Dynamic PSpice Model of CO_2 Laser Tube

Yasen Kostadinov Madankov, Aleksandar Stoyanov Vuchev and Nikolay Dimitrov Bankov

Abstract –**A PSpice realization of dynamic simulation model of CO_2 laser is proposed. Simulations of the model, supplied by LCC resonant DC/DC converter are made. The transient process of gas excitation is shown. A sufficient coincidence of the results with real laser laboratory experiment are obtained.**

Keywords – **CO_2 laser, PSpice model, LCC DC/DC converter**

I. Introduction

High-frequency resonant converters are proved to be a proper choice for high-voltage power supply realization. Their main advantages are high efficiency, small dimensions and relatively low costs. There are plenty of simplified methodologies for design of such kind of converters. A harmonic analysis, as well as experimental results, of LCC resonant converter for CO_2 laser power supply is proposed in [1].

The modern software products for electrical circuit simulations offer an opportunity to prove the designed supply functionality before its manufacture, which usually is quite complicated. However, there are elements with specific characteristics, which are not available in the programs libraries. For example gas discharge is particular kind of load, characterized with nonlinear negative dynamic resistance and specific exciting process. It is most commonly used for a laser beam generation or in the realization of light sources (fluorescent lamps). In this case, to achieve an appropriate simulation results a suitable model of the gas discharge is needed.

Models of such loads, based on kinetic equations, could be found in the literature [2, 3]. Their main disadvantages are complexity and requirement of in-depth knowledge in plasma physics. For this reason the so-called "curve-fitting" models are quite common [4].

Disadvantage of all existing models is the impossibility for adjustment of the excitation process. This paper aims to propose an electrical model of CO_2 laser discharge tube which includes the possibility to simulate the dynamic process of ignition. The results are compared with experimental investigations with a laser, similar to the one described in [1].

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II. Model Realization

A. Volt-Ampere (V-I) Characteristics

A main step of the model realization is the load's V-I characteristics achievement. The experimental values of the average voltage (U_{0AV}) and current (I_{0AV}) of one section of the laser tube are shown on Fig. 1 with Δ.

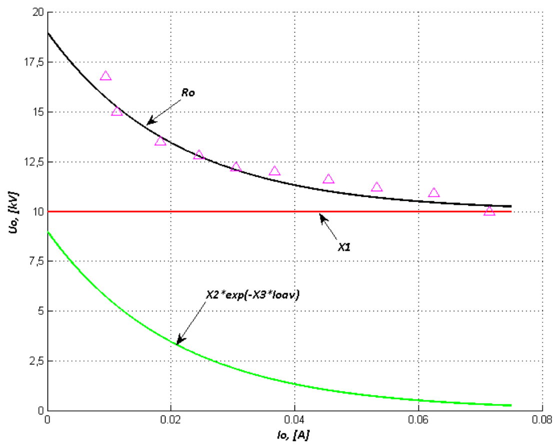

Fig. 1. Volt-Ampere characteristics of the laser tube

The desired dependence $U_{0AV} = f(I_{0AV})$ could be easily obtained using the equation:

$$U_{0AV} = X_0 + X_1.e^{-X_2.I_{0AV}} \quad (1)$$

The first term (X_0) has meaning of basic value of the load curve, and the negative dynamic resistance is achieved with parameters X_1 и X_2. The values of the parameters at which the coincidence is satisfactory are: $X_0 = 11000$, $X_1 = 8500$ и $X_0 = 48$.

Examining the laser tube as active resistance, its impedance (R_0) could be obtained by I_{0AV} and than the instantaneous value of the voltage is:

$$u_0 = R_0.\mathrm{i}_0 = \frac{U_{0AV}}{I_{0AV}}.i_0 = \frac{X_0 + X_1.e^{-X_2.I_{0AV}}}{I_{0AV}}.i_0 \quad (2)$$

Fig. 2 shows the proposed PSpice model. By the current controlled voltage supply H1, the instantaneous value of the current trough the laser tube (i_0) is converted to voltage. Its average value is obtained by the integrating circuit R_1-C_1. Its time constant has to be large enough to the current pulsation frequency in order to obtain good filtration. On the other side, an excessive increase would affect the transient processes. An appropriate value could be 5÷10 times higher.

