Effective excitation of DBD lamp with a long feedline

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Abstract. The proposed solution makes possible the transfer of high-voltage excitation pulses through the long coaxial cable with the minimum losses and the excilamp efficiency. Use of resonant topology of the pulse converter provides ZCS at switching-ON and ZVC at switching-OFF of the transistors. The values of efficiency of radiation of ~ 9% at the feedline of 2.5 m in length obtained during the experiments are about twice as much as the efficiency at the XeCl-excilamp excitation by the quasi-square pulses power supply due to the decrease of losses at switching and the increase of electric efficiency of a resonant power supply with the long coaxial feedline.

1. Introduction

“Excilamp” is a source of gas-discharge spontaneous narrow-band radiation created by decomposition of excimer or exciplex molecules. This process occurs in working gas or gas mixture excited by barrier, capacitive or glow discharges [1]. A specific feature of these molecules is their stability in the excide electronic state and the absence of a strong bond in the ground state. Excimer and exciplex molecules have an intense B→X transition in the UV or VUV spectral ranges and up to 80% of total radiation power and even more concentrated in a relatively narrow (1.5-10 nm of FWHM) band of corresponding molecule. Electrodeless structure of barrier- and capacitive-discharge bulbs except chemical contact of metal electrodes with working gas and provide long life-time of a radiator up to 10 000 h [2].

The unique properties of excilamps are: simple construction, single narrow-band of radiation, long life-time and feasibility of various geometry of a radiator. The absence of mercury and other vapor of metals as part of working gas lead to instant availability to work (not required warm-up), feasibility of operation at wide range of a radiation power and wide range of bulb temperature. Consequently, excilamps have stable energy and spectral characteristics specifying their application in medicine, photochemistry, photolithography etc., where precision of UV or VUV dose is required.

Traditionally sine [3] or pulsed [4] voltage is used to excite active gas media of excilamps. The excitation of DBD lamps through a long coaxial feedline by subnanosecond front pulses is non-productive because of considerable reactive load for pulsed power supplies that leads to the efficiency decrease of a device “a power supply and a radiator”. In this paper we used paused sine voltage with a near-resonant frequency to excite DBD excilamps and demonstrated the efficiency increase and impedance matching at lamp feeding through a long coaxial feedline.

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2. Model description

Investigations of electrical process in DBD excitation circuits were described in works [5, 6]. For detailed analysis of electrical processes at DBD excitation a complete equivalent circuit should be considered. DBD parameters consist of parasitic parameters of inverter elements, a step-up pulse transformer and a long feedline. Figure 1 shows a complete equivalent circuit, where C_b – nonlinear capacitors of dielectric barriers, C_g – capacitor of gas gap, R_{pl} – nonlinear resistance of plasma, L_{s1}, L_{s2} – transformer leakage inductances, L_u – magnetizing inductance, r_u – equal resistance of magnetic core losses and r_1, r_2 – active resistance of primary and secondary coils L_s – total inductance of a resonant choke and inverter circuits, C_u – a DC-blocking capacitor, r_{lss} – resistance of total active losses (connector wires, coil of a choke, ON transistors of the inverter).

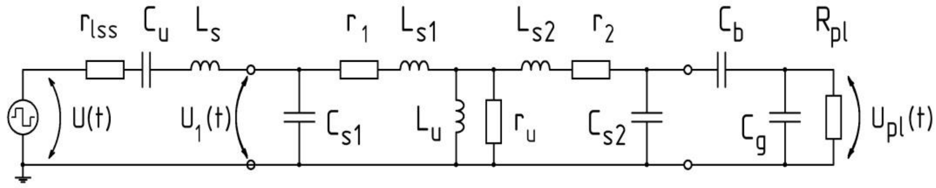

Figure 1. Complete equivalent circuit.

Capacitance C_{s2} includes capacitance of secondary coil of a transformer, connector wires and a long feedline. *U(t)* is a pulse voltage of the ideal inverter. Modeling of the system shows the amplitude-response curve has a maximum in the range of 0.5-2 MHz at the wide equivalent circuit parameters, but specific interest in the application of resonant circuits presents the load compensation mode of reactive power, when $X(f)=\text{Im}[Z_{in}(2\pi if)]=0$, where $Z_{in}(2\pi if)$ is impedance of the system.

