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Current Source Power Supply for DBD Excilamps

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ABSTRACT

The electrical power delivered to the gas in a XeCl Dielectric Barrier Discharge exciplex lamp, is analyzed, applying causality criteria based on an equivalent circuit model of the DBD; this power is shown to be controllable by the current supplied to the lamp.

This highly desired property is obtained by means of a specific power supply topology, which concepts and design are discussed. Experimental prototype of a current-mode converter operating in discontinuous current mode around 50 kHz is presented and its capability to control the amount of energy transferred during each current pulse is shown.

The capability of this power supply to sustain specific operating conditions for the DBD lamp, with a very stable behavior, (even with a very low current, thus obtaining a single discharge channel) is illustrated. The results concerning the coupling of this converter with a XeCl excilamp are presented and the influence of the supply parameters on the 308nm emission of a Xenon/Chlorine excilamp is analyzed. The shape of the pulsed UV power radiated by the lamp is experimentally shown to be very similar to the one of the current which actually flows into the gas mixture.

The UV radiation is demonstrated to be tightly correlated to the current injected into the gas and controllable by means of the available degrees of freedom offered by the control of the power supply. Measurements of the output characteristics and performances of the system are discussed.

Keywords: DBD, excimer, current-mode, power supply, static converter.

1. INTRODUCTION

Dielectric Barrier Discharge exciplex lamps are usually associated with voltage-controlled electric generators: the classical solutions for laboratories experimental setups are built around large bandwidth linear amplifiers connected to step-up transformers [1]; for more industry oriented solutions, pulsed voltage sources are often considered, where switched voltages are generated by means of circuits including power semiconductors [2], [3]. When submitted to such voltages, the DBD lamp in return imposes current of very narrow spike shape in the circuit. The analysis of the UV response of the excilamp shows a similar behavior, concerning the UV radiation, with spikes which duration are also very short, compared to the operating period of the whole equipment. The characteristics of the current spikes (magnitude, duration, frequency) are really difficult to control by means of voltage-controlled electric generators [6], [7].

The aim of our approach is to consider the power supply as a mean to control the UV emission of the excilamp. On the basis of an analysis of the causality of the power transfers between the power supply and the lamp, we have favored current controlled topologies.

A specific solution is described in this paper and key aspects of the design of the latter, being absolutely different from the classical one (with voltage source behavior) are also introduced.

The performances of this electric generator, associated with a XeCl excilamp are presented; they confirm the validity of the reasoning which has driven us to consider current-source power supplies.

2. POWER TRANSFER

In this section, an analysis of the power transfers between an electric generator and a DBD excilamp is carried out. Causality considerations, derived from a classical model of a DBD, are the basis of this analysis.

An equivalent circuit for a DBD apparatus [1]-[5], which has proven to be very representative in the case of excimer lamps, is reminded on Fig. 1.

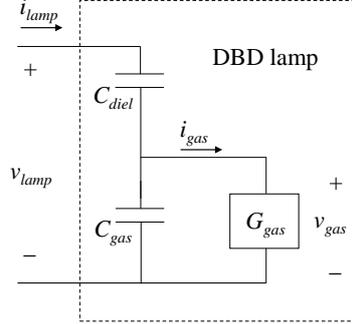


Fig. 1 equivalent circuit model of the excilamp.

The capacitors are, as usual, on the one hand the capacitance of the dielectric walls (C_{diel}) and, on the second hand, the capacitance of the gas (C_{gas}). This capacitor is the main electric characteristic of the gas, as long as the discharge remains in OFF state; G_{gas} is the conductance of the gas: it describes the behavior of the latter when the discharge is in ON state; furthermore, the voltage across the gas v_{gas} being the state variable which causally defines the state (ON, OFF) of the system, G_{gas} is the adequate choice to evaluate the current flowing in the gas, i_{gas} . A good approximation of the behavior of G_{gas} has shown to be given by equation (1).

$$\frac{dG_{gas}}{dt} = K_{gen} \times \left[1 + \exp\left(\frac{V_{th} - |v_{gas}|}{\Delta V}\right) \right]^{-1} - K_{ext} \times G_{gas} + K_{pro} \times |i_{gas}| \quad (1)$$

The 3 terms of the right hand side are respectively associated with three phenomena:

- breakdown, which occurs when v_{gas} reaches the threshold voltage V_{th} ,
- the extinction of the created species (K_{ext} controlling the extinction rate),
- the creation of the excited species, which is assumed to be proportional to the magnitude of the $|i_{gas}|$ current.