The load V-I characteristics is given by the EVAULE element E1. Its output is actually the value of the tube resistance (R_0) for particular I_{0AV}. The usage of the LIMIT

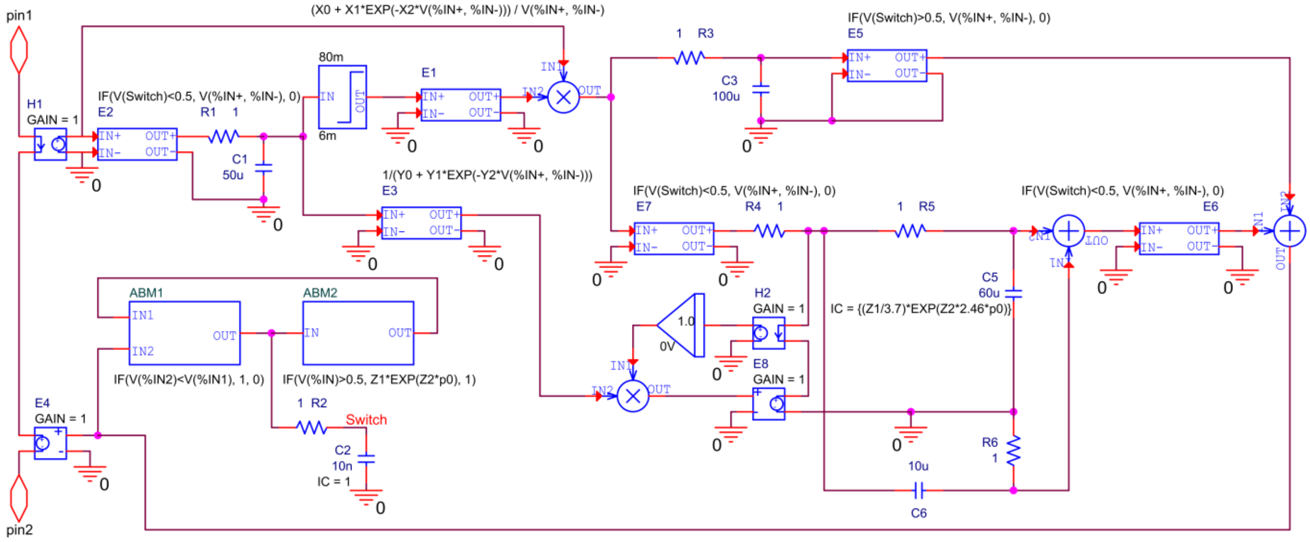

Fig. 2. PSpice model of the laser tube

component is imposed by the zero division in E1 at initial conditions. Its values define the tube average current for the operating range of the laser. The voltage u_0 is obtained by multiplication of resistance R_0 and the instantaneous value of the current, expressed by voltage, using MULT1.

B. Capacitive Characteristics

In this way, the model has only active impedance. A highly expressed capacitive component is characteristics for each gas discharge, which has to be taken into account. Equation (3) is used to obtain the tube capacitance of the examined laser in function of I_{0AV}. The results with $Y_0 = 6{,}1\,\mu$, $Y_1 = 45\,\mu$ И $Y_2 = 60$ are presented on Fig. 3.

$$C_0 = Y_0 + Y_1.e^{-Y_2.I_{0AV}} \qquad (3)$$

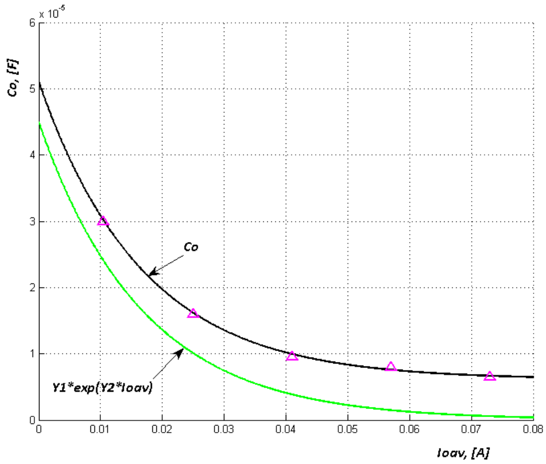

Fig. 3. Capacitive characteristics of the laser tube

A capacitor, controlled by the average value of the current trough the tube, has to be realized for this part of the simulation model. It is well-known that the voltage drop across the capacitor might be expressed as a function of its current. If (3) is used as a capacitance value the next equation is obtained:

$$u_{C_0} = \frac{1}{C_0}.\int i_{C_0}.dt = \frac{1}{Y_0 + Y_1.e^{-Y_2.I_{0AV}}}.\int i_{C_0}.dt \qquad (4)$$

In the model on Fig. 2, Eq. (4) is realized by elements H2, E8, INTEG and MULT2. The capacitance value is given by E4, where Eq. (3) is defined. Its input variable is the average value of the laser current, expressed by voltage.

