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Development of High-Frequency Power Source Utilizing Electronic Ballast by Employing a Half-Bridge Inverter for Water Purification

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Abstract: This paper outlines the design of a high-frequency power supply, specifically an electronic ballast based *PWM* inverter, intended to power a low-pressure *UV* Mercury-Argon lamp. The lamp emits germicidal *UV* radiation at a wavelength of 253.7 nm, which effectively targets *DNA* viruses and bacteria present in the water to be treated. The system underwent thorough modeling, encompassing both the electronic ballast and the discharge lamp. The power supply employs a standard converter setup, comprising a half-bridge rectifier and inverter controlled by *PWM*. Simulations conducted using the MATLAB software environment yielded satisfactory results aligned with our objectives. The primary aim was to achieve a sinusoidal *rms* current precisely at 0.65 A, operating at a frequency of 50 kHz, to maximize *UVc* radiation at 253.7 nm. Hence, contemporary converters employing semiconductor switches operating at high-frequencies (over 50 kHz for MOSFETs) have been employed with proportional-integral control techniques.

Keywords: Low-pressure UVc Lmap, Germicide, Electronic ballast, *PWM* inverter, Half-bridge inverter, *PI* controller

Introduction

In recent years, high-frequency electronic ballasts have emerged as a viable alternative to magnetic ballasts for discharge lamps due to their numerous advantages, including improved system performance (enhanced power factor), lightweight design, high luminous efficacy, long lifespan, lighting control capabilities, absence of flickering and audible noise (Aissa Bokhtache et al., 2024). However, it's crucial to carefully consider the cost implications associated with electronic ballasts (De Oro et al., 2014). During normal operation, discharge lamps exhibit negative differential resistance, necessitating effective current limiting mechanisms to prevent uncontrolled current growth. The presence of a ballast to regulate current is thus essential. The radiative characteristics of the lamp are influenced by factors such as gas mixture composition, discharge geometry, and

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electrical supply parameters like frequency and waveform. Key requirements for optimal operation include achieving zero average current, fast switching times, ensuring rapid re-ignition of the discharge at consistent currents, and the ability to operate as a cyclic current source with variable frequency.

Description and Operating Principle of the System

Figure 1 shows the block diagram of the proposed system, Electronic ballast connected with half-bridge inverter. In this type of source, the inverter is configured as a high-frequency generator. The source consists of: A single-phase rectifier, The *DC* bus (link circuit), The transistor half-bridge inverter generating an output frequency of 50 kHz, A resonant circuit comprising L_r and C_r to facilitate lamp ignition, A filter is typically included between the main terminals and the rectifier to comply with electromagnetic compatibility (*EMC*) regulations and an additional preheating circuit is necessary to prevent filament damage. (Aissa Bokhtache et al., 2015).

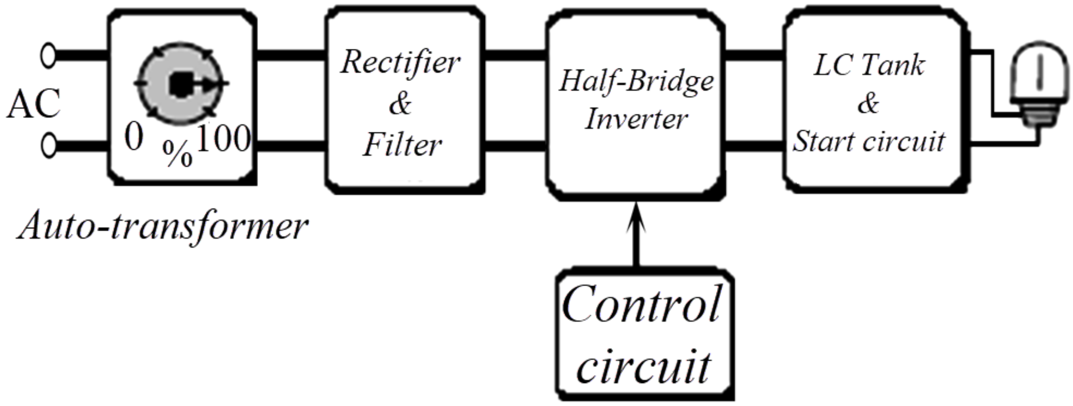

Figure 1. Block diagram of system consisting of a half-bridge inverter.

