

Drinking Water Disinfection System based on 222 nm DBD Excimer Lamp

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ABSTRACT – The design of a compact, powerful and simple-to-use drinking water purifier intended for domestic use, based on a DBD driven, 222 nm UV Excimer lamp, is described, presenting key equations for dimensioning. The operating point is selected to optimize electrical efficiency of the lamp and the converter. Validation of electrical performance and disinfection effectiveness with *E. Coli*, total coliform and CB390 micro-organisms indicators, in real operating conditions, is presented.

Keywords—Water treatment, UV, DBD, Excimer lamp, Power supply, Water quality.

1. INTRODUCTION

Although access to drinking water of quality is a human right, in many rural areas around the world, effective methods for the treatment of pathogens in drinking water obtained from wells, surface water or rainwater, are not available.

Among the different water treatment methods, the effectiveness and benefits of UV radiation-based system is well known since decades [1][2][3]. However, its massive use for residential water treatment is still a challenge.

Based on research on the optimization of UV output from Dielectric Barrier Discharge (DBD) Excimer lamps [4][5] and their power supplies, a compact, powerful and simple-to-use drinking water purifier intended for final users, was developed. Safety aspects including lamp electrodes grounding, system reliability and research of environmentally friendly solutions (excimer lamps are mercury-free UV sources) were addressed. More details about the device can be found in the website [6].

2. SYSTEM DEVELOPMENT

The system is made up of two main elements: a DBD reactor (UV lamp) that allows a thin water layer to surround the UV emitting surface (Fig. 1) and a compact power supply integrating embedded software for controlling variables of the reactor operating point. In this application the UV Excimer lamp is a DBD reactor so in this article we use both terms to refer to the same element.



Fig. 1. Drinking water purifier intended for domestic use. The DBD Excimer UV lamp is surrounded by the water during UV irradiation.

2.1. Power Supply

Next, the UV Excilamp operating conditions, power supply topology and implementation considerations are described.

2.1.1. Operating point

From previous research results, an optimal operating point for the 222 nm UV Excimer lamp was found in laboratory [7][4]. To obtain the required UV dose for effective water disinfection, an electrical power of 160 Watts, with current pulses of approximately 0.5 A of intensity, and 80 kHz must be injected into the lamp, with a sustained lamp peak voltage around 4 kV and up to 5 kV during ignition.

2.1.2. Topology

There exists a plurality of power supplies schemes for DBD based reactors, going from simple audio frequency generators with step-up transformer to fine tuned resonant converters, operating at MHz [8][9][10][11].

For the desired operating point of this application, the Series Resonant Inverter (SRI) topology for DBD supplies is found to be effective for an efficient Excilamp operation. This topology operates from a DC voltage source and features zero current switching (ZCS) thanks to the use of thyristor-like switch devices[8][11].

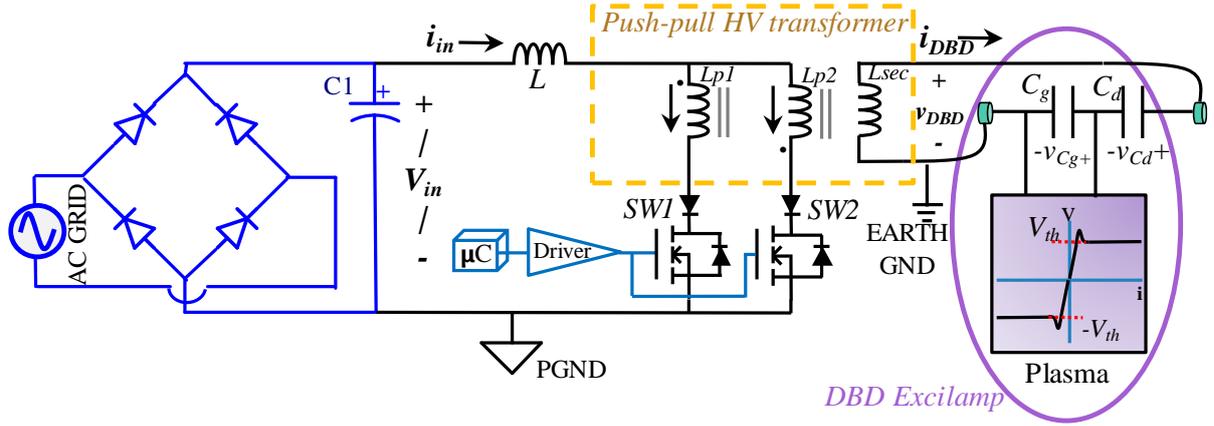


Fig. 2. Power Supply Topology. (a) DC voltage supply (b) Push-pull SRI.

