further analysis of the plasma itself. The lifespan of plasma from generation to arc is broken into three regions that are separated by the amount of current present [2]. The three regions are referred to as, dark discharge, glow discharge, and arc discharge [2]. Based on those regions, we get that Inverter Boost Kit 15 kV produce corona discharge plasma type.

Corona discharge plasma happens in the dark discharge region. One aspect that characterizes corona discharges is the current-voltage curves (CVCs) in which the current increases from the inception voltage (V0) up to the breakdown voltage [3]. The types of electrodes affect the characteristics of corona discharge. The corona inception voltage is the lowest while the maximum charge magnitude is the highest from the sharp electrode compared to the flat and sphere electrodes [4]. Corona discharge is a partial breakdown of gas at a relatively strong electric field that is...
established between two inhomogeneous electrodes at or near the atmospheric pressure [5]. The characteristics of corona discharge are important both in theoretical researches and practical applications [6]. Corona discharge is currently found at the basis of an increasing number of industrial and technological applications such as electrostatic precipitator (ESP) and separators, surface treatment, ozone generator, electrophotography, painting, and spraying powders, etc [7]. Recently, important applications of the corona discharges include the surface treatment of hazardous gases and in the field of the food industry [8]. Moreover, corona discharge plasma is also used as water treatment. Water treatment technology is plasma technology [9].

Based on the amount of current and voltage that occurs in the plasma, further analysis can also be carried out on the electric charge and capacitance at the time of the plasma. The amount of electric charge obtained, based on the amount of current that occurs when plasma occurs can be defined based on the following formula

$$Q = \int i \, dt$$  \hspace{1cm} (1)

Where $Q$ is the value of the electric charge, $i$ is the current that occurs per $dt$ as the time derivative. From this equation, it can be concluded that the amount of electric charge depends on the amount of current that occurs in units of time. This analysis method is also used in arc discharge plasma, to get the value of power consumption and discharge gap [10].

Capacitance in the plasma occurs due to the presence of two electrodes separated by air, which can be likened to atmospheric pressure in the air. Breakdown voltage occurs at the beginning of the process of formation of a plasma in the air so that it can be likened to a failure of the capacitor in holding the breakdown voltage. The capacitance value is obtained from the magnitude of the electric charge and the voltage as in the following formula.

$$C = \frac{Q}{V}$$  \hspace{1cm} (2)

Where $C$ is the value of capacitance, and $V$ is the potential difference. Capacitance value used to analyze the distance or discharge gap of electrodes when the plasma discharge occurs.

2. Experimental Setup and Method
The circuit to produce a plasma source that we use in this study is a 15KV High-Frequency DC High Voltage Arc Ignition Generator Inverter Step Up Boost Module 18650 DIY Kit U Core Transformer Suite 3.7V. This device using a voltage source derived from a 3.7 V Lithium Battery which produces a high voltage plasma with a maximum voltage reaching 15 kV and 2A maximal working current [11]. High voltage plasma produces from the transformer with a ratio of 1:1000.

![Figure 1. a) Schematic system for simultaneous current-voltage measurement of Inverter Boost Kit 15 kV b) plasma event](image)
The schematic circuit for measuring currents and voltages on high voltage plasma Inverter Boost kits 15 kV is shown in Fig 1a. The current sensor used is the current sensor ACS712 5A with Arduino as Vcc. Current sensor connected to the primary side of the transformer in series, measuring only in the primary current section. To get the current value on the secondary side will be done by predictions using calculations. For voltage measurements, the PC-Oscilloscope connector, connected in parallel on both sides, the primary and secondary side of the transformer. For secondary voltage measurements, high voltage digital multimeter probes are used because of the magnitude of the high voltage that may occur on the secondary side of the transformer. All measurement data are measured simultaneously and recorded in the Multi Virtual Analyzer application using PC-Oscilloscope.

### Table 1. Resistance Measurement

| Measurement | Rp(Ω) | Rs(KΩ) | Rs(Ω) |
|-------------|-------|--------|-------|
| 1           | 0.8   | 0.811  | 811   |
| 2           | 0.7   | 0.81   | 810   |
| 3           | 0.9   | 0.81   | 810   |
| 4           | 0.8   | 0.809  | 809   |
| 5           | 0.6   | 0.81   | 810   |
| Average     | 0.76  | 0.81   | 810   |

Table 1 shows the result of resistance measurements. The measurement made five times, then calculate the average of the result. The result is for validation that the ratio number is more or less 1:1000.

From current-voltage data, calculations will be performed to obtain predictive data about currents on the secondary side or can also be considered as current flowing when plasma occurs. The formula to get the current value on the secondary side is based on the principle of conservation of energy because we assume that no energy is lost along the way, conservation of energy requires that

\[ P_p = P_s \] (3)

\[ \frac{V_p}{V_s} = \frac{I_s}{I_p} \] (4)

\[ V = I \cdot R \] (5)

Then, we add Equation 5 to Equation 4 to get the secondary current value

\[ I_s = \sqrt{\frac{I_p^2 R_p}{R_s}} \] (6)

Where \( V_p \) is the voltage on the primary side, \( V_s \) is the voltage on the secondary side, and \( I_p \) is the current on the primary side.