The identification of the parameters of the model is achieved by means of an automated method: the set of values (K_{gen} , V_{th} , ΔV , K_{ext} , K_{pro} introduced in equation (1)) is iteratively adjusted so as to obtain a good agreement between experimental and simulated waveforms; this approach and its implementation are detailed in [6]. The parameters, corresponding to the 60W XeCl excilamp used for experimentations are given in appendix. The behavior of the circuit of Fig. 1 is driven by following electric differential equations (2), (3):

$$v_{gas} = v_{lamp} - \frac{1}{C_{diel}} \int i_{lamp} dt \quad (2)$$

$$i_{gas} = G_{gas} \times v_{gas} \quad (3)$$

Once the parameters of the model are identified, G_{gas} , v_{gas} and i_{gas} , which are non-measurable quantities, are computed according to measurements realized with a classical sinusoidal voltage supply and using equations (1), together with (2) and (3).

To note that the formulation of these state equations favors the expression of the actual causality chain between the physical quantities: derivatives are avoided and i_{lamp} current in the lamp clearly appears to be the origin of the behavior of the whole system. Concerning the lamp used for experimentations, the obtained ($i_{gas} - v_{gas}$) characteristic of the gas is presented on Fig. 2.

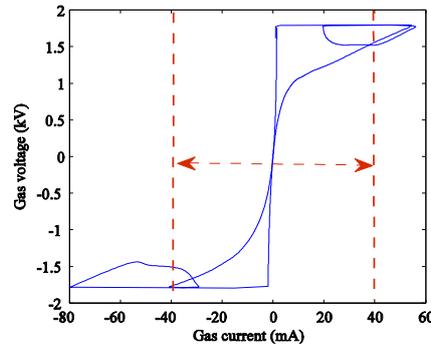


Fig. 2 ($i_{gas} - v_{gas}$) characteristic of the gas

This hysteretic form is characterized by the voltage plateau, with a value very near to the V_{th} threshold voltage. When the gas is in ON state, the operating point remains on this plateau: the gas voltage v_{gas} remains constant, in a quite large domain for the i_{gas} current values. Thus, the instantaneous power transferred from the supply to the gas, being the $i_{gas} \times v_{gas}$ product, is directly controlled by the i_{gas} current. As appears on Fig. 1, the generator supplies the i_{lamp} current, which will be shown later very similar to i_{gas} , except when the discharge is OFF.

3. CURRENT CONTROLLED SUPPLY FOR EXCILAMPS

According to the conclusions of the previous section, the mostly desirable characteristic of a power supply for a DBD excilamp is the ability of controlling the current which circulates in the lamp. Additionally, the electric generator must supply a current, which mean value is zero, at a timescale corresponding to the operating period, because of the capacitive characteristic of the lamp.

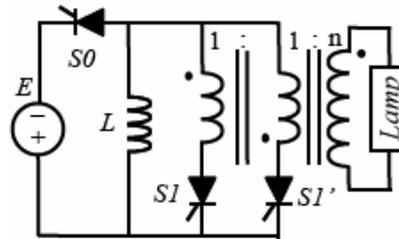


Fig. 3 current controlled power supply

In this scope, several topologies have been considered [9]. The circuit of Fig. 3 presents one of them, with a circuit which permits:

- to invert the sign of the current in the lamp after each half period, thanks to the switches SI and SI' , which both are associated with one of the primary windings of the transformer (oppositely pointed);
- to control the amount of energy which is supplied to the lamp during each half operating period, thanks to switch $S0$.

3.1 Operation

Fig. 4 presents the idealized expected waveforms (current in the L inductance – red and blue lines- and current in the lamp – blue line), and the operating sequences, according to the states of the switches of the converter. These plots are obtained with a circuit simulation program [10], [11]: the step-up transformer is supposed ideal (ratio : n) and the lamp is sketched, according to the characteristic of Fig. 2, as a $\pm V_{th}$ voltage source in series with the dielectric capacitor C_{diel} .

