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ELECTRONICS AND RADIO ENGINEERING

Instability of Thyratron Operation in Power Supply Units of Metal-Vapor Lasers

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Abstract—The causes of an increase in the ТГИ1-1000/25 thyratron jitter from 5 to ~30 ns in pumping sources of metal-vapor lasers (MVLs) upon changes in the excitation-pulse repetition frequency from 700 Hz to ~10 kHz are analyzed. It is shown that to provide the thyratron operation with an instability of the grid–cathode gap breakdown of ~1 ns, a hydrogen generator, and a device that forms an igniting pulse at the thyratron grid must be connected to stabilized dc power-supply units. Engineering solutions are proposed that allow control of the anode-current delay time at a thyratron jitter of ~1 ns.

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INTRODUCTION

The unstable operation of pulse hydrogen thyratrons with respect to a triggering pulse (jitter) is one of the main causes that hinder the practical use of thyratrons connected in parallel for increasing the switched energy in lasers on self-contained transitions of metal atoms (self-contained lasers, metal-vapor lasers (MVLs)) and in systems for summing laser radiation of MVLs: "master generator–amplifier" [1, 2]. The jitter of a ТГИ1-1000/25 thyratron, which is most widely used in power supply units of MVLs, is ~5 ns according to the certificate characteristics at a pulse repetition frequency of ~700 Hz [3]. A typical value of the jitter of a ТГИ1-1000/25 thyratron that operates in the discharge circuit of an MVL with a repetition rate of excitation pulses of ~10 kHz is ~30 ns, which is comparable to the duration of MVL-generated pulses. The true causes of the appearance of this jitter are unknown.

It was supposed in [4] that the jitter may be associated to a certain degree with the instability of the thyratron filament current, which is in turn determined by voltage fluctuations in the mains. However, the thyratron jitter can be hardly related to the filament current of the thyratron cathode because the time of changes in the temperature of a massive thermionic cathode substantially exceeds ~0.01 s. In fact, supplying the filament voltage of the ТГИ1-1000/25 thyratron cathode from the source of a dc voltage of 6.3 V in a copper-vapor laser with a ГЛ-201 commercial gas-discharge tube [5] did not change the observed value of the thyratron jitter.

Let us consider the discharge development in a thyratron in more detail in order to assess the possible causes of appearance of a ТГИ1-1000/25 thyratron jitter of ~30 ns for a pulse repetition frequency of ~10 kHz. As is known [3, 6], pulse thyratrons have a high electric strength. The thyratron grid has a low penetrability, so that the anode field does not actually act in the near-cathode region. To initiate a discharge between the anode and cathode, it is first necessary to apply a positive voltage pulse (ignition pulse) between the grid and cathode, which produces an auxiliary discharge in this gap. The latter initiates a discharge in the main anode–grid gap.

At the beginning of the switching period when the concentration of charged particles between the cathode and grid is still low, the resistance of the thyratron is high. As the charged-particle concentration increases, the ion current to the grid in the anode–grid gap also increases and at a certain moment, the total current of the grid $I_g = I_e + I_i$ (where I_e and I_i are the electron and ion currents, respectively) changes its sign.

The moment when the grid current changes its direction coincides with the thyratron enabling onset (a noticeable anode current appears). The instantaneous value of the electron current before the change in its direction is the grid current that enables the thyratron in the pulsed mode. A high ion current flows to the grid for a very short time, as long as there is a considerable potential difference between the grid and anode and the charged-particle concentration in the cathode–grid discharge gap is insufficient.

An increase in the plasma concentration in the thyratron reduces the grid–anode voltage, and the electron current of the cathode again becomes the main fraction of the grid current. An ion-current surge is accompanied by a short rise of the grid voltage relative to the cathode, which is called the "grid peak." A grid peak increases a discharge current between the cathode and grid and accelerates the termination of the switching process. The grid-peak amplitude reaches 20–30% of the anode voltage, and the peak duration is ~10^{-7} s.