Figure 2 illustrates the electrical circuit of the proposed system.

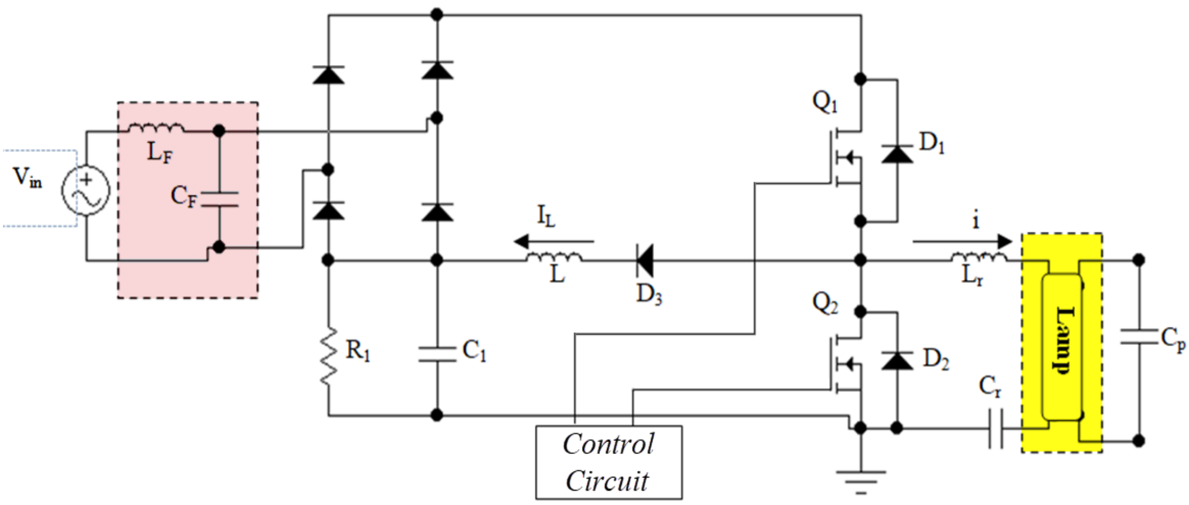

Figure 2. The electrical circuit of the proposed system.

The MOSFET is commonly employed in low-voltage applications with switching frequencies that can reach or exceed 100 kHz. It is also utilized for low-power applications. The operational principle of the proposed ballast's is described in steady-state modes, from mode 1 to mode 4. The equivalent circuit for each mode is depicted in Figure 3. To illustrate the circuit's equilibrium operation, all internal components are assumed to be ideal. This can be described as follows: (Aissa Bokhtache et al., 2016), (Kazufuni, et al., 2000).

Mode 1: $t_0 < t < t_1$: Between t_0 and t_1: Prior to Q_1 and Q_2 entering their respective modes, both are in the off state. When Q_1 is switched on at time t_0, a current flows through Q_1 and is split into two components: i_{load} and i_L. The component i_L flows through D_3, L, and C_r, while i_{load} flows through the fluorescent lamp.

Mode 2: $t_1 < t < t_2$: During Mode 2 ($t_1 < t < t_2$): Following the turn-off of Q_1 at t_1 while Q_2 remains off until t_2, i_L flows through C_1, D_2, D_3, L, and R, while i_{Load} flows through D_2, L_r, C_r, and the fluorescent lamp.

Mode 3: $t_2 < t < t_3$: At t_2, Q_2 is turned on. i_L reaches 0 between t_2 and t_3. Subsequently, after i_{ch} reaches 0, it flows in the opposite direction compared to the operational state of Q_1, leading to a decrease in the negative peak.

Mode 4: $t_3 < t < t_4$: when stopped at t_3 Q_2 and Q_1 remains off status for the period from t_3 to t_4, t_4 i_L through D_3, Q_1 is on. The next mode is the mode 1.