The proposed capacitor, in combination with R_4, forms an RC circuit on the MULT1 output. $R_2 = 1\,\Omega$, hence, its time constant is defined by I_{0AV}.

C. Excitation Process

The described model is functional and by using it reliable steady state results could be obtained. In order to achieve the characteristic transient process of gas discharge excitation it has to be supplemented. Such kind of processes are found in the literature and are analyzed [5, 6]. Experimental investigations with the examined laser are also made. The following conclusion could be defined – the transient process is dependent on a number of factors and in great degree is individual for each separate load. In spite of this, it could be generalized with the transient waveform on Fig. 4.

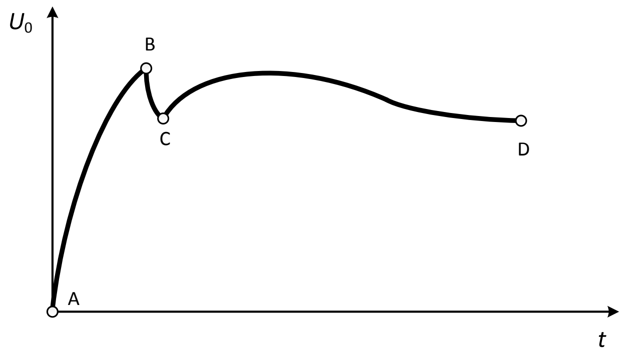

Fig. 4. Waveform of U_0 during the excitation process.

During interval **A-B** the gas discharge is not excited yet. This happens at point **B**, when the breakdown voltage (U_{0br}) is reached. The interval **B-C** is characterized with sudden voltage decrease. During interval **C-D** the transient process is settled to steady state mode. It could have aperiodic or oscillating form, which is determined by various influences, such as gas pressure, proportion between the particular gases, their flow rate etc. It is found

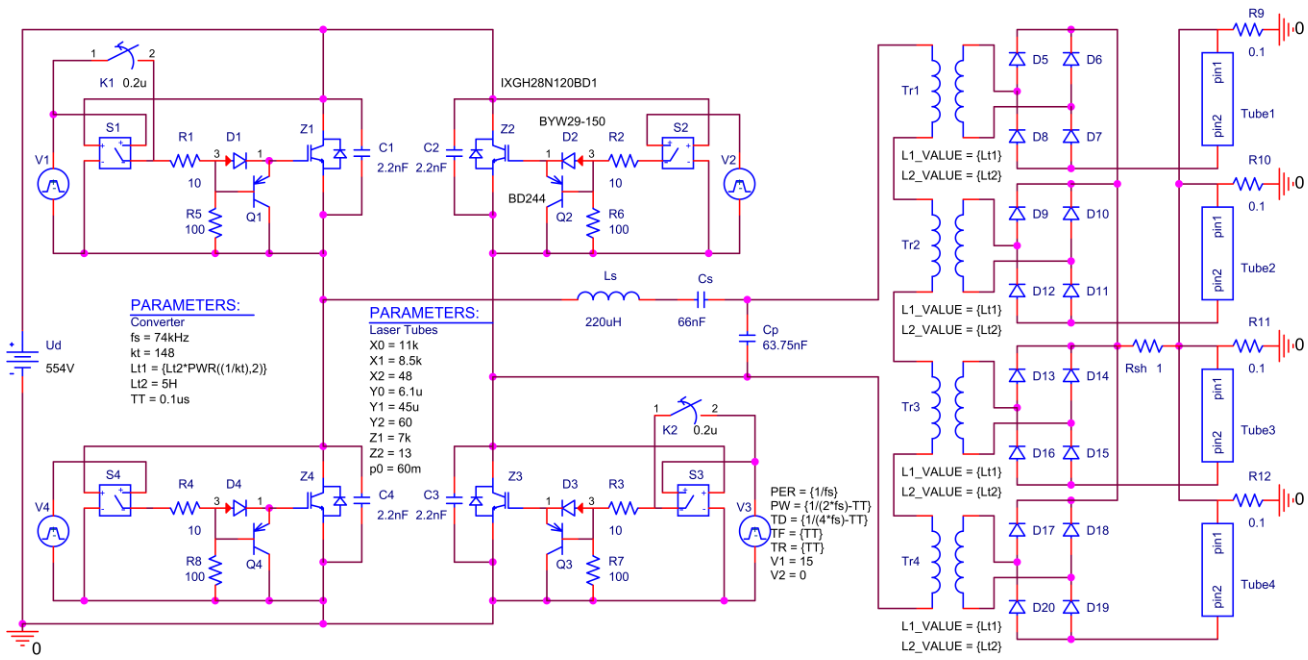

Fig. 6. PSpice simulation circuit of LCC resonant converter with the laser tubes models

that for the examined laser this process usually has critical aperiodic form, as shown on Fig. 4.