To maintain the gas-pressure constancy in hydrogen thyratrons, there is a special generator—accumulator of hydrogen, which is an element heated with a special heater. Hydrogen is liberated under heating, and a required pressure is maintained during long-term operation of the device. To compensate for the effect of the ambient temperature and stabilize the filament current of the hydrogen generator, a wire resistor with a high temperature coefficient of resistance, which is placed beyond the housing of the instrument, is connected in series to the hydrogen generator. The heater of the hydrogen generator with the compensating resistor is connected in parallel to the thyratron filament circuit or has a separate lead, thus allowing the hydrogen generator to be powered from a separate source.

Along with the jitter, another important characteristic of the thyratron is the anode-current delay time (τ_{del}), which is the interval between the moment corresponding to the onset of the voltage-front rise of an igniting pulse in the grid circuit and the moment of the discharge onset in the thyratron-anode circuit. The anode-current delay time for the ТГИ1-1000/25 thyratron is ~0.35 ± 0.15 μs [3] and is determined by the sum of two components: $\tau_{del} = \tau_{brd} + \tau_{dis}$, where τ_{brd} is the time from the onset of the voltage-front rise of the igniting pulse to the breakdown voltage of the grid—cathode gap, and τ_{dis} is the time from the breakdown moment to the moment of the discharge initiation in the thyratron anode circuit. An increase in the thyratron jitter with an increase in the pulse repetition rate may be correspondingly related to both instabilities of the parameters of the igniting pulse and breakdown voltage of the grid—cathode gap and an instability in the discharge development in the thyratron anode circuit after the breakdown.

INFLUENCE OF THE PARAMETERS OF THE IGNITING PULSE ON THE THYRATRON JITTER

From the above description of the discharge-development process in the thyratron, it can be presumed that an increase in the thyratron jitter with an increase in the pulse repetition rate is determined by the power supplies of the hydrogen generator and the igniting-pulse forming device. The hydrogen generator in the MVL is connected (as a rule) in parallel to the thyratron filament circuit and is powered from an ac power supply of ~6.3 V/50 Hz; this may determine a hydrogen-pressure modulation in the thyratron. According to the Paschen law, the breakdown voltage is a function of the gas pressure. Correspondingly, a hydrogen-pressure modulation in the thyratron must modulate the breakdown voltage across the thyratron grid—cathode gap and determine the thyratron jitter.

Connecting the hydrogen generator of the ТГИ1-1000/25 thyratron to a stabilized source of a 6.3-V dc voltage allowed the observed thyratron jitter to be reduced by 18 ns at an igniting-pulse repetition frequency of ~10 kHz. This directly indicates that the hydrogen pressure in the thyratron is modulated by the electric-mains frequency of ~50 Hz.

When the hydrogen generator was supplied by the dc voltage, a change in the ТГИ1-1000/25 thyratron jitter from 5 to 12 ns was observed under changes in the pulse repetition rate from 700 Hz to ~10 kHz, and the instability in the breakdown of the grid—cathode gap changed from ~1 to 7 ns in the absence of a voltage at the thyratron anode. This allows one to conclude that the minimum thyratron jitter (~5 ns) is not associated with the discharge-development instability in the thyratron-anode circuit after a breakdown of the grid—cathode gap.

Our studies showed that a breakdown of the grid—cathode gap in the ТГИ1-1000/25 thyratron occurs when the amplitude of the igniting-pulse voltage reaches ~500 V, if the hydrogen generator is powered by a stabilized voltage. The observed increase in the thyratron jitter with an increase in the repetition frequency of igniting pulses is caused by an amplitude instability of the igniting-pulse voltage and determined by the pulsation value at the output of the rectifier, which provides powering of the igniting-pulse-forming unit.