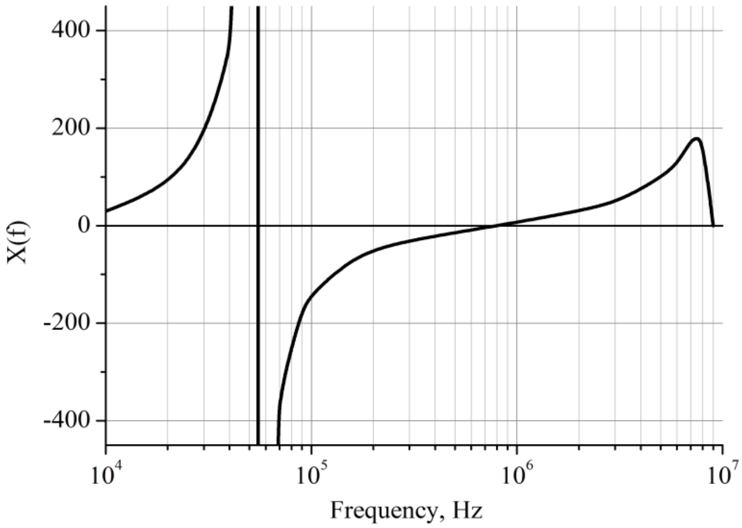

Figure 2. Curve of the imaginary part of impedance of the system.

On the described curve *X(f)* (see figure 2) there is a frequency point where impedance of the system has near active type of load, it is, therefore, possible for matching of a power supply and load with dielectric barrier. The results of circuit simulation with a step-up pulse transformer indicate the possibility to achieve high efficiency of energy transmission through a long coaxial feedline and a dielectric barrier at sine voltage excitation on a resonance frequency f_{res} (maximum of the amplitude-response curve). A matching load mode takes place when reactive power circulating in parasitic capacitances is generally compensated by inductivities L_s, L_{s1}, L_{s2}, L_u.

In fact, generation of pauseless harmonic oscillations with the amplitude of 2-5 kV and a frequency of several megahertz is practically difficult. The excitation of DBD lamps with pauseless sine voltage has low efficiency of radiation due to absence of a current pause, which is necessary for plasma relaxation in a discharge gap [7]. The increase of efficiency at pulse excitation of DBD with a pause which is much long than the pulse is in evidence due to formation of the optimal electron energy distribution function and minimization of elastic and inelastic losses of electron energy in processes which do not lead to creation of excimer or exciplex molecules [1].

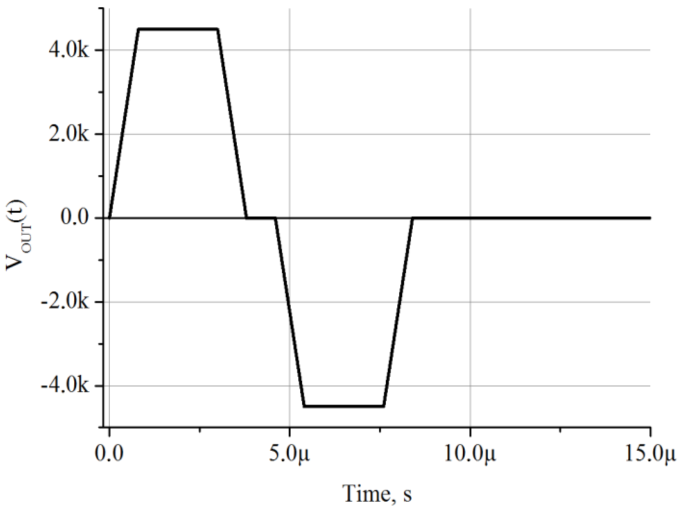

Figure 3. Model curve of voltage pulses.

As a result we can list the requirements for the waveform (spectral distribution) of excitation voltage:

- main part of excitation energy have to be concentrated in the narrow band of spectra;
- conditions of rate of voltage and current rise and the amplitude of excitation pulses for effective input of energy into gas media have to be specific;
- current pauses for plasma relaxation have to be happened.