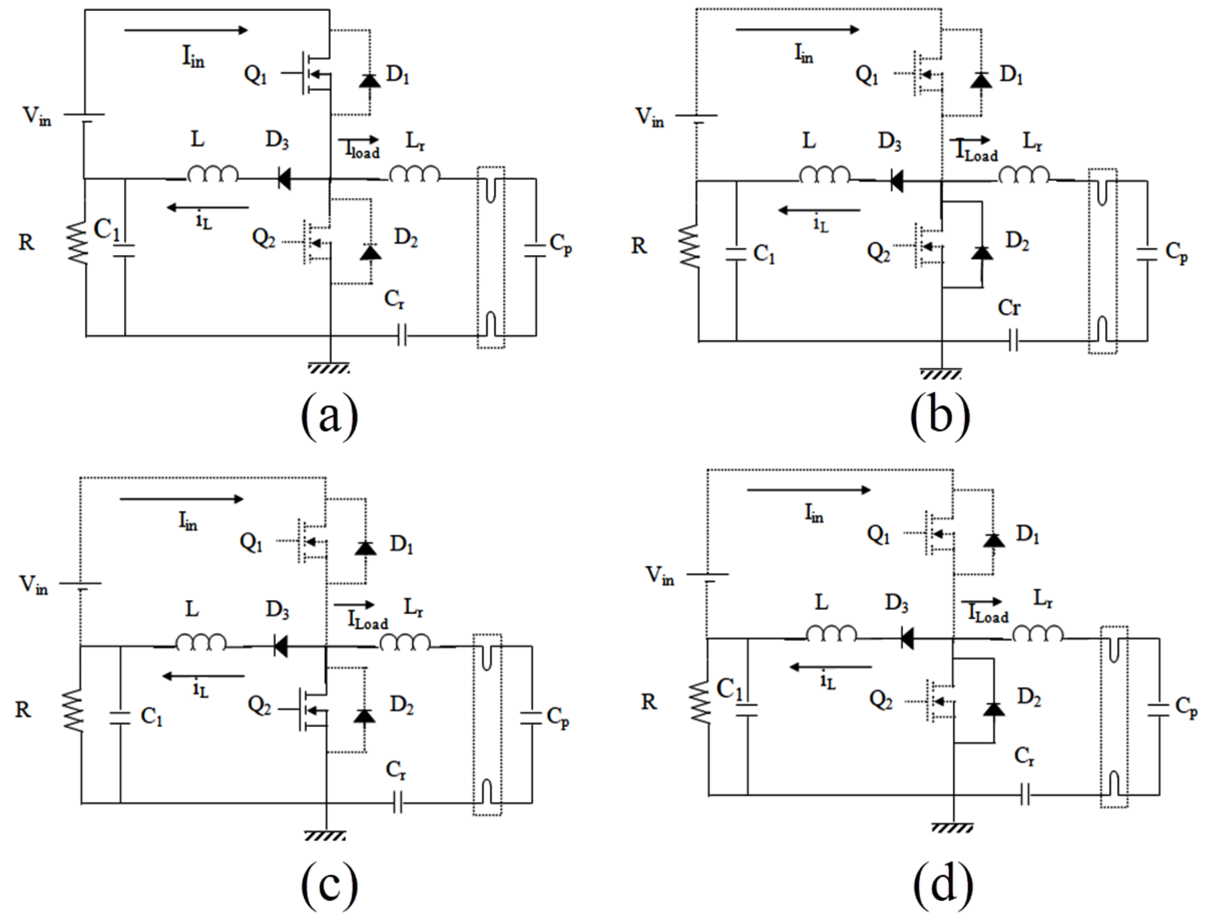

Figure 3. The equivalent circuits of the system operation modes.

