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LOSS ANALYSIS IN THE DISCHARGE LOOP OF A HIGH-POWER ARTIFICIAL LINE PULSED MODULATOR

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Abstract. A technique is proposed for analysis of the energy losses in the discharge loop of an artificial line pulsed modulator used for high-power current-pulse shaping in solid state laser power supplies. It is applied for determining the maximal admissible repetition rate of the modulator output pulses using single-pulse mode experimental data.

Резюме. Пледложен метод анализа энергийных потерь в разрядной цепи импульсивного модулятора с изкусственной линией, формирующего мощных токовых импульсов в газоразрядных лампах твердотельных лазеров. Используя данные полученные в однократном режиме, метод применен для определения максимально допустимой частоты повторения выходных импульсов модулятора.

Pulsed modulators with artificial lines are used in pulsed-mode oscillators and are the essential pulse-shaping components of radar stations, radio-frequency experimental physics equipment, as well as of power supplies for flashlamp-pumped pulsed solid state lasers, where the artificial line is used as an energy storing device [1, 2].

Two of the most important parameters characterizing the performance of such laser power-supplies are the shape and duration of the discharge current pulse. They change insignificantly for a wide range of pumping-energy variation when care is taken that the load impedance R_d varies within the limits $\rho \leq R_d \leq 2\rho$ (ρ being the line wave-impedance) [1]. The third important parameter concerning laser power supplies is the maximal possible discharge-pulses repetition rate; it is limited mainly by the losses in the capacitors C of the pulse-shaping artificial line. In the present work we propose a simple and useful method for determining the maximal pulse repetition rate based on analysis of the losses in a pulsed modulator operating in a single-pulse mode. Fig. 1 presents the block-diagram of a pulsed

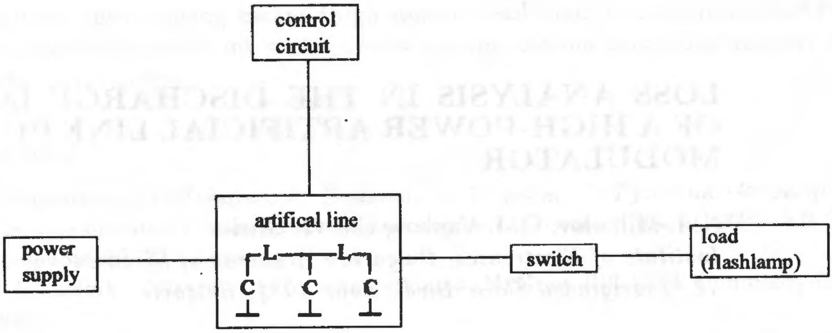

Fig. 1. Block-diagram of a pulsed solid-state laser power supply with an artificial line

modulator employing a homogeneous pulse-shaping artificial line; the high power current pulse generated is of square shape. The technique used for calculation of the artificial line parameters consists in considering its operation as consequtive switching of "K"-type low-pass filters; the solution is a superposition of waves travelling along the artificial line, the wave components are described by Bessel functions (the inhomogeneities in the separate sections are neglected).

The total losses in the shaping-line elements are determined by the expression:

$$W_t = W_c + W_l + W_s = W_i - W_f - W_d,$$

or

$$W_c + W_l = W_i - W_f - W_d - W_s \tag{1}$$

where W_i and W_f are the initially stored and the finally remaining energy in the line, respectively; W_d is the energy dissipated on the load; W_c, W_l, W_s are the energy losses in the capacitors, inductances and the switching loop and the switching elements, respectively.

The losses in the capacitors are determined approximately based on experimental data obtained when the pulsed modulator operates with active resistance load with value of 0.1 Ω (0.5 Ω): the line voltages U_i and U_f are measured before the output pulse is formed and after the processes in the line are completed, respectively.

Having neglected the influence of the impedances of the switching loop and the switching elements and devices on the discharge-current magnitude, one can rewrite (2) in explicate form

$$W_c + W_l = \frac{C_l U_i^2}{2} - \frac{C_l U_f^2}{2} - I_d^2 R_d \tau_p - I_d^2 R_s \tau_p - I_d^2 \Delta U \tau_p$$

where $I_d = \dfrac{U_i}{\rho + R_d}$ is the discharge current, ΔU is the sum of the voltage falls across the switching devices, R_s is the impedance of the switching loop, C_l is the total capacitance of the line, and τ_p is the pulse duration. After simple transformations and after substituting $q = U_f/U_i$ and

$$m = \frac{2\tau_p[R_d + R_s + \Delta U/U_i(\rho + R_d)]}{C_l(\rho + R_d)^2},$$

one obtains

$$W_c + W_l = \frac{C_l U_i^2}{2}(1 - q^2 - m). \tag{2}$$

One can calculate the losses in the inductances of the artificial line if the active component R_l of the inductance of a single section of the line is known. The ratio of the effective current in the k-th section of the artificial line to the effective discharge current in the load is [1]

$$\Theta_k = \frac{I_{lk}^{eff}}{I_d^{eff}} = \left[[3.2(1 - k/n) - 0.57/n]\right]^{1/2} \tag{3}$$

where k is the inductance order-number decreased by one, and n is the number of the artificial line's sections.