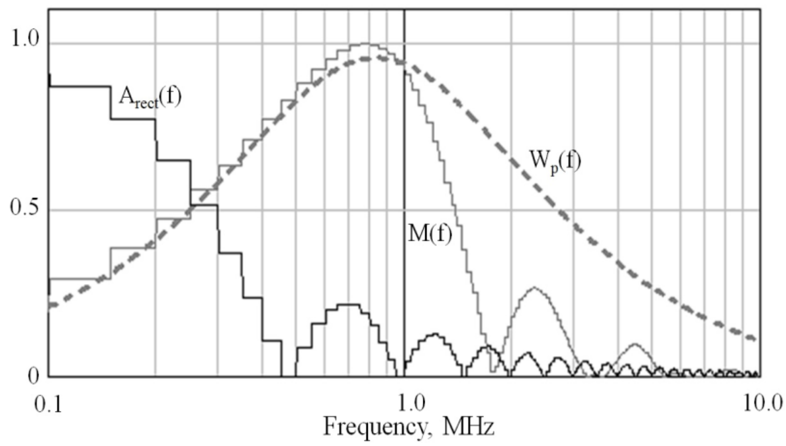

Figure 4. Spectra of different waveforms of excitation voltage and the amplitude-response curve of the system.

The adherence of these requirements gives the opportunity to obtain a resonant mode of operation of the circuit which is characterized by high efficiency of energy transmission and compensation of

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the majority of the reactive power circulated in the discharge circuit. The feature of a resonant mode is ZCS which provides decreasing dynamic losses in the inverter.

To fulfil all the above requirements it is necessary to receive a pulse burst of sine voltage with a resonant frequency of the system f_{res}, which consists of even number of oscillation periods of sine voltage on secondary winding of the pulse transformer. A model curve of voltage pulses V_{OUT} on the inverter output, which can be obtained with pulsed transistor bridge inverters, is shown in figure 3.

The Fourier spectrum of the model curve of voltage pulses *M(f)* is very much different from a single-frequency sine spectrum and it has an intense frequency band where the main energy is concentrated (Figure 4). The amplitude-response curve $W_p(f)$ of the system and the spectrum of square voltage $A_{rect}(f)$ (pulse duration 2 μs, frequency 100 kHz) are shown in figure 4 too. Proposed bipolar signal V_{OUT} with a period of $t_p \sim ½ f_{res}$ has a clear advantage, as its main energy is concentrated in harmonics fits in the bandwidth of the filter formed by the elements of the resonant system.

3. Circuit of the resonant power supply

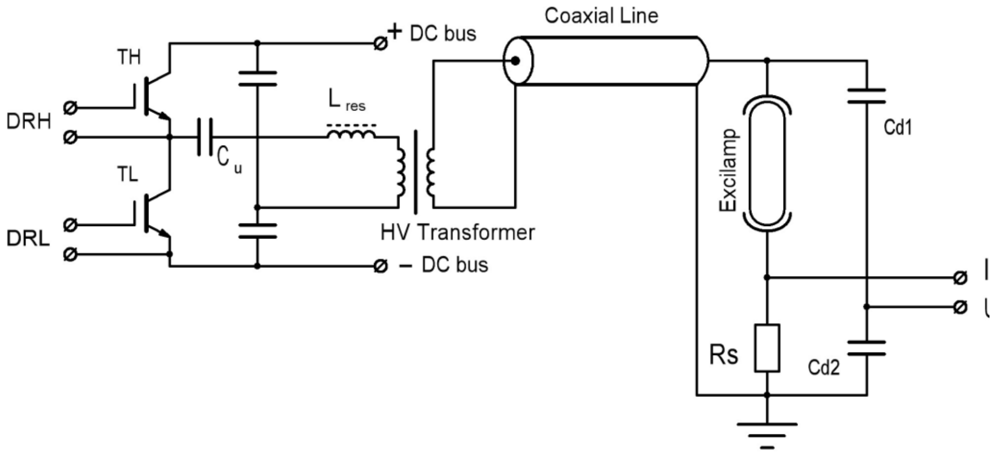

Figure 5. Circuit of the resonant power supply.