The Electrical Circuit Model of the Lamp

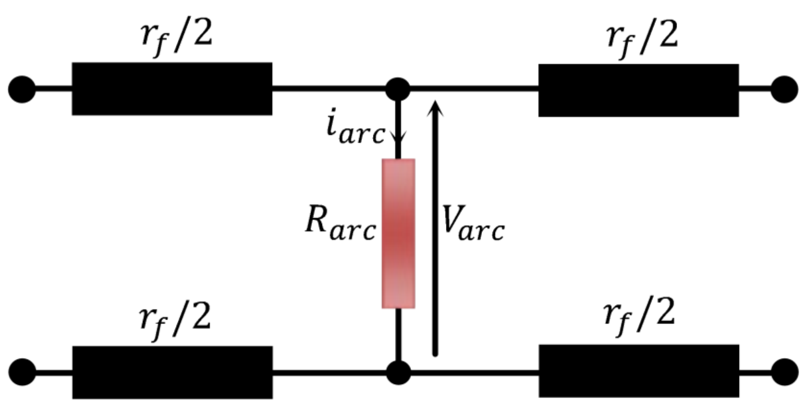

Figure 4. The fluorescent lamp electrical circuit model.

An electrical circuit model, depicted in Figure 4, has been proposed to characterize the electrical behavior of the fluorescent lamp when powered by a high-frequency electronic ballast. This model represents the lamp using two resistors: R_{arc}, which accounts for the electrical properties of the lamp's *arc* and is dependent on both power and temperature, and r_f, which represents the cathode filament (Aissa Bokhtache et al., 2017). Figure 5 illustrates the equivalent circuit of the system.

Where:

$$R_{arc} = \frac{V_{arc}}{i_{arc}} \tag{1}$$

$$P_{arc} = V_{arc}.i_{arc} \tag{2}$$

With : R_{arc}: *arc* resistance,i_{arc}: *arc* current, V_{arc} :*arc* voltage, P_{arc} :*arc* power.

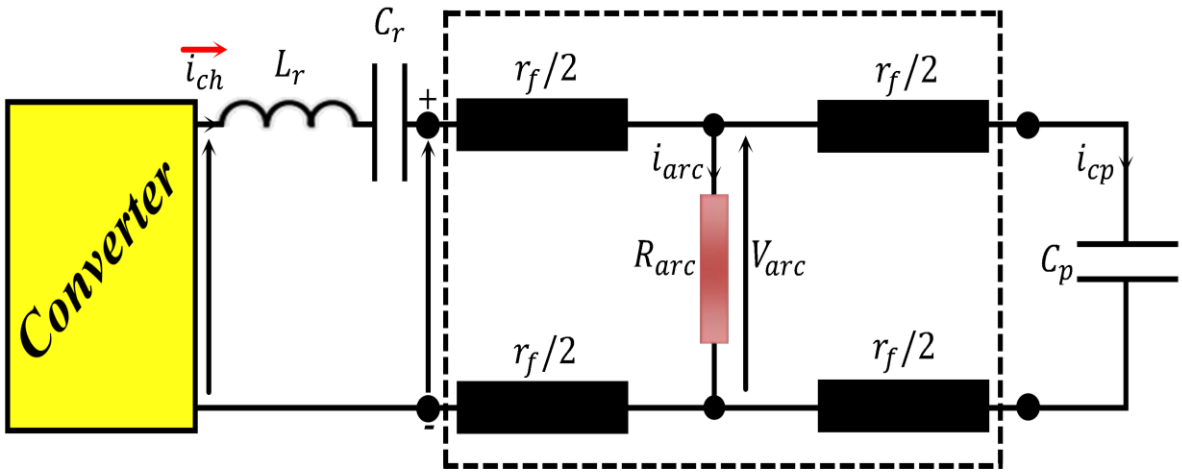

Figure 5. Equivalent circuit of the system.

The lamp voltage can be calculated as follows (7):

$$\vec{V}_{lamp} = \vec{V}_{arc} + 2\left[\frac{r_f}{2}(\vec{i}_{arc} + \vec{i}_{Cp})\right] = V_{arc} + i_{arc}r_f + \frac{r_f V_{arc}}{r_f - jZ_{Cp}}$$

$$= \left[\left(1 + \frac{r_f^2}{r_f^2 + Z_{Cp}^2}\right)V_{arc} + r_f i_{arc}\right] + j\frac{r_f Z_{Cp}}{r_f^2 + Z_{Cp}^2}V_{arc} \tag{3}$$

Therfore,

$$\vec{V}_{Lamp} = \left[\left(1 + \frac{r_f^2}{r_f^2 + Z_{Cp}^2}\right)V_{arc} + r_f\frac{P_{arc}}{V_{arc}}\right] + j\frac{r_f Z_{Cp}}{r_f^2 + Z_{Cp}^2}V_{arc} \tag{4}$$

