Inverter System with Pulse-Density-Modulated Power Supply for a Wide Range of Non-thermal Plasma Discharge

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Abstract – Inverter system is used to produce power supply for plasma discharges by switching DC to AC. Its frequency is in range of 5–15 kHz correlated to maximum voltage output of 0-35 kV\textsubscript{p}. A high voltage and high frequency transformer was designed and constructed. It was used for converting a low square wave AC to high frequency AC. These high AC voltage direct supplied to bipolar plate electrodes covering with dielectric barrier disk (Teflon). The power density of dielectric barrier discharge (DBD) can be controlled by pulse-density-modulated (PDM) technique. So the power density of stable DBD plasma of a few electron volts was precisely varied percentages of 3-100 among various operating condition. The Lissajous pattern of charge-voltage and micro-discharge pattern were characterized in various discharge conditions. Due to dielectric property, the near atmospheric DBD plasma was uniform pattern and can used to modify surface of membrane. The conclusion stated that the energy transfer of the DBD using novel PDM technique was succeed and capable to modify surface biological membranes and gas treatment.

Keyword: Plasma Discharge, Dielectric Barrier Discharge, DBD, Pulse-Density-Modulated, PDM.
1. Introduction

In the last few years, the technology of gas treatment, gas separation process and biomaterial surface modification using the non-thermal plasma discharge was highlight interesting. The famous non-thermal atmospheric plasma discharges are corona and dielectric barrier discharge (DBD) which are generated by applying a high voltage to a pair of electrodes. If at least one of electrode is coated with a dielectric barrier, it will be called dielectric barrier discharge (DBD) or silent discharge (SD). Namely dielectric barrier was made of quartz, glass or ceramic. The main advantage of this type of DBD is that the non-thermal plasma conditions in atmospheric-pressure gases can be established in an economic and reliable method. This property has led to a number of industrial applications, including ozone synthesis, microorganism disinfection, surface modification, pollution control, CO2 lasers, excimer lamps and flat plasma-display panels [16]. The near atmospheric pressure and non-thermal plasma discharge system can be supplied by various type of energy supplier such as DC magnetron, radio frequency irradiation, microwave and AC high voltage [1, 3, 5-7, 9-10 and 16]. Consequently, the energy will transfer to neutral gases. The feed neutral gas species in discharge chamber will be excited and ionized depending on energy supply and its ionization energy. De Geyter et al.[1] reported this DBD technique to modify the surface properties of polyactic acid (PLA) with 4 purified gas treatment (air, argon, nitrogen and helium). Physical and chemical analysis of PLA samples were investigated by surface tension and hydrophilic property, morphological structure analysis (Atomic force microscopy, AFM), PLA composition (x-ray photoemission spectroscopy, XPS). In addition, plasma characterization in each gas media was interpreted by current-voltage waveform. Many fundamental micro-discharge properties were determined from Lichtenberg figures, image-converter recordings [15-16], current measurements [13, 15-16] and charge measurements [13, 16]. Mathematical models describing the formation of a micro-discharge in a gas gap bounded by a dielectric surface were formulated by many researchers [17-21]. In these models, a feedback mechanism at the cathode surface (metal or dielectric) is incorporated. Impinging ions and photons produce secondary electrons that are fed into the discharge channel. At the time the streamer bridges the gap, a cathode-fall region of high electric field and high positive-ion densities is established within a fraction of a nanosecond. Therefore, it is necessary to develop static inverters able to operate at frequencies higher than that of the line.

The main purpose of this work was to investigate the inverter circuit for generating 5-15 kHz of high voltage supply of 35 kVp. Additionally, the physical properties of DBD current and voltage were presented.

2. Experimental set-up

Figure 1 shows schematic diagram of inverting unit which consists of pulse generator unit, driver circuit board, high current semiconductors switches and step-up transformer. Each part of block diagram will be given more detail in the next subsection.

As the Figure 1, the step-up ferrite core transformer was constructed for generating high frequency and high voltage. This transformer with ferrite core has a turn ratio of 1:48 and use 2 step of cascade technique to increase the turn ratio of transformer. The cascade transformer has a turn ratio is 1:96. Output of the cascade transformer is in range of 0-35 kVp depending on a DC input voltage of full-bridge inverter.

2.1. Pulse generator

According to Figure 1, the pulse generator’s output signal was generated by using microcontroller (ARM-7 (ADUC7024), Analog Device Corp.). Then the driving circuit amplifies the logic control signals for turning on and off power switches (semiconductor switches). This microcontroller can collect data up to 41.78 MHz by using XTAL 32.768 kHz. The driver (IR2113) circuit will also amplify the signal from pulse generator to required signal level and will provide electrical isolation (TLP250) between the power switch and pulse generator. Metal-Oxide Semiconductor Field-Effect Transistors (MOSFET) power switches (APT5020BN) are used to switch on and off power circuit as shown in Figure 2.

The power MOSFET is a voltage-controlled device that can be turned on and off by applying voltage to the gate. The gate-to-source voltage (Vgs) can be produced by gate drive circuit; it has two side of power MOSFET driver: low-side and high-side driver.
2.2. Pulse-density-modulated system

The power supply for DBD plasma can be operated by varying frequency, voltage amplitude increment and duty cycle of electrical source as the same as some previous works [2-3]. Another way to control a power of plasma can be done through varied number of pulse, which is applied to the electrodes in unit time, though a frequency and amplitude of the ac-voltage will be unchanged. This technique is commonly called a Pulse-Density-Modulated (PDM) [4].