Based on the experimental results will be measured the amount of energy needed for the occurrence of plasma and the distance of the electrode at the time when the plasma occurs. To get the amount of energy needed, we can use the following formula

\[ U = \frac{1}{2} \times Q \times V_s \] (7)

Where \( U \) is the potential energy, \( Q \) is the electric charge, and \( V_s \) is the voltage on the secondary side of the circuit. To get the electrode distance at the time of the plasma is as follows
\[ d = \frac{k\varepsilon_0 A}{C} \]  

(8)

Where \( d \) is the distance between the electrodes, \( k \) is the space constant, \( \varepsilon_0 \) is the permittivity with a value of \( 8.85 \times 10^{-12} \), \( A \) is the area of the electrodes used, and \( C \) is the value of the capacitance obtained.

3. Results and Discussions

![Graph showing measured secondary voltage value for 10 seconds and secondary current value](image)

**Figure 2.** (a) Measured secondary voltage value for 10 seconds and (b) secondary current value

Based on the graph shown in Fig 2a, the experiment was carried out for 10 seconds. During the experiment, the electrodes on the secondary side are deliberately kept away so that the plasma goes out. It was shown at 5s – 6.5s. When the plasma discharge occurs in the electrode, there is a surge value in the secondary current value side and also occurs on both sides voltages. On the secondary side, the voltage jumps to approximately 57 kV in positive notation and -47 kV in negative notation.

Based on the measured current-voltage value, a calculation is performed to obtain the secondary current value for further analysis. The graph is marked with ON/OFF to explain the presence of plasma events and when there is no plasma event. Using Equation 4, we get the secondary current value shown in Fig 2b. Based on the graph, the value of the secondary current reaches the microampere order. The largest current value with positive notation is 0.905 µA. The sign notation indicates the direction of an electric current [13]. Based on the current value, can be assumed that the type of plasma that occurs is the type of corona discharge that occurs in the dark discharge regime [14], but it needs more experimental setup and calculation variable to prove the discharge type of plasma.

Furthermore, In Fig 2b because the secondary current value predicted with a calculation based on Equation 6, the values when there is no plasma on the electrode will still have value, but actually when there is no plasma between the electrodes, the current value should be obtained when the absence of plasma is zero. When the plasma in OFF condition, there is no plasma event and there is no current flowing between the electrodes on the transformer secondary side. Because when the discharge gap increases, the current density decreases [15], thus the current value must be decreased. That means the peak value of the secondary current, is the value of current flowing at the electrodes. Then, the normalized secondary current value will be used to analyze the electric charge value.
Figure 3. Histogram graph of (a) electric charge, and (b) enlarged histogram graph

Based on the electric charge histogram graph, we can get the value of ionized charged particles. The ionization process is the phenomenon associated with stripping electrons from an atom thus creating a pair of negatively and positively charged particles [16]. Electric charge histogram graphs used the secondary current value data and the data value on the graph has been absolute.

Based on the histogram graph shown in Fig 3a, it can be seen the value of the electric charge obtained when plasma occurs. The electric charge value with range $0 \times 10^{-12}$ C is negligible because the data value obtained when there is no plasma event. This is because, in making the graph using the calculation results of the whole secondary current value, the electric charge obtained is the value of the electric charge at the time of the plasma on the electrode. Therefore, the secondary current value used is only when there is plasma on the electrode, or when the secondary current value gets the peak value. The ionized charged particles are the value of electric charge that happens when there is plasma on the electrode, shown in Fig 3b. It shows that the ionization process isn’t continuous.

Table 2. Comparison Data Based on Range of Time

| No | Time (s) | Data Is (A) | Data Q (C) | Data C (F) | Data d (m) |
|----|---------|------------|------------|------------|------------|
| 1  | 2.165906| 7.71×10^{-7} | -2.41×10^{11} | 1.48×10^{-14} | 5.98×10^{-4} |
| 2  | 2.170969| 4.80×10^{-7} | -1.50×10^{11} | 7.21×10^{-15} | 1.23×10^{-3} |
| 3  | 2.177688| -8.65×10^{8}  | 2.95×10^{-12} | 1.81×10^{-15} | 4.89×10^{-3} |
| 4  | 2.18075 | -4.72×10^{8}  | 1.47×10^{-12} | 7.09×10^{-16} | 1.25×10^{-2} |
Based on the electric charge value, we calculate the capacitance value, according to Equation 2. The highest capacitance value is 0.0259 pF. Based on the capacitance value obtained, a calculation is performed to obtain the magnitude of the distance between the electrodes at the time of the plasma, according to Equation 8.

The result is shown in Table 2. The table shows the peak value of the secondary current value for a 0.2 s period from 2.1 s – 2.3 s. Based on all the data value on the table, the average distance range for electrodes is about 5 mm. This comparison data value means that its data occurs at the same time, and that means when the discharge gap or we can say the distance between the electrodes increases, the value of capacitance will decreases.

### 4. Conclusion

The plasma measurement system has been designed and analyzed. From the result of the predicted secondary current value can be concluded that the discharge type of the plasma is corona discharge. The electric charge value depends on the secondary side current value, which means all the calculation data based on the secondary current value. The capacitance value affected when the discharge gap change. The average discharge gap value is around 5 mm. When the discharge gap increase, the capacitance value will decrease.

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