With : Z_{CP} is the reactance of the C_P capacitor and I_{CP} is current which flows through it. The resonant load current is in fact the sum of both *arc* current and filament current. As a result, by calculating the transfer function of the open-loop system indicted in figure 5 we have:

$$\frac{I_{Load}}{V_{Load}} = \frac{(R_{arc} + r_f)C_rC_pS^2 + C_rS}{(R_{arc} + r_f)L_rC_rC_pS^3\left[(2R_{arc} + r_f)L_rC_rC_p + L_rC_r\right]S^2 + \left(R_{arc} + r_f\right)\left(C_r + C_p\right)S + 1} \tag{5}$$

Results and Discussion

The simulation results were conducted under the MATLAB/Simpower environment and are provided in the following figures. The converter frequency needs to be higher than the audible range, ensuring it operates effectively above 50 kHz. Additionally, the resonant circuit's resonant frequency is set at 42 kHz (Aissa Bokhtache et al., 2020; 2021).

Two tests are selected for comparison. The discharge lamp-electronic ballast system is first tested in an open-loop setup. Following this, the system is evaluated in a closed-loop arrangement using a traditional proportional-integral (*PI*) controller. The lamp used in the simulation is a real discharge lamp described in references (Aissa Bokhtache et al., 2023), the main characteristics of the discharge lamp-electronic ballast are given in (Table1) below:

Table 1. Characteristics of the discharge lamp-electronic ballast assembly.

Variables	Symbol	Values
Capacitance	C_r	*0.47 µF*
Capacitance	C_P	*3900 PF*
Inductance	L_r	*0.9 mH*
Power	P_{Lamp}	*65 W*
Frequency	f	*50 KHz*
Resistance	R_{arc}	*170.769 Ω*
Resistance	r_f	*5 Ω*
Voltage	V_{in}	*500V, 50Hz*
RMS Current	I_{arcrms}	*0.65 A*
Inductance	L	*1.27 mH*
Capacitance	C_1	*33 F*
Inductance	L_F	*1.5 mH*
Capacitance	C_F	*220 nF*

Open-Loop Simulation Results

Figure 6 illustrates the obtained currents and voltages of the discharge lamp. Figure 7 resumes the *THD* of the *arc* voltage and the *arc* current of the discharge lamp. Figure 8 illustrates the waveform of the discharge lamp filament current, and Figure 9 shows the effective *arc* current of the discharge lamp.

