Power supply instrumentation for pulsed dielectric barrier discharges

V E Quiroz Velázquez¹, R López Callejas¹, 2, B G Rodríguez Méndez², R Peña Eguiluz², A de la Piedad Beneítez¹, A E Muñoz Castro², S R Barocio², A Mercado Cabrera² and R Valencia Alvarado²

¹ Instituto Tecnológico de Toluca, AP 890, Toluca, Estado de México, México
² Instituto Nacional de Investigaciones Nucleares, AP 18-1027, CP 11801 México DF

E-mail: regulo.lopez@inin.gob.mx

Abstract. The design and implementation of a pulsed high voltage supply intended to the production and control of pulsed dielectric barrier discharges are reported. The instrumentation includes three independently built DC sources coupled to Flyback-like converters using three 1:50 high voltage transformers. The system is capable of supplying voltages up to 70 kV at a 100-2000 Hz repetition rate, delivering 1-500 µs wide pulses. The system has been applied to the development of pulsed dielectric barrier discharges in a stainless steel coaxial reactor 30 cm long and with a 2.54 cm diameter. The inner nickel electrode diameter is 0.005 cm and is embedded in alumina. The discharges have been carried out in room pressure air. Discharges have been implemented. The discharge is made in a water environment for purposes of bacterial elimination.

1. Introduction
Advanced oxidation technology (AOT) is based on the use of oxidize radicals such as ozone (O₃), hydrogen peroxide (H₂O₂) and hydroxide (OH⁻) in order to remove both organic and inorganic compounds from the environment. One shortcoming of this technique is that the radicals are not produced in situ whereby their often depleted population diminishes the effectiveness of the process [1]. However, a cold (or out of equilibrium) plasma produced at room pressure could perform the oxidation process required by the production of oxidize radicals. One case in point is the dielectric barrier discharge (DBD) technique which has often been applied to the control and removal of volatile organic compounds [2], elimination of bacteria [3] and decontamination of gases [4] among other uses. The present report describes the electronic and mechanical instrumentation required to carry out DBDs aimed at the elimination of bacteria in water, which implies voltages of 30-50 kV magnitudes, operation frequencies in the 500-2000 Hz range and pulse widths (tₚ) in the order of micro seconds.

2. Experimental set-up
The array shown in figure 1 has been conceived in order to conduct PDBD discharges. It is constituted by three sections: a pulsed power source (PPS), a data acquisition system capable of monitoring the behavior of the discharge electrical parameters, and a coaxial discharge reactor (figure 2) consisting in a stainless steel cathode, a Ni/Cu anode and an alumina (Al₂O₃) dielectric barrier.

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An electric circuit that models the electrical evolution of the discharges has been studied elsewhere [5]. The circuit takes into consideration: (1) the physical dimensions and its contents, $R_m$ is a function of the water conductivity and $C_m$ refers to capacitance reactor, (2) parameters previous to breakdown, $R_S$ involves the resistance between electrodes and $C_S$ refers to a capacitive which depends on the gap and the voltage applied, and (3) during breakdown, $R_b$ and $L_b$ represent the inductance and the discharge resistance respectively [6] in the case of a pulsed corona discharge (PCD). The circuit in figure 3 incorporates the parameters $C_B$ and $R_B$ that estimate the Al$_2$O$_3$ dielectric capacitance and resistance during the discharge. Thus, $R_B$ can be expressed by [7]:

$$R_B = \left(\sigma_A e\right)^{-1}$$

where $\sigma_A$ is the electric conductivity of the barrier ($\sim 1 \times 10^{-11}$ S/m) and $e$ denoted its thickness ($\sim 0.0014$m) whereby $R_B \sim 140$ M$\Omega$. The dielectric layer entails a capacitance given by [7]:

$$C_B = \frac{\varepsilon_r \varepsilon_0 A_r}{\delta}$$

where $\varepsilon_r \varepsilon_0$ is the absolute permittivity of the material ($\sim 8.8541 \times 10^{-11}$ F/m), $A_r$ its area ($\sim 1.885$ m$^2$) and $\delta$ represents the ratio between the diameters of the barrier that covers the anode ($\sim 0.876$), so that $C_B \sim 190$ pF. On its part, $R_m$ [$\Omega$] can be put in the form [8]:

$$R_m = \ln \left(\frac{D_{IC}}{D}\right)$$

where $l$ is the reactor length (0.3 m), $D_{IC}$ is the internal cathode diameter (0.0254 m) and $D$ is the diameter of the anode (0.0005 m), $\sigma_m$ is the prevailing conductivity, 0.0005 S/m in the case of sweet water and $1 \times 10^{-13}$ S/m in the air. Then, it follows from equation (3) that $R_w \sim 4.17$ k$\Omega$ (water) and $R_f = 20.81$ T$\Omega$ (air). As to $C_m$, according to [8]:

$$C_m = \frac{2\pi \varepsilon l}{\ln \left(\frac{D_{EB}}{D_{IB}}\right)}$$

where $D_{EB}$ is the external diameter (0.00254 m) and $D_{IB}$ is the inside diameter (0.001 m) of the dielectric barrier respectively, $\varepsilon$ is the permittivity of the medium where the discharge takes place, for water $\varepsilon_w \sim 7.08334 \times 10^{-10}$ F/m and for air $\varepsilon_A \sim 8.8541 \times 10^{-12}$ F/m. Then, from equation (4), $C_w \sim 340$ pF (water) and $C_A \sim 4.25$ pF (air). $C_S$ and $R_S$ describe, as mentioned, the state previous to breakdown,
characterized by a capacitive transient and an inductive one created by the electric current that precedes the discharge [9]. $C_S$ and $R_S$ depend on the gap between electrodes ($d_g$) and the voltage between them ($U$). The value of $R_S$ [$\Omega$] becomes [10]:

$$R_S = \frac{d_g}{nq \, \mu \, A_S} \quad (5)$$

where $q$ is the elementary charge ($\sim 1.60256 \times 10^{-19}$ C), $n$ is the electron density namely $\sim 1 \times 10^{26}$ m$^{-3}$ [10], and $\mu$ is the mobility ($\sim 1 \times 10^{-5}$ m$^2$/V·s) [11]. Thus, if $d_g \sim 0.01245$ m and the streamer area $A_S \sim 3.1416 \times 10^{-8}$ m$^2$ [13] then, given equation (5), $R_S \sim 2473$ Ω. Now, $C_S$ can be expressed as [9]:

$$C_S = \frac{\mu_d}{U} (d_g) \quad (6)$$

where $U \sim 70$ kV, $\rho_d$ is the streamer charge $\sim 1 \times 10^{-6}$ C/m [9], and (6) $C_S \sim 177$ fF. The breakdown onset is estimated by means of $R_b$ and $L_b$, which depend in turn on the current conveyed by the streamer [12]. $R_b$ [$\Omega$] is determined by [13]:

$$R_b = \frac{d_g}{\sigma_c \, \pi \, r_s^2} \quad (7)$$

where $r_s$ is the streamer effective radius ($\sim 1 \times 10^{-4}$ m [14]) and $\sigma_c$ is the conductivity of the ionized medium given by [9]:

$$\sigma_c = 1.5 \times 10^3 \, T^{3/2} \quad (8)$$

here $T$ is the temperature ($\sim 2$ eV [9]), and, therefore, from (8) $\sigma_c \sim 4242.7$ S/m whereas, from (7), $R_b \sim 94$ Ω. $L_b$ can be described by [9]:

$$L_b = \frac{\mu_0 \, d_g}{2\pi} \left[ \frac{1}{4} + \ln \left( \frac{d_f}{r_s} \right) \right] \quad (9)$$

where $\mu_0$ is the vacuum permeability $\sim 4\pi \times 10^{-7}$ N/A$^2$ and $d_f$ is the gap between streamer and the null electric field point. Then, $d_f \sim 4$, and, from (9), $L_b \sim 20.56$ nH.

**Figure 3.** Equivalent PDBD circuit.

**Figure 4.** PPS sub-system.

The pulsed power source (PPS) circuit developed to conduct PDBDs is displayed in Figure 4. It is structured as three identical sub-systems separated by relays labeled as Sw. Each sub-system contains a DC voltage supply ($V_{DC}$) operating within 5-300V in order to feed a flyback converter constituted by a semiconductor (HGTG27N120N transistor) operating as a Q switch, and by a 1:50
pulse transformer (PT) characterized by the parameters: \( L_1 = 20.1 \, \text{mH} \), \( L_2 = 40 \, \text{mH} \), \( L_m = 20.1 \, \text{mH} \), \( L_f = 55 \, \mu\text{H} \), \( R_1 = 70.6 \, \text{mH} \), \( R_2 = 196 \, \Omega \), \( C_{D2} = 90.48 \, \text{pF} \), monitored by a 4263B *Agilent* LRC bridge operated at 1 and 10 kHz.

One driver has been implemented in each sub-system, formed by a pulse width (\( t_w \)) modulator circuit type PWM (SG3524) specifically designed to generate \( t_w \) values within 1-500 \( \mu \text{s} \), at frequencies in the order of 100-2000 Hz, which provides for the recovery time of water subjected to electric discharges [15]. The PWM supplies the commutation signal for the controller (M57962L), and through it, maintains the electric parameters of the Q switch.