In the SRI topology, the DC voltage source (V_{in}) is connected in series with an inductance L , and then through a controlled current inverter, to the DBD reactor, producing a series L - C resonance. The capacitive element of the resonant circuit corresponds to the DBD reactor inherent capacitance, illustrated in the simplified equivalent electrical model in Fig. 2, right-hand side. This model incorporates the DBD Excimer lamp gas breakdown voltage V_{th} , the gas capacitance C_g , and the bulb walls capacitance C_d [12][13].

2.1.3. Design

Aiming for compactness, the SRI design was adapted to operate directly from the main supply (i.e. 120Vac in Colombia), without the need for additional equipment (e.g. AC/DC converter), while providing the lamp with the desired operating point described at the begin of this section.

The DBD UV Excilamp employed for this device is based on a Kr-Cl gas filled, quartz bulb, with a metallic stainless-steel pipe as inner electrode and a stainless-steel spring as external electrode. The lamp equivalent electrical parameters V_{th} , C_g and C_d , were identified using Q-V Lissajous figures technique (Manley diagram) [11][12][13], obtaining the values shown in Table I.

Table I. DBD UV Excilamp equivalent electrical model parameters

V_{th}	C_g	C_d
2094 V	18 pF	59 pF

In the SRI topology, three key parameters for the converter design are calculated as function of the lamp model [11], those are the DBD reactor peak voltage V_{pk} , peak current I_{pk} , and current pulse duration T_p [11]:

$$V_{pk} = V_{th} + \frac{V_{th}^2 \times C_g}{C_d \times (V_{th} - V_{in} \times n)} \quad (1)$$

$$I_{pk} = (V_{pk} + V_{in} \times n) \frac{C_d \times C_g}{L_{sec} \times (C_d + C_g)} \quad (2)$$

$$T_p \approx \pi \sqrt{L_{sec} \times C_d} \quad (3)$$

In equations (1) and (2), V_{in} corresponds to the DC input applied to the resonant circuit input, in the transformer primary side, and n is the transformer's step-up ratio. Thus, the DC voltage seen in the DBD Excilamp side is $V_{in} \times n$. In equation (3), L_{sec} corresponds to the L inductance value seen in secondary side of the transformer.

In this case, a V_{pk} value of up to 5kV is expected. To drive the reactor at this voltage value, a step-up transformer was found necessary for compatibility with available semiconductor switches. To reduce the number of switches (Thyristor like device implemented with a Diode in series with MOSFET), to simplify the driver, and to improve the size of the system, the SRI topology reported in [11] is implemented with a step-up push-pull transformer, specially designed for this device with deadtime, allowing to implement the selected discontinuous operation mode (DCM) [11], instead of a full-bridge inverter. Accordingly, the switches SW1, SW2, are controlled with complementary signals, with deadtime.

To determine the transformer ratio (n), the available input voltage (120 Vac mains supply) and the required lamp operating point were considered, and Equations (1) – (2), were used. To obtain the DC input voltage, the line is rectified using a full-wave diodes bridge rectifier, producing a non-regulated DC voltage (V_{in}) of approximately 169 V (Fig. 2-left). Accordingly, the switch peak voltage value is calculated using (1) with $V_{in} = 169$ V. In Fig. 3 the switches peak voltage (V_{pk_switch}), for different values of n , is plotted.

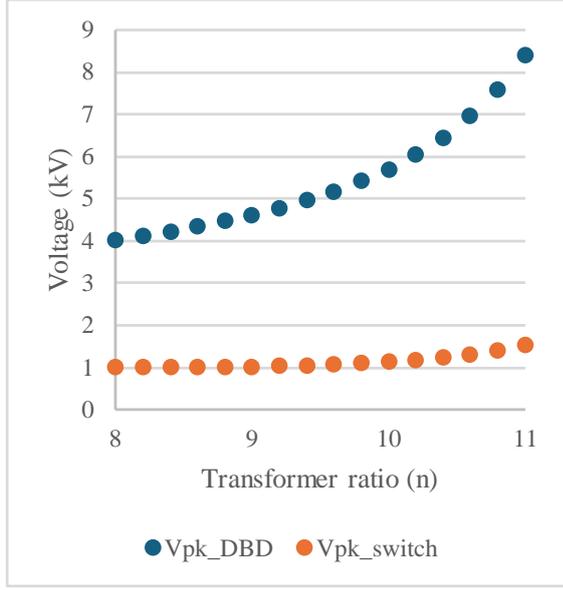


Fig. 3. DBD reactor peak voltage (V_{pk_DBD}) and switch peak voltage (V_{pk_switch}) as a function of the transformer ratio. $V_{in}=169$ V.