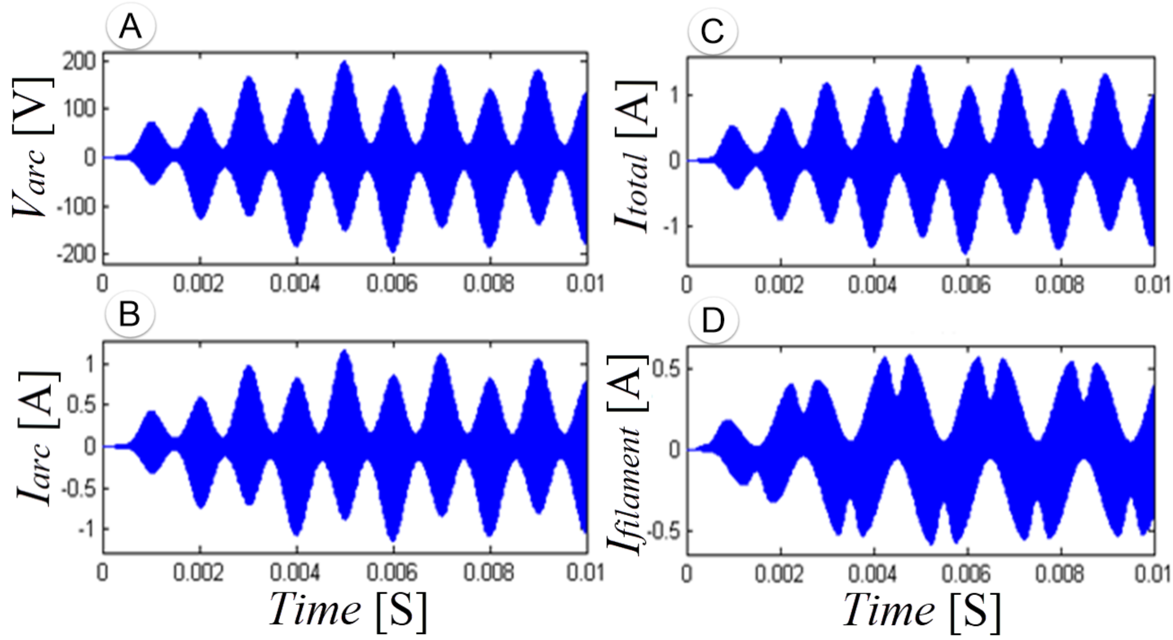

Figure 6. Curves of currents and voltages of the discharge lamp, (A) *arc* voltage, (B) *arc* current, (C) Total current and (D) filament current.

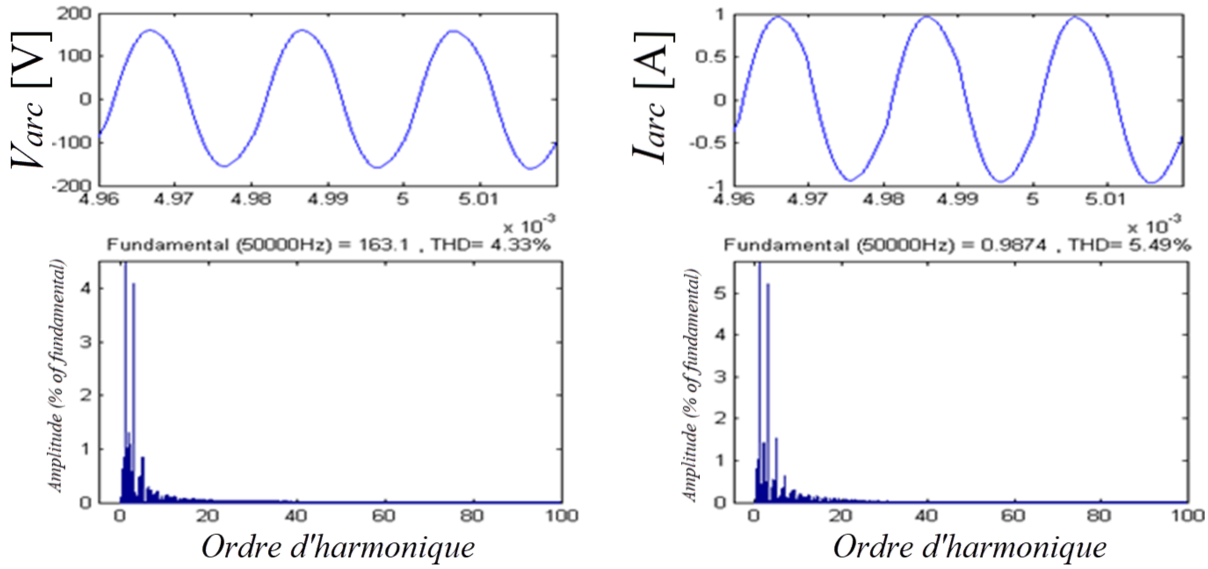

Figure 7. THD of the *arc* voltage and the *arc* current of the discharge lamp.