Measurements have shown that 10% voltage pulsations at the rectifier output lead to a variation in the leading edge of the igniting-pulse voltage (Fig. 1) and, correspondingly, in the time within which the breakdown voltage is reached. This leads to an instability of the grid—cathode gap breakdown of ~20 ns. To reduce the instability of the grid—cathode gap breakdown, it is necessary to reduce the pulsations at the rectifier output by increasing the filter capacitance. To provide the thyratron operation with a grid—cathode gap breakdown instability of ~1 ns, it is necessary to connect the hydrogen generator and the igniting-pulse-forming unit to stabilized dc voltage sources with voltage pulsations at the source output of ≤1%. In this case, the thyratron jitter is determined only by the discharge-development instability in the thyratron-anode circuit after the grid—cathode gap breakdown.

A specific feature of thyratrons [3, 6] is that the higher the slope of the grid current dI_g/dt, the higher the instantaneous grid-current value at which the thyratron is. This regularity can be explained in the following way. The thyratron is enabled at a certain value of the anode current, which is extracted from plasma of the auxiliary grid discharge. This current at a given anode voltage corresponds to a definite plasma concentration in the grid region into which the anode field penetrates.

The critical concentration is formed as a result of two processes: the accumulation of charged particles and their diffusion to the walls that surround the dis-

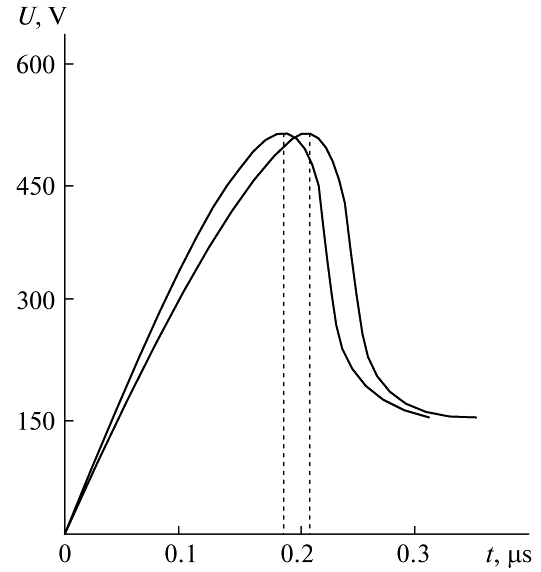

Fig. 1. Voltage of the discharge initiation in the grid–cathode gap and the ТГИ1-1000/25 thyratron as a function of 10% voltage pulsations of the power source in the device for forming a positive voltage pulse at the thyratron grid. Measurements were performed in the absence of a voltage at the thyratron anode.

charge space. The thyratron is enabled upon pulsed ignition when the grid-plasma concentration has not yet been settled and charged particles are accumulated more rapidly than their diffusion to the walls occurs. Therefore, the plasma concentration is proportional not to the instantaneous current value but to the amount of the electric charges that passed through the discharge gap.

The aforementioned features can be used for reducing the thyratron unblanking time and its jitter time (<5 ns).

FORMATION OF A THYRATRON TRIGGERING PULSE IN THE FORM OF A GRID PEAK

The possibility of forming a thyratron-triggering pulse in the form of a grid peak is determined by the fact that a grid peak arises at the thyratron grid in any case and, consequently, its artificial formation, at least, must not impair the operating characteristics of the thyratron and in the best case, must result in reducing both the thyratron-enabling and jitter times. Investigations showed that the use of a thyratron-triggering pulse in the form of a grid peak allows the enabling time of the ТГИ1-1000/25 thyratron to be reduced to ~30 ns, and the thyratron jitter is virtually absent (<1 ns) in this case.

The use of a thyratron-triggering pulse in the form of a grid peak should be preferred in systems intended for synchronizing the operation of several lasers, e.g., in master oscillator–amplifier laser systems, because, in this case, a device for forming a grid peak can be manufactured most easily (Fig. 2). Figure 2 shows a diagram of the oscillator–amplifier laser complex with synchronization of the operation of thyratrons in pumping generators.