In Table II, the designed transformer specifications are shown. Transformer ratio $n = 8$ was selected to provide enough security margin for the switches rating. Thus, the V_{in} value seen at the reactor side is equivalent to $n \times 169$ V = 1358 V, and a $V_{pk} = 4$ kV in normal operating conditions is obtained.

Table II. Transformer specifications

Core	Primary	Secondary	Insulation
Size ETD	17 turns single layer (each)	136 turns single layer	1mm 3D printed PLA
Material 3C90 (Ferroxcube)	81 Strands of 38 AWG Litz wire	AWG 32 solid copper wire	and 1 layer of Kapton tape

2.1.4. Non-idealities and waveforms

As may be evident, parasitic elements and losses are neglected in equations (1)-(4). During operation, the main parasitic elements impacting the SRI converter behavior are:

- Transformer strain capacitance and magnetizing inductance.
- Transformer losses and leakage.
- Grounding effect.

Nevertheless, the previous equations are powerful for a first step in dimensioning the converter. For validation of the design, simulation of the circuit, including the transformer magnetizing inductance was performed. As a consequence, the DBD voltage (V_{DBD} in Fig. 4 middle) presents a low frequency, small oscillation, so it decreases even with the switches OFF. Simulation results for the main waveforms are presented in Fig. 4, illustrating the converter behavior.

As expected, the DBD lamp is supplied with alternating current pulses, which shape reflects the I_{in} discontinuous current

drawn from the L inductance (the magnitude difference comes from the transformer's turn ratio).

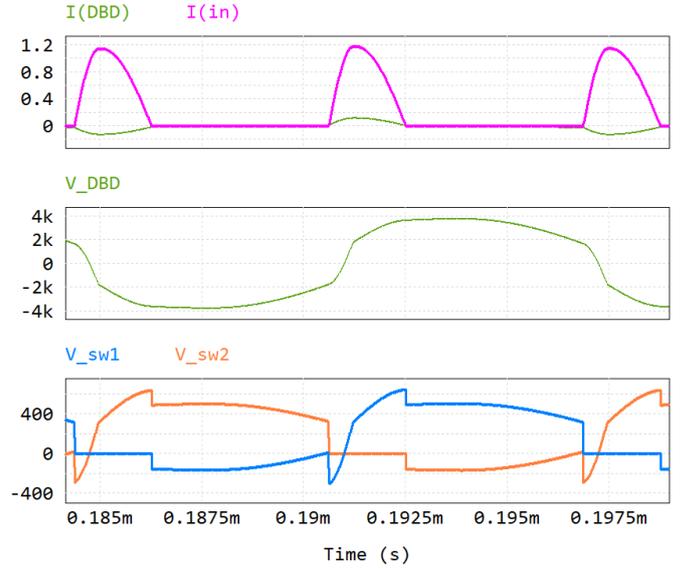


Fig. 4. Top: DBD current (I_{DBD}) and input current (I_{in}) in A. Middle: DBD voltage, in V. Bottom: Switches voltage in V. For: $n=8$, magnetizing inductance=0.5 H, $V_{in}=169$ V, $f_{sw}=80$ kHz

Considering the V_{pk} value to be reached and the need for fast turn OFF, SiC Diode and MOSFET were selected to drive the transformer primary side. Note that the use of the push-pull configuration produces a switch peak voltage twice the value seen by a switch in a full-bridge inverter. In this case, 1 kV peak voltage across the switches is reached.

Considering the following aspects, SiC MOSFETs and Diodes were selected for the implementation:

- Switching frequency (80 kHz)
- Low capacitance
- High voltage blockage (1.2 kV)

Now, in the SRI topology the DBD power can be adjusted with two degrees of freedom, related to the power supply operating point: DC input voltage V_{in} , and the inverter operating frequency f_{sw} , according to (4). Given that in this application V_{in} is not adjustable, the power is only adjusted via the switching frequency.

$$P_{DBD} = 4 f_{sw} V_{th}^2 C_g \left(\frac{V_{th}}{V_{th} - n \times V_{in}} - 1 \right) \quad (4)$$

2.2. Controller

The system controller is an embedded system based on Arduino MKRZero and a set of sensors and actuators allowing the user to start the disinfection process and to guarantee a safe operation.