A very important feature of this converter appears on Fig. 4: the duration of sequences (A) and (C), during which the energy is stored in the L inductance ($1/2 L I_{L0}^2$) permits to control the amount of energy which is injected into the lamp during each half period. The stored energy is transferred through the transformer into the lamp during the oscillating sequences (B) and (D), involving L and C_{diel} .

The duration of the sequences (B) and (D), $t_{discharge}$, is defined by the values of C_{diel} , L , n (step-up ratio of the transformer) and I_{L0} [9]; they naturally finish when the i_L current matches a zero value (spontaneous turn-off of the

thyristors). A blanking time interval, added between sequences (B) and (C) on the one hand and between (D) and (A) on the second hand, is introduced to adjust the relaxation time interval between two current pulses in the lamp.

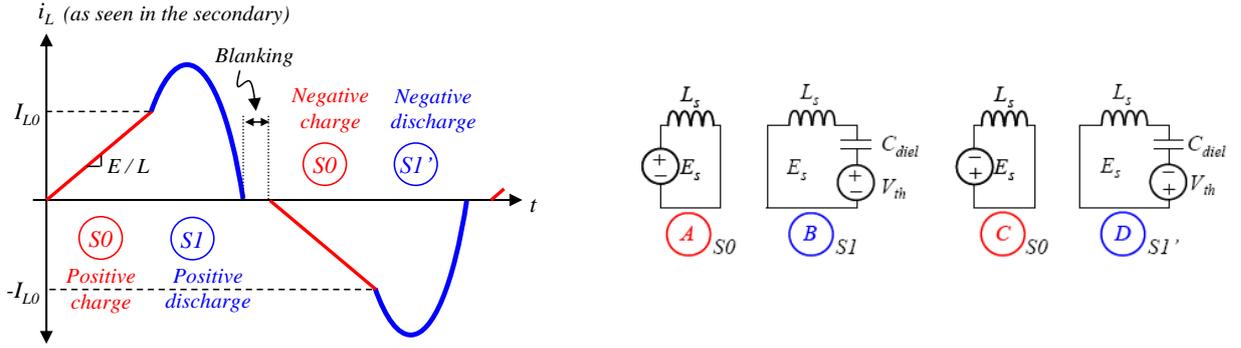


Fig. 4 operating sequences

It additionally defines, with t_{charge} which is the duration of sequences (A) and (C), the operating period of the converter:

$$T = (t_{charge} + t_{discharge} + t_{blanking}) \times 2 = 1 / f_{switch} \quad (4)$$

The I_{LO} value of the current in L at the end of sequences (A) and (C) – equation (5) –, defined by the controlled turn-on of either SI or SI' to start the (B) or (D) sequences, is a direct method of controlling the power transferred to the lamp as expressed in equation (6), where f_{switch} denotes the operating frequency of the supply.

$$I_{LO} = E \times t_{charge} / L \quad (5)$$

$$P_{lamp} = 2 \cdot f_{switch} \cdot \left(\frac{1}{2} L \cdot I_{LO}^2 \right) \quad (6)$$

3.2 Design and control considerations

Concerning the design of such a supply, one should mention, that the 3 switches of the converter require thyristor-like operating characteristics (unidirectional current in *ON* state, bidirectional voltage in *OFF* state with controlled turn-on and spontaneous turn-off). The usual operating frequencies of classical devices are not compatible with the frequency expected in the considered application (some kHz). So, a synthesized function based on a power MOSFET, in series with a high voltage fast diode, associated with an electronic management circuit has been especially studied and designed.

Concerning the step-up transformer, a critical point for the set-up of such a supply, the design of the latter is a very important issue: indeed, the parasitic parameters of the windings (especially the high voltage one) have a critical effect on the quality of the waveforms and of the operating conditions. The magnetizing inductance must have a large enough value to avoid current flow in the lamp during sequences (A) and (C). Leakage inductances should be minimized to avoid high frequency oscillations during sequences (B) and (D). As for the capacitance of the secondary winding, it derives a percentage of the current in the lamp and should be minimized as well.

As introduced by equations (4) to (6), the proposed power supply offers several degrees of freedom (DOF) to achieve the control of the power transfer:

- t_{charge} permits to choose the values of current (I_{LO}/n) which will be injected in the lamp; it also defines the energy transferred into the lamp during the next pulse.
- $t_{discharge}$ is not directly controllable and depends upon the value of I_{LO} .
- $t_{blanking}$ is adjustable and defines the duration of the relaxation time interval (no current injected into the lamp) and contributes to the definition of the operating frequency.