The square of the effective value of the current in the load is given by [2]:

$$(I_d^{eff})^2 = \frac{U_i^2 \tau_p}{(\rho + R_d)^2 T} \tag{4}$$

where T is the pulse repetition period.

Using (3) and (4), one can write the total energy losses for one period in the line's inductances as follows:

$$W_l = \sum_{k=0}^{n-1} W_{lk} = \frac{U_i^2 R_l \tau_p}{(\rho + R_d)^2} \sum_{k=0}^{n-1} \Theta_k^2. \tag{5}$$

The losses in the capacitors are then

$$W_c = \frac{C_l U_i^2}{2}(1 - q^2 - m) - \frac{U_i^2 R_l \tau_p}{(\rho + R_d)^2} \sum_{k=0}^{n-1} \Theta_k^2. \tag{6}$$

Under steady-state conditions, the maximal power released in the capacitors must be equal to the power dissipated by the cooling surface [4].

$$P_c^{max} = P_{cool}; \qquad W_c^{max} = W_c f_{max}; \qquad P_{cool} = S\alpha_h(t_{ss} - t_0) \tag{7}$$

where S is the cooling area of the capacitors battery, t_0 is the ambient temperature, t_{ss} is the steady-state temperature of the capacitors' surface, and $\alpha_h = 1 \times 10^{-3}$ W/cm^2.deg is the heat-transfer coefficient.

Using (7), and bearing (5) in mind, one can determine the maximal discharge-pulses repetition rate for unlimited power dissipated in the load:

$$f_{\max} = \frac{2S(t_{ss} - t_0)(\rho + R_d)^2 \alpha_h}{U_i^2 \left[C_l(1 - q^2 - m)(\rho + R_d)^2 - 4R_l \tau_p \sum_{k=0}^{n-1} \Theta_k^2 \right]} \tag{8}$$

where all terms, except q, are constants.

We should add here that when the artificial-line pulsed modulators are employed in laser equipment, $f_{\max}$ depends also on the average power which flashlamps, used as modulatorr's load, can withstand. The nonlinear characteristics of these flash-lamps are approximated in the way described in [5] so that the above calculations can be carried out in that case, too.

In order to determine the dependence of the variable q on the artificial line voltage U_i, one can assume that the energy losses in the line elements are dissipated on an equivalent active resistance R_e placed in series with the artificial line. The dielectric losses (tgδ) in the line capacitors are practically constant. The skin effect in the inductances can also be neglected since the pulse duration is large. Moreover, because the artificial line operates in a near short-circuit mode, the frequency of the discharge-current harmonics does not depend on U_i and on the load's nonlinearity, while their amplitudes are proportional to U_i. One can, therefore, further assume that when U_i exceeds a critical value $U_{cr'}$, R_e is linear and does not depend on the value of U_i. The artificial line losses then are determined by the equivalent resistance R_e and the pulsed line current, and can be written as

$$W_t = \frac{U_i^2 R_e \tau_p}{(\rho + R_d)^2}. \tag{9}$$

Combining (2) and (9), one can determine q as a function of U_i

$$q = (1 - a - b/U_i)^{1/2} \tag{10}$$

where

$$a = \frac{2\tau_p(R_d + R_s + R_e)}{C_l(\rho + R_d)^2}; \qquad b = \frac{2\Delta U \tau_p}{C_l(\rho + R_d)}.$$

The last term in equation (10) decreases as U_i increases. If the inequality $b/U_i \leq 0.1a$ holds, the effect of U_i on q can be neglected. Then for

$$U_i \geq U_{cr} = \frac{10\Delta U(\rho + R_d)}{(R_d + R_s + R_e)}, \tag{11}$$

the value of q can be assumed constant.

In a typical case for laser power supplies, $\tau_p = 2 \times 10^{-3}$ s, $R_d = 0.2\ \Omega$, $R_s = 4.6 \times 10^{-3}\ \Omega$, $\Delta U = 25$ V, $U_i = 2\ 000$ V, $q = 0.05$, $C_l = 640\ \mu$F, $\rho = 1\ \Omega$ and one can calculate using (2) the energy losses in the artificial line elements as $W_t = 162$ J.

The equivalent resistance R_e is therefore

$$R_e = \frac{W_t(\rho + R_d)^2}{U_i^2 \tau_p} = 2.9 \times 10^{-2}\ \Omega.$$

Substituting this value in (11), one obtains U_{cr} = 1300 V, a value commonly observed in most practical situations.

Therefore using (8) one can easily estimate the maximal admissible pulse repetition rate of the artificial-line modulator bearing in mind the specific system characteristics, such as engineering design, type of capacitors used, etc.

In conclusion, the analysis of the energy losses in the discharge loop of an artificial-line pulsed modulator using data most often encountered when the line is used as an energy-storage device in solid state laser power supplies allowed us to derive a simple expression determining the maximal pulse repetition rate of the modulator.

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