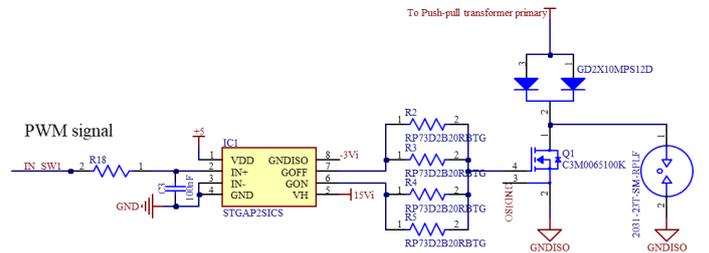


Fig. 5. Isolated SiC driver schematic. Shown for one switch.

The controller integrates complementary PWM signals with an optically isolated bipolar SiC driver (STGAP2SICS). The driver produces 15V/-3V pulses for turn-on and turn-off, respectively. The microcontroller adjusts accurate deadtimes necessary for the push-pull transformer's proper operation. EMI management is a challenge in this application and was carefully considered in the PCB design. Fig. 5 shows a detail of the switch driver schematic.

3. PERFORMANCE RESULTS

The operating point of the system was adjusted in laboratory to achieve total reduction of the micro-organisms selected as indicators.

With this aim, the Standard Method 9060A (2017) was applied, according to the protocols of the Microbiology Laboratory of Pontificia Universidad Javeriana (Bogota) and to international recommendations for UV based treatment [14]. The main parameters of the applied protocol are:

- Micro-organism's indicators:
 - Bacteria: Total coliforms, E. Coli
 - Virus: CB390
- Number of treated samples: 3.
- Number of baseline samples: 1
- Sample size: 1.5 L

The indicators concentration in water was measured in number of Colony-Forming Units (UFC). Using water samples taken from surface water in different locations near to Bogota city backcountry, successful total reduction of UFC was obtained at 153W of average power in the Excilamp and 350 mL/min flow.

The device design constrains the water layer around the lamp to 5mm by using a lamp container of appropriate diameter, and provides a predictable path for water around the lamp thanks to the use of a spiral shape external electrode.

The water samples were injected into the device by gravity and the treated water was immediately stored in the corresponding containers for laboratory analysis.

For performance validation in real operating conditions, the device was installed in the different places of origin of the samples, treating the water with the device operating conditions determined in laboratory (153 W, 350 mL/min) and applying the corresponding protocol. The disinfection results in real operating conditions are summarized in Table III for one of the validation sites. R1, R2 and R3, correspond to the water sample identifier.

Table III. Water treatment results for one of the validation sites

PureStream test in San Javier, La Mesa, Cund., Colombia. 160 W-350 ml/min.					
Date	Sample	Turbidity (UNT)	concentration		
			C total (UFC/100mL)	E. coli (UFC/100mL)	CB390 (UFP/L)
21/01/2021	Baseline	5,28	5,90E+04	3,0E+03	25
21/01/2021	R1-Tratada	4,67	<1	<1	<1
21/01/2021	R2-Tratada	4,9	<1	<1	<1
21/01/2021	R3-Tratada	4,14	<1	<1	<1

Léase como: UFC: Unidades Formadoras de Colonias en el volumen analizado, UFP: Unidades Formadoras de Placa en el volumen analizado, UNT: Unidad Nefelométrica de Turbidez.

As observed in Table III, the baseline indicator for bacteria and virus microorganism indicators, shown in the first line, was totally eliminated.

In Fig. 6, the obtained electrical waveforms for this operating point are presented.



Fig. 6. Waveforms during operation. DBD lamp voltage (blue), current (Yellow) and instantaneous power (orange).

4. CONCLUSIONS

The UV Excilamp based water disinfection system was designed to be compact and with an operating point of high-efficiency, optimizing the UV dose received by the water under treatment. The operation with direct contact of the water with the lamp surface was achieved, increasing the UV dose compared with sleeve configurations.

The water disinfection system implemented achieves total elimination in the water of the tested microorganisms, at real operating condition, with a performance of 350 mL/min for 200 W of electrical power consumption.

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