The breakdown voltage is mainly influenced by the gas pressure (p_0) [6]. This dependence for the particular laser is experimentally determined and the results are shown on Fig. 5 with Δ. The mathematical expression is defined by Eq. (5) with values $Z_1 = 7000$ and $Z_2 = 13$.

$$U_{0br} = Z_1.e^{Z_2 \cdot p_0} \qquad (5)$$

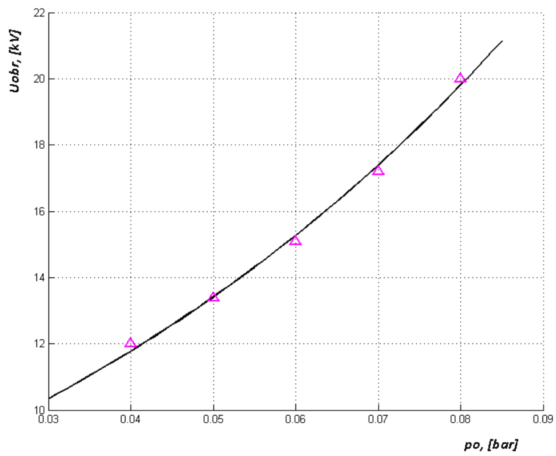

Fig. 5. Breakdown voltage U_{0br} in dependence of p_0

The excitation process modelling is based on switching between two circuits – for interval **A**-**B** and after it. Both of them have the same input which is MULT1 output. The circuit corresponded to the first interval is realized by the first-order filter R_3-C_3. Its time constant defines the excitation time of the gas and the degree of filtration of u_0. The circuit to obtain the desired capacitive characteristics, as explained before, take part into the second one. Its output is passed to the R_5-C_5 and the differentiator R_6-C_6. The first one is to achieve the desired form of the transient process for interval **B**-**D**. The second is appended to preserve the voltage amplitude, provided that high-frequency power supply is used. The output signals of these circuits are added by SUM2.

Elements E2, E5, E6 and E7 are switches, which state is defined by the moment in which point **B** is reached. They have to provide hysteresis characteristics – to trigger when $u_0 \geq U_{0br}$ and to retain this state no matter that $u_0 < U_{0br}$. The PSpice primitive switches implement soft transition of their resistance and therefore could not be used. That is the reason why elements ABM1 and ABM2 are added. ABM1 compares voltage u_0 with the value of U_{0br}, given by ABM2, where Eq. (5) is implemented. ABM1 output is used to control the switches by the voltage on the node "Switch". The switches are realized by EVALUE elements and the trigger effect is obtained by IF() statements against the voltage V(Switch).

It has to be noted that the time for reaching U_{0br} is influenced by several factors:

- ✓ lower value of LIMIT;
- ✓ time constant of R_3-C_3 circuit;
- ✓ U_{0br} value, defined by the gas pressure p_0;
- ✓ the values of the parameters, defined by Eq. (1).

III. Simulation and Experimental Results

The examined laser tube consists of four identical sections, as explained in [1], and the designed model is for one section. On Fig. 6 is presented the simulation circuit where LLC DC/DC converter with four matching transformers is used. An instance of the laser tube simulation model is connected on each output. The values of the converter parameters are: supply voltage - $U_d = 554\,V$, operating frequency - $f_S = 73\,kHz$, resonant elements - $L_S = 240\,\mu H$, $C_S = 66\,nF$, $C_P = 63{,}75\,nF$.

Transient simulation waveform of the voltage across one tube section, at $p_0 = 80\,mbar$, is shown on Fig. 7. The experimental results with power supply with the same parameters are presented on Fig. 8.