2.3. Dielectric barrier discharge reactor

The DBD can be operated in two modes of discharge. Filamentary mode is the one in which DBDs are generally operated, whereas under special condition, a diffuse (glow) mode can be generated [5, 6]. For filamentary, if the local electric field strength in a gas gap arrives at the ignition level, the breakdown will start at many points followed by the development of filaments, so-called microdischarge. Both modes were used to separate them by electrical characterization (current pulse shape). The current pulse shape can be registered using a resistance by means of an oscilloscope [5]. For filamentary, every current pulse corresponds to a series of microdischarge and the single current pulse lasts for some nanoseconds [7]. On the hand, the time scale for diffuse mode is determined by the frequency of feeding voltage [8].

In this work, the DBD plasma discharge system was composed of 3 main parts. Firstly, the glass bell jar DBD plasma reactor and finally, the optical spectrometer unit as shown in Figure 3. The input voltage of plasma reactor was measured by high voltage divider (Tektronix P6015A 1000X) connected to digitized storage oscilloscope (Tektronix TDS3014B 100 MHz) while current and voltage across electrodes were determined by current probe and voltage probe (IWATSU SS-0110), respectively. During DBD plasma generated by PDM high voltage power source the CCD (SONY XCD-V60CR) was focused at electrical discharge gap width of 2 mm and connected to the computer for recording. Computer was also used to control the frequency and pulse density of PDM power supply.

Plasma reactor consists of upper electrode, lower electrode and dielectric barrier disk attaching to the lower electrode. The upper electrode is connected to a PDM high voltage power source, while the lower electrode is connected to earth through a resistor R (50 Ω) or a capacity C (47 nF). Dielectric barrier disk of 2 mm thickness was made of Teflon. Photographs of plasma pattern were taken with a high speed CCD camera during operating period. In addition, the TDS oscilloscope was used to measurement the high voltage signal that applies to electrode, current was induced by the discharges through the resistor R. The frequency was used at 10 kHz and 15 kV of applied voltage. Pulse density (number of pulse per unit time) was varied from 1/20 to 20/20 for control the power of discharge. Voltage-charge Lissajous figure was used to compute a power of discharge. An electric energy consumed per voltage cycle (Eo) can be evaluated from an area of voltage-charge Lissajous figure. The power of plasma (Pd) is determined by Eo/T, when T is period time of high voltage output from power source as the same evaluation as Wagner et al. [5].

3. Results and Discussion

Figure 4 showed a switching mode of the voltage-source PDM inverter, which a full-bridge inverter circuit. The PDM inverter operation consists of 4 switching-device, load and dc power supply. In Figure 4(a) when switch S1 and S2 are closed, +Vdc applied to the load (b) whereas −Vdc applied to the load when switch S3 and S4 were closed (c) and when switch S4 and S2 were closed, no voltage or zero-voltage state (0 V) applied to the load. The PDM can be operated in three modes; mode I and mode II in Figure 4(b) and (c) showed produce a square-wave ac-voltage state whereas mode III in Figure 4(d) provided a zero-voltage state at its output terminals. For example, pulse density is 2/3
was showed in Figure 2 that have two of square-wave ac-voltage state (dense line) and one of zero-voltage state (dash line).

The measured voltage and current were illustrated in oscillogram and the current values were presented in form of current density. This current density values and voltage were used illustrated in form of Lissajous pattern. An area of Lissajous pattern related to electric energy consumption per voltage cycle ($E_{el}$) [5]. The electric energy can be computed by Equation (1) as follows:

$$E_{el} = \int_{t}^{t+T} V(t) dQ = C_{\text{meas}} \int_{t}^{t+T} V(t) dV_{\text{meas}}$$  \hspace{1cm} (1)$$

Where $V(t)$ means voltage that applied to upper electrode, $V_{\text{meas}}$ is voltage across the capacitor ($C_{\text{meas}}$), $t$ is time, $T$ is period of applied voltage (period time of PDM), $f$ is frequency of applied voltage and $Q$ is charge that transferred by plasma discharge.

And electrical power is determined by Equation (2)

$$P_{el} = \frac{E_{el}}{T} = E_{el} f$$  \hspace{1cm} (2)$$

Figure 5-7 showed the experimental waveforms of high voltage signal and instantaneous current (a), photograph of discharge (b), and voltage-charge Lissajous figure (c) when the frequency is 10 kHz, applied voltage is 15 kVp. Figure 5 correspond to the case of maximum power (100%). Power of discharge is 32.68 W. Figure 6, operation at a pulse density of 10/20 and the power of discharge is 11.05 W, which is only 33.81 % of the maximum power. Figure 7 shows the measured waveforms under a pulse density of 1/20 and power of discharge is 1.23 W, which is 3.76 % of the maximum power. The current shape of plasma discharge that showed in Figure 8 is similarly with figure 5(a) to figure 7(a). The current waveform consists of numerous short peaks, which are an indication of the microdischarge activity. The current shape of maximum
and minimum plasma power can be conclude about the discharge is in the filamentary mode. Photographs of plasma show a strong of discharge for the maximum power and a weak of discharge for the minimum power (PDM=1/20) and the relation between PDM and power of plasma was showed in figure 9.

![Fig 8. Experimental waveforms of voltage and current for filamentary discharges](image8)

Fig 8. Experimental waveforms of voltage and current for filamentary discharges

![Fig 9. Relationship between power of discharge and pulse density modulated (PDM)](image9)

Fig 9. Relationship between power of discharge and pulse density modulated (PDM)

4. Conclusion

This paper has proposed the PDM power source to generate plasma by pulse electrical discharges. This PDM power source of 10 kHz with high voltage of 15 kVp can provide pulsed plasma corona discharges for modification membranes in the next step of our research. The PDM inverter can be used to control the discharge power in a wide range of 3–100% which performs both strong and weak membranes modification processes.

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