In the experimental setup, these DOF are managed by means of a DSP-FPGA based control unit, which accurately defines all the events through the firing orders of each power switch and offers possible transient analysis and time domain measurements.

4. PERFORMANCES AND CHARACTERISTICS OF THE UV PRODUCTION

4.1 Electric behavior of the supply

A prototype of the proposed supply has been implemented (the main characteristics are summarized in the following table); Fig. 5 shows the current measured in the L inductance, and the i_{lamp} current in the lamp. These quantities appear to be very similar to the theoretical ones; higher frequencies oscillations, which appear on the i_{lamp} signal, are caused by the mentioned parasitic elements of the step-up transformer. On the basis of the model described in section 2, non-measurable quantities are calculable; the computed current flowing through the gas, i_{gas} , is also presented.

Electric characteristics of the supply	
f_{switch} (switching frequency)	50 kHz
L (primary inductor)	160 μ H
N (step-up transformer ratio)	12
E (voltage supply)	150 V
I_{Lo} (current at end of seq. (A) or (C))	≤ 1.5 A
η (measured electric efficiency)	# 70%

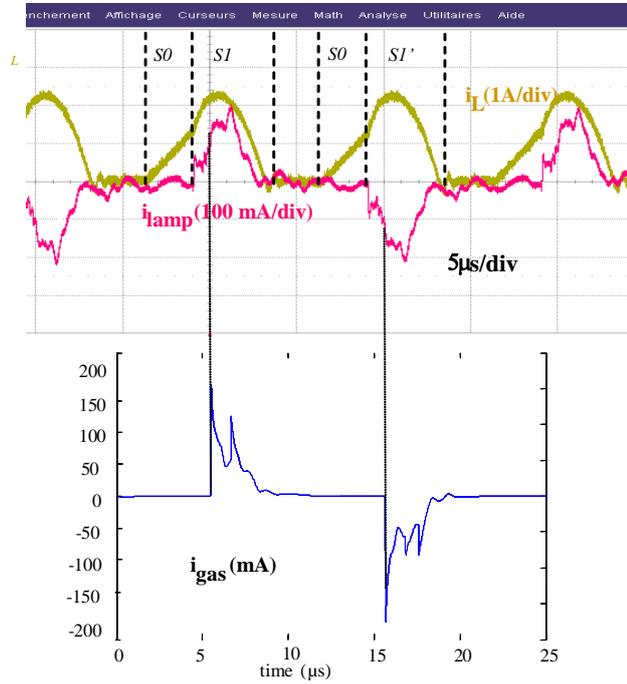


Fig. 5 Main characteristics of the supply; measured currents: i_L (brown) and i_{lamp} (red) – computed current i_{gas} (blue)

4.2 UV production

Associated to the power supply, an optical apparatus has also been developed: it offers time-resolved (with synchronization on the control signals of the power supply) and mean measurements of the produced light, both in the visible and UV domains [12]. The comparison between the shapes of the instantaneous UV power level and the computed i_{gas} current is proposed on Fig. 6(a).



Fig. 6 (a) shapes of the measured instantaneous UV power (blue) compared to the computed i_{gas} current (black) - (b) instantaneous control of the i_{lamp} current - (c) UV production controlled by the power supply.

Thanks to the synchronization between the power supply and the optical measurements, the similarity of the waveforms is stated. Several similar measurements, with different i_{gas} pulse durations, have been realized and give identical conclusions: the UV production is very tightly correlated to the i_{gas} current in the gas, and any changes in the latter (by mean of one of the DOF of the supply) is immediately followed by the same change on the UV. The timescales concerning the use of this property for UV emission control purpose start from half the operating period of the converter.

Fig. 6(b) shows the capability of the supply to change the current in the lamp at the half-period timescale. Fig. 6(c) exhibits the capability of the supply to define the UV level by mean of the controllable i_{lamp} current, even in transient conditions.

The quality of the produced UV has been checked with different levels of power injection (controlled by mean of the t_{charge} duration): Fig. 7(a) proves that the spectral quality of the radiation of the lamp is not affected by the transferred power.