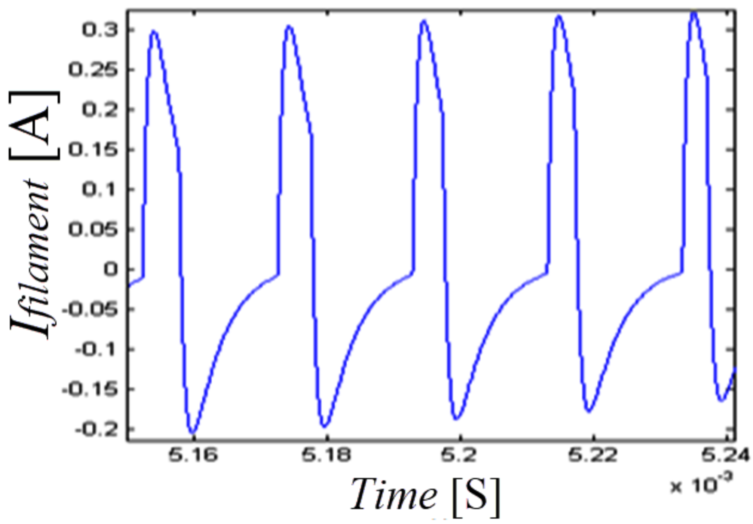

Figure 8. Waveform of the discharge lamp filament current.

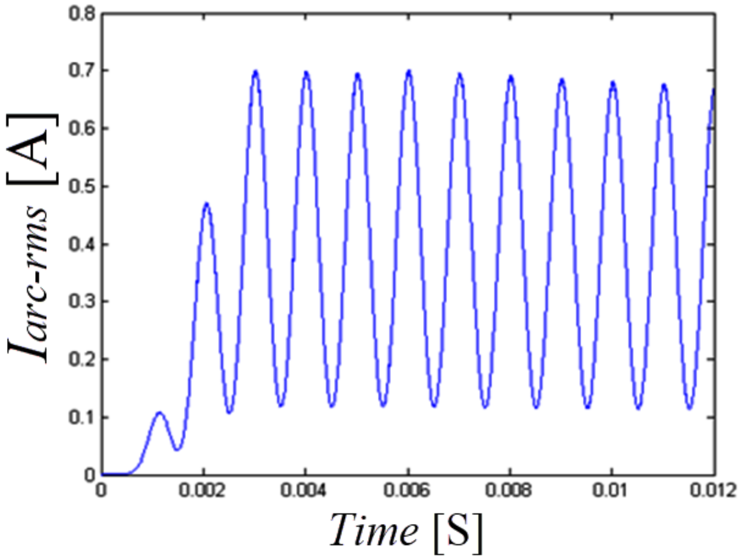

Figure 9. Effective *arc* current of the discharge lamp.

From figure 6, the obtained current and voltage exhibit sinusoidal waveforms, it can be observed that the voltage and current are modulated at a frequency of 50 kHz and contained in an envelope oscillating at 1 kHz with a modulation rate maximum/minimum values equal 5 approximately. From Figure 7, we can observe that the waveforms of current and voltage closely resemble sine waves, with *THD* values of 5.49 % for lamp *arc* current and 4.33 % for lamp voltage. The effective discharge lamp *arc* current varies as shown in Figure 9, indicating the need to regulate the current in our model to precisely achieve the targeted root mean square (*rms*) value of 0.65 A.

Closed-Loop Simulation Results

To enhance the efficiency of water treatment and extend the lamp's lifespan, it is essential to operate the lamp with a constant root mean square (*rms*) value of the arc current. To meet this requirement, we initially investigated a closed-loop system incorporating a proportional-integral (*PI*) controller, commonly utilized in industrial applications. The closed-loop transfer function of the lamp-ballast system and its corresponding block diagram, implemented in the Matlab Sim-Power environment, are illustrated in Figure 10.

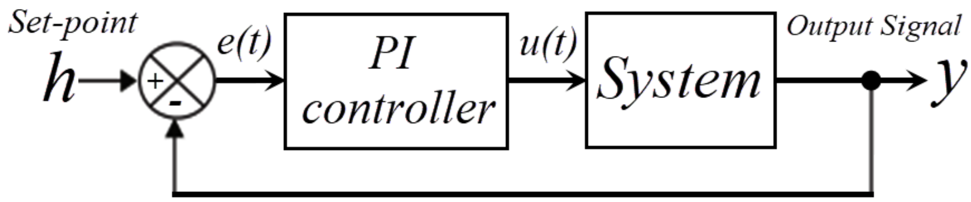

Figure 10. Closed-loop system with *PI* controller.

The simulation parameters were determined based on the lamp's characteristics and by solving the characteristic equation of the closed-loop transfer function using the pole placement method. The resulting simulation outcomes, including the time-domain behavior of the *arc* voltage, *arc* current, and its root mean square (*rms*) value, are presented in Figure 11.