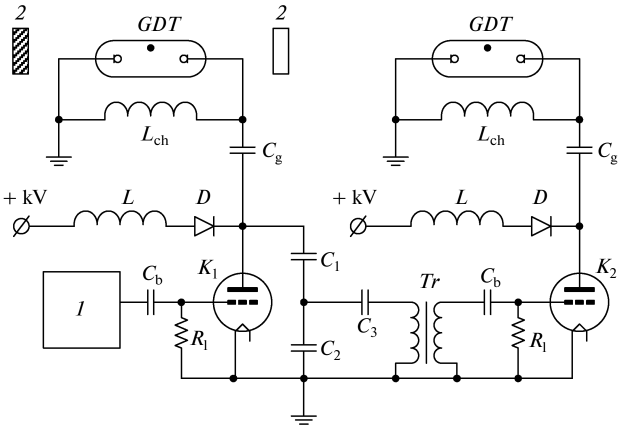

Fig. 2. Schematic diagram of the oscillator–amplifier laser system with synchronization of the operation of two thyratrons: (*1*) master oscillator, (*2*) resonator, (*GDT*) gas-discharge tube, (C_g) storage capacitors, (C_b) blocking capacitors, (C_1, C_2) capacitive voltage divider, (C_3) storage capacitor, (R_l) leakage resistor, (L, D) charging choke and diode, (L_{ch}) shunting inductance, (Tr) pulse transformer, and (K_1, K_2) thyratrons.

The device for forming a grid peak in this circuit was based on the elements C_1–C_3 and a pulse transformer *Tr*. The operation of the oscillator–amplifier complex with synchronization of the operation of two thyratrons is accomplished as follows. The storage capacitors C_g and capacitors C_1–C_3 are charged from high-voltage rectifiers through charging chokes L and diodes D.

After the storage capacitors are charged, a triggering pulse arrives at the thyratron K_1 from master oscillator *1*. The thyratron K_1 is unblanked and a discharge of the corresponding storage capacitor, which forms an excitation pulse across the gas-discharge tube (GDT), occurs. In this case, the capacitors C_1–C_3 are also discharged, and the discharge of the capacitor C_3 through the transformer *Tr* (the transformation ratio is 1 : 1) forms a grid peak at the grid of the thyratron K_2, which unblanks the latter.

The capacitors C_1 and C_2 form a voltage divider and determine the charging voltage of the capacitor C_3. The capacitance of the capacitor C_3 is chosen on the basis of the certificate characteristics of the thyratron with allowance for the provision of the required energy for unblanking the thyratron. For the ТГИ1-1000/25 thyratron, it is ~100–150 pF at a voltage of ~5–7 kV. In this case, the grid-peak duration is ~30 ns. The thyratron K_2 is enabled 30 ns after the thyratron K_1. As the capacitors C_1–C_3, КВИ-3-type capacitors are used.

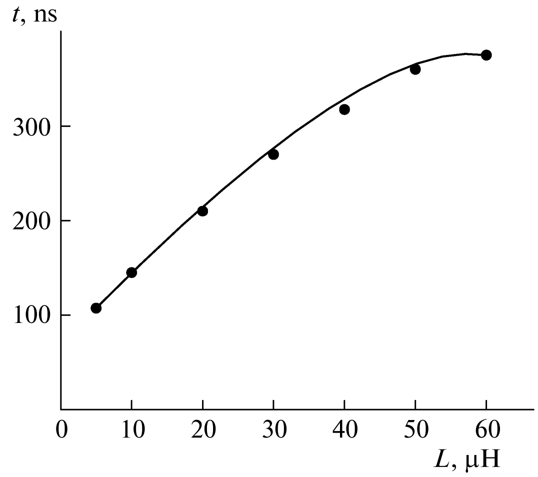

Fig. 3. Time of the discharge initiation in the ТГИ1-1000/25 thyratron grid–cathode gap as a function of the choke L inductance. Measurements were performed in the absence of a voltage at the thyratron anode.

CONTROLLING THE ANODE-CURRENT DELAY TIME

The performed studies showed that a breakdown of the grid–cathode gap in the ТГИ1-1000/25 thyratron occurs when the amplitude of the positive voltage pulse at the grid is ~500 V. In this case, the anode-current delay time depends on the slope of the grid-voltage pulse front, and the thyratron jitter decreases with an increase in the current in the grid–cathode gap. A simple technical solution that allows control of the anode-current delay time at a thyratron jitter of ~1 ns follows from the above.