The circuit of the developed resonant power supply with a coaxial long feedline is shown in figure 5. The half-bridge transistor inverter *TH* and *TL* is loaded on the oscillating loop which consists of a choke L_{res} and step-up HV transformer connected to the excilamp through coaxial line. Voltage and current of the excilamp are registered using a capacitive voltage divider C_{d1}-C_{d2} and a current shunt R_s.

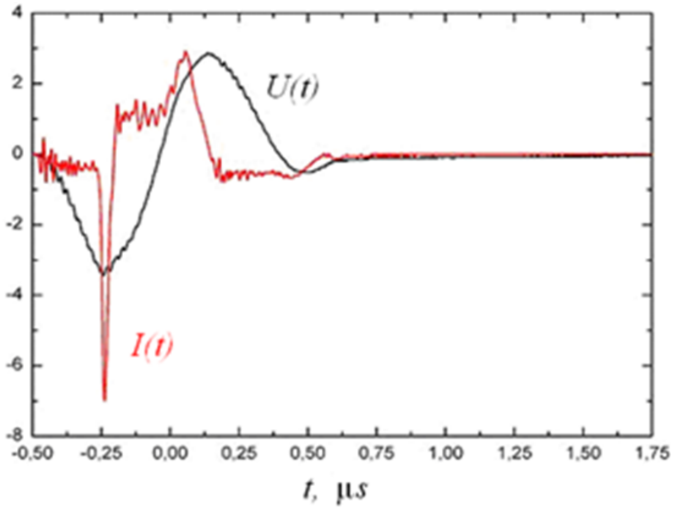

Figure 6. Oscillograms of voltage and current pulses at excilamp excitation by a source of quasi-sinusoidal pulses of voltage.

A control circuit makes it possible to receive the pulses on transistor gates with the amplitude of 16V, duration pulses t_p = 50-800 ns and frequency of pulses f_p = 0.5-5 MHz at dead time 80-200 ns. Pulses are formed as bursts with periods from 1 to 4 in a burst and the frequency of bursts f_b is adjusted in the range of 10-80 kHz.

The energy transfer mode in the resistive impedance of DBD plasma through the long coaxial feedline up to 7.5 meters in length is carried out at the resonant frequency. Pauses between excitation pulses provide necessary degree of plasma relaxation in a gas-discharge gap, i.e. optimal pre-pulse electrons concentration of gas discharge plasma. This parameter is satisfied at excitation on the burst frequency f_b = 15 kHz by bipolar pulse with t_p ~ 250 ns which corresponds to the resonant frequency of the system f_p ~ 2 MHz (see figure 6). The frequencies of 1 MHz and below are usually specified in other publications about resonant sources of excilamp excitation [8]. Design features of the excilamp and the pulse transformer provide the high resonant frequency. In this case the combination of measures for decrease the parasitic inductance and the distributed capacities were carried out.

4. Experiment results

The sealed-off XeCl-excilamp of the barrier discharge with mixture parameters Xe/Cl = 200/1, total pressure 102 Torr and radiating area surface of 155 cm^2 was used in experiments. Optimization of gas mixture and pressure of a working gas using a power supply with quasi-square pulses at output and without the coaxial line was carried out before sealing. Then two power supplies (power supply with quasi-square pulses and created quasi-resonant power supply) excited the excilamp through the long coaxial feedline. The RK-50-4-11 cable of 2.5, 5 and 7.5 meters in length was used as a coaxial long feedline. Radiation power was measured with a H8025-222 photodetector (Hamamatsu Photonics) with the known spectral sensitivity. Excitation power of the excilamp was calculated on the basis of oscillograms of current and voltage on excilamp electrodes according to the method described in [5]. Consumption power was calculated by multiplying current and voltage measured on the input of the power supplies.

Experiments show, that there are considerable losses of energy due to switching of transistors at excilamp excitation by the high-voltage quasi-square pulse generator with the feedline of 50 cm and more in length. They are caused by the high peak current arising during the operation of the inverter with the pulse transformer connected to capacitor load. The developed quasi-resonant power supply operates with efficiency ~ 9%, it is about twice as much as the unipolar quasi-square pulse power supply. The period increase in the burst leads to the decrease in efficiency of excilamp radiation due to overexcitation of the active gas medium even with low frequencies of burst repetition rate.

Acknowledgments
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