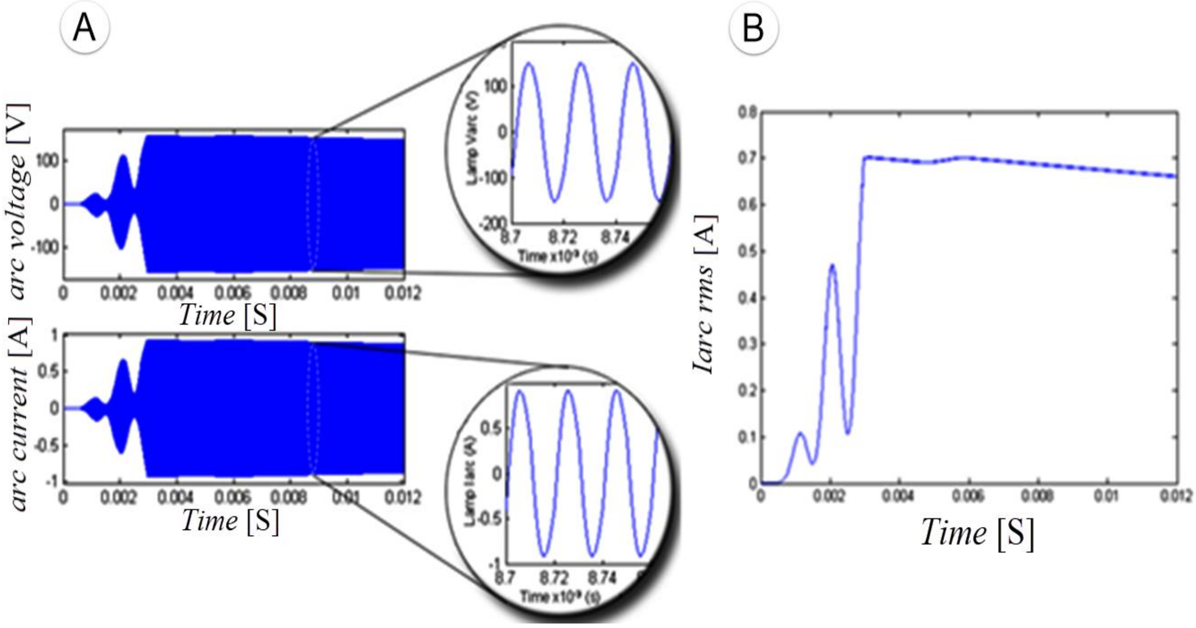

Figure 11. (a) Waveforms of the *arc* current and the *arc* voltage of the discharge lamp with a *PI* regulator. (b) *rms* value of the *arc* current of the discharge lamp after the application of a *PI*.

The analysis of the simulation results indicates that the control strategy employing a *PI* regulator exhibits a transient state similar to that of the open-loop controller. However, in steady state, it demonstrates excellent static and dynamic performance, with a current frequency of 50 kHz and a constant root-mean-square (*rms*) value of 0.65A, aligning with the desired values that optimize the germicidal effect.

Conclusion

The implementation of discharge lamps in industrial applications requires interdisciplinary knowledge, including electrical engineering, optics, plasma physics, and chemistry. We have established the foundational aspects of our study on the power of discharge lamps with electronic ballasts. The first part focused on presenting the general structure of an electronic ballast, utilizing a half-bridge inverter, selecting switches and their characteristics, modeling the electrical circuit of the fluorescent lamp, and assessing the relative influences of various parameters of the electronic components comprising the electronic ballast. The electrical behavior of the fluorescent lamp, powered by a high-frequency electronic ballast, can be represented by a power-dependent resistor and temperature. The second part of this study involved MATLAB simulation of the electronic ballast circuit. Although the current and voltage waveforms closely resembled a sine wave (with a total harmonic distortion of 5.49 % for current and 4.33 % for voltage) at a frequency of 50 kHz, we encountered challenges in achieving a consistent current of 0.65 A. The implementation of a feedback loop with a *PI* controller eliminates the oscillations in the effective current and enables the system to stabilize around the desired value of 0.65 A.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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