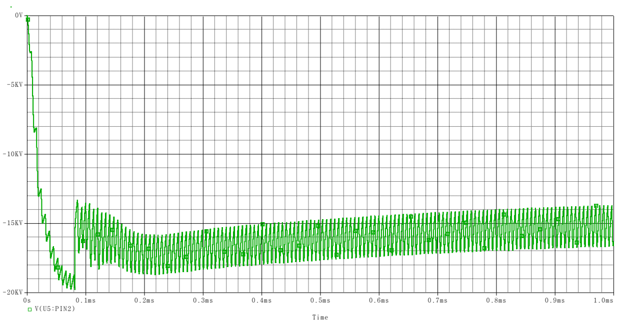

Fig. 7. Simulation waveform of u_0 during excitation process

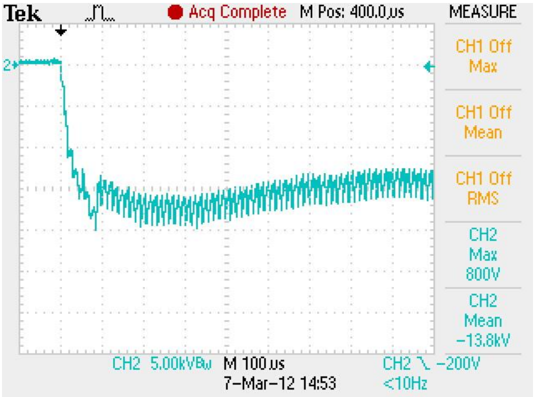

Fig. 8. Experimental waveform of u_0 during excitation process

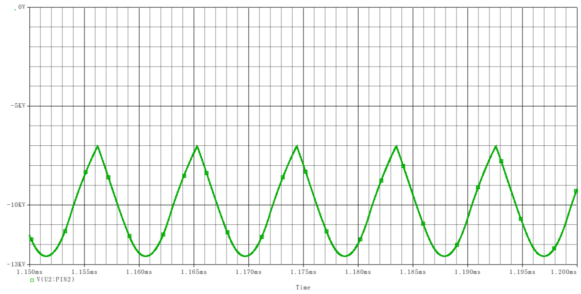

Fig. 9. Simulation waveform of u_0 at steady state

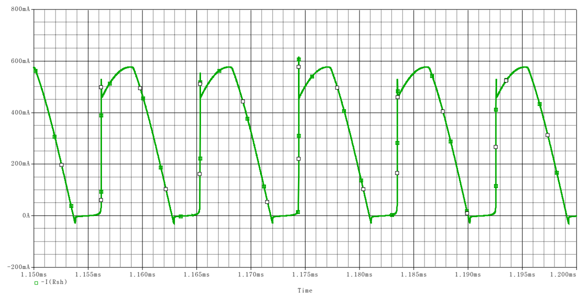

Fig. 10. Simulation waveform of i_0 at steady state

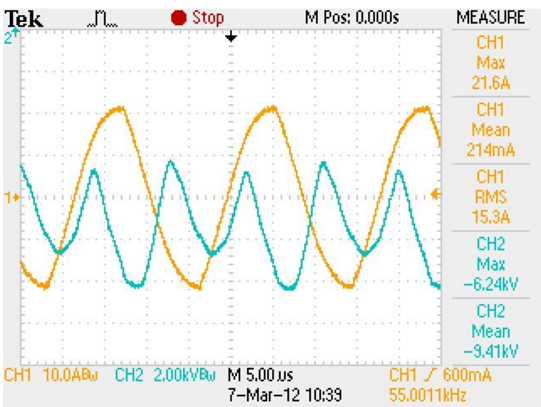

Fig. 11. Experimental waveform of u_0 and i_{Ls} at steady state

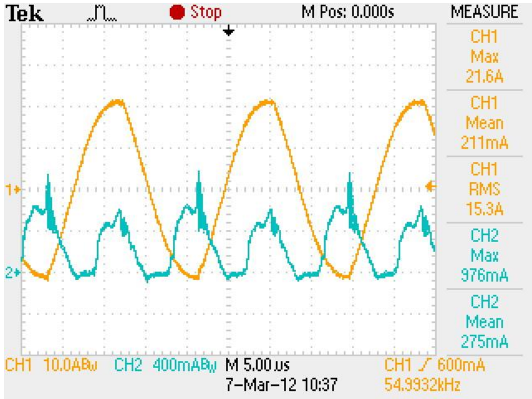

Fig. 12. Experimental waveform of i_0 and i_{Ls} at steady state

The steady state mode simulation waveform of voltage u_0 and the summarized current trough all tubes at $f_S = 55\,kHz$ are shown on Fig. 10 and 11. The experimental results at same conditions are presented on Fig. 12 and 13.

IV. Conclusion

A dynamic PSpice model of CO_2 laser is proposed. Its volt-ampere and capacitive characteristics are obtained using curve-fitting. The gas pressure and its influence on breakdown voltage is taken into account. The dynamics of the excitation process is based on a simple circuits, allowing modeling of the excitation process.

PSpice simulations of the designed laser model, supplied by a LCC resonant DC/DC converter are made. The results are compared to experimental study with the real laser and a prototype of the proposed power supply. The suggested model is suitable for verification of the efficiency of designed power supply before their practical realization.

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