### 3. Results and discussion

The simulation of the PPS with the three subsystems connected as shown in figure 5 led to a ratio value \( n:1:150 \). Figures 6(a), 6(c), 6(b) and 6(d) exhibit the waveforms simulated and experimental where the output generated voltage corresponds to \( \sim 28 \, \text{kV} \) at a \( \sim 60 \, \text{mA} \) current. Figures 7(a), 7(b), 7(c) and 7(d) describe the experimental voltage and current behavior at several frequencies and pulse widths in order to identify the regime of maximal energy transference during the discharge. Thus, the effectiveness of the system is given by \( \eta = \frac{V_{\text{out}_{\text{rms}}} I_{\text{out}_{\text{rms}}}}{V_{\text{in}_{\text{rms}}} I_{\text{in}_{\text{rms}}}} \) [16], where, according to the measurements taken during the discharge represented in figures 6.a and 6.c, \( V_{\text{out}_{\text{rms}}} \sim 3.62 \, \text{kV} \) and \( I_{\text{out}_{\text{rms}}} \sim 11.54 \, \text{mA} \). As \( V_{\text{in}_{\text{rms}}} \sim 68.737 \, \text{V} \) and \( I_{\text{in}_{\text{rms}}} \sim 0.6 \, \text{A} \), then the efficiency is \( \sim 82\% \).

![Figure 5. PPS model.](image)

**Figure 5.** PPS model.

![Figure 6.](image)

**Figure 6.** Simulation waveforms for: (a) voltage, (c) current. Experimental waveforms: (b) voltage and (d) current. In both, simulation and experimental \( t_w = 50 \, \mu\text{s} \) and \( f = 1 \, \text{kHz} \).

### 4. Conclusions

An electrical model capable of predicting the operational characteristics of a voltage/current controlled PDBD plasma source has been developed. The flexibility of the proposed model enables one to adjust several electrical parameters like voltage, width pulsed and frequency. Also, it allows to modify discharge parameters such as pre-breakdown and breakdown time. In addition, it can change electrical characteristics that involve the physical reactor model. The electric and electronic instrumentation has been carried out and can operate one, two or three subsystems connected simultaneously. This arrangement provides an output voltage in the order of 70 kV. Experimental tests have been carried...
out in a cylindrical reactor with room pressure air obtaining an efficiency of around 82%. The system has been applied to a PDBD in order to generate non-thermal plasma aimed at a treatment for the removal of microorganisms in water.

![Waveforms experimental for several frequencies with pulse width ~40µs: (a) voltage, (b) current; and several pulse widths with a frequency ~1 kHz: (c) voltage and (d) current.](image)

**Figure 7.** Waveforms experimental for several frequencies with pulse width ~40µs: (a) voltage, (b) current; and several pulse widths with a frequency ~1 kHz: (c) voltage and (d) current.

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**References**

[1] Fridman A 2008 Plasma Chemistry (United States of America: Cambridge University) pp 450-750

[2] Dorai Rajesh and Kushner M J 2002 J. Phys. D: Appl. Phys 35 2954–68

[3] Gweon Bomi, Kim D B, Moon S Y and Choe W 2009 Current Applied Physics 9 625–8

[4] Dong-Joo Kim and Kyo-Seon Kim 2003 IEEE Transactions on Plasma Science 31 227–35

[5] Rodriguez-Mendez B G, López-Callejas R, Peña-Eguiluz R, Mercado-Cabrera A, Valencia-Alvarado R, Barocio S R., de la Piedad-Beneitez A, Benitez-Red J S and Pacheco-Sotelo J O 2008 IEEE Transactions on Plasma Science 36 185–91

[6] Gao Lan, Larsson A, Cooray V and Seuka V 1999 IEEE Transactions on Dielectrics and Electrical Insulation 6 35–42

[7] Han-Jun Oh, Yongsoo Jeong, Su-Jung Suh, Young-Jik Kim and Choong-Soo Chi 2003 Journal of Physics and Chemistry of Solids 64 2219–25

[8] Grenier J, Jayaram S H, El-Hag A H and Kazerani M 2005 A study on effect of medium conductivity on its electric strength under different source conditions in nanosecond regimes (Ontario: Waterloo Univ.) pp 261–64

[9] Grearson W D 1999 IEEE Transactions on Industry Applications 35 2 359-65

[10] Jones H M and Kunhardt E E 1996 Nanosecond pre-breakdown and breakdown phenomena in water: influence of pressure, conductivity, and ionic sheath formation (Roma, Italy) pp 15–19

[11] Kupershtokh A L and Karpov D I 2006 Technical Physics Letters 32 406–9

[12] Fofana I and Béroual A 1996 IEEE Transactions on Dielectrics and Electrical Insulation 3 273–82

[13] Kefu Lui, Qiong Hu, Jian Qui and Houxiu Xiao 2005 IEEE Transactions on Plasma Science 33 1182–85

[14] Lisitsyn I V, Nomiyama H, Katsuki S and Akiyama H 1999 IEEE Transactions on Dielectrics and Electrical Insulation 6 351–6

[15] Xiao S, Kolb J, Kono S, Katsuki S, Joshi R P, Laroussi M and Schoenbach K H 2004 IEEE Trans. Dielectrics Electrical Insulation 1 604–12

[16] Rashid M H 1988 Power Electronics 2th edition (USA: Prentice Hall) p 52–55