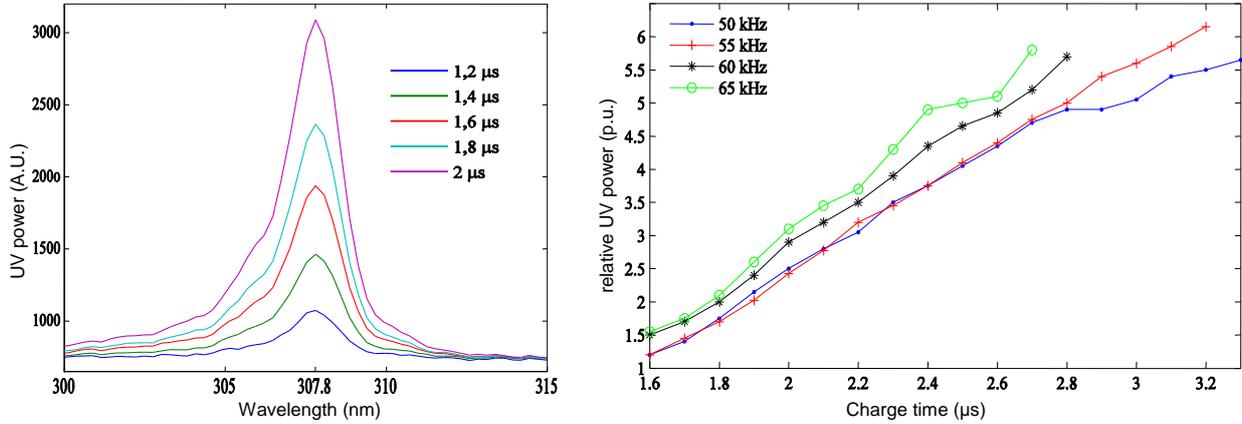


Fig. 7 (a) power distribution of the produced UV, for different power injection levels - (b) Control of the radiation of the lamp with DOFs of the power supply (frequency and injected energy): relative mean UV power, vs t_{charge} , for several operating frequencies

Considering the mean values of the UV power (measured with a 308 nm radiometer) the DOFs of the supply have been used to study the correlation between the relative UV power and the injected power, for several operating frequencies.

Fig. 7(b) shows the UV power increase:

- with the t_{charge} duration, which defines the energy sent to the lamp – see equation (6) – (theoretically, according to equations (5) and (6), with a quadratic shape),
- for a given level of injected electric power, with the switching frequency (which is proportional to the injected electric power – see equation (6)).

One can notice that the lower curve at 50 kHz remains very near to the one at 55 kHz. This can be interpreted as better conversion, from electrical to optical power (higher efficiency), of the lamp at 50 kHz. The last result is very interesting, letting imagine that the current-mode power supply can be used to identify the optimal operating frequency of the lamp.

5. CONCLUSION

The concept of a current-controlled static converter has been selected, to control the power transfer to a DBD lamp, on the basis of causality criteria. The proposed topology has shown its capability to control the current and the power injected in the lamp at each half operating period.

An UV optical measurement apparatus, synchronized with the power supply has been associated with the experimental set-up: it has highlighted the fact that the UV production is directly controlled by the current which actually flows into the gas – this non observable current is controllable by mean of the current which is injected in the lamp.

The proposed static converter offers two main degrees of freedom to define the operating conditions of the system: the injected power level at each half period and the frequency. These DOF have been explored and the UV emission has shown tightly correlated to the electric power. Specific behavior (depending for instance upon the operating frequency)

has been observed and let consider that the power supply presented in this paper can be useful for further studies, carried by plasma physicist, in order to define the optimal operating parameters of a DBD lamp.

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APPENDIX: PARAMETERS OF 60W XE-CL EXCILAMP

The parameters of the 60W excilamp used for experimentations have been identified, as described in section 2. The following table summarizes the values introduced in equation (1) and Fig. 1.

	V_{th} (V)	ΔV (V)	K_{gen} ($\Omega \cdot s^{-1}$)	K_{ext} (s^{-1})	K_{pro} ($V^{-1} \cdot s^{-1}$)	C_{diel} (pF)	C_{gas} (pF)
initial guess	1500	20	130	$2,7 \times 10^6$	1835	39,81	13,07
final result	1800	2,9	2×10^4	1×10^6	100	40,03	13,87

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