In fact, if the voltage rise time across the thyratron grid–cathode gap is varied, this must lead to a change in the onset time of the discharge initiation in this gap; thus, the anode-current delay time can be controlled. The possibility of changing the moment of the discharge initiation in the thyratron grid–cathode gap in a wide range was experimentally tested using different circuits for forming thyratron-triggering pulses. Direct changes in the discharge-initiation moment for the thyratron grid–cathode gap were performed via connection of an additional choke L between the thyratron grid and the device for forming a positive voltage pulse at the grid.

Figure 3 shows the dependence of the time of the discharge initiation in the ТГИ1-1000/25 thyratron grid–cathode gap on the choke L inductance. By changing the inductance of the choke L from 5 to 60 μH, one can control the time of the discharge initiation in the thyratron grid–cathode gap within a range of 200–300 ns. In this case, the inductance of L limits the discharge current in the grid–cathode gap. In this case, the grid-current development rate decreases; this increases the thyratron enabling time and must inevitably result in the appearance of a thyratron jitter.

However, if a capacitor is connected in parallel to the thyratron grid, in this case, the voltage rise rate at the thyratron grid determines the time of the capacitor charging to a breakdown voltage of ~500 V of the grid–cathode gap. After the thyratron breakdown, the current development in the grid–cathode gap is determined by the discharge time of this capacitor and is independent of the choke-L value. This simple technical solution allows elimination of the thyratron jitter in the mode of controlling the discharge initiation time in the grid–cathode gap. The optimal value of the capacitance of this capacitor (КВИ-3) is ~470–1000 pF for the ТГИ1-1000/25 thyratron.

On the basis of the performed investigations, a unit for forming a positive voltage pulse at the ТГИ1-1000/25 thyratron grid was developed. A circuit diagram of this unit is shown in Fig. 4. The unit for forming a positive voltage pulse is triggered by a generator of rectangular pulses with an amplitude of 15 V and a duration of ~0.5–1 μs. The generator specifies the repetition frequency of pulses that initiate a discharge in the grid–cathode gap.

The resistor R_2 limits the current in the gate circuit of the field-effect transistor Q_1. The resistor R_3 protects the transistor in the case of a break in the resistor R_2 resistor. The elements R_1, C_1, D_1, C_2, R_4, and D_2 form the required shape of pulses, eliminate the parasitic generation at the fronts, and protect the transistor against high-power voltage pulses. The inclusion of the capacitor C_3 into the circuit is determined by the necessity of connecting the source of a negative bias voltage to the thyratron grid through the resistor R_5. The time-setting elements L and C_4 determine the anode-current delay time, and the delay time is controlled via a change in the choke L inductance.

It is expedient to use this control method for providing the simultaneous triggering of thyratrons connected in parallel, because each of them is triggered from its individual positive-pulse forming unit. The necessity of adjusting the L and C_4 circuits in the pulse-formation units arises because of the fact that circuit elements have a certain spread of parameters, and the breakdown voltage of the grid–cathode gap of the ТГИ1-1000/25 thyratrons is ~500 ± 10 V.

The thyratron-triggering delays in the master oscillator–amplifier systems in the absence of a jitter can be also performed via introduction of an appropriate delay between pulses that arrive at the gate of the transistor Q_1 from the rectangular-pulse generator. In this case, a choke of the ДПМ-0.6-16 or ДПМ-1.2-30 type with a constant inductance of ~10–30 μH can be used as the choke L. As was mentioned above, the development of a current in the grid–cathode gap after the breakdown is determined by a discharge of the capacitor C_4 and does not depend on the choke L inductance. This eliminates the necessity of minimizing the leakage inductance of the pulse transformer *Tr*, thus simplifying its production. The transformer *Tr* is wound on a ferrite core with an ETD39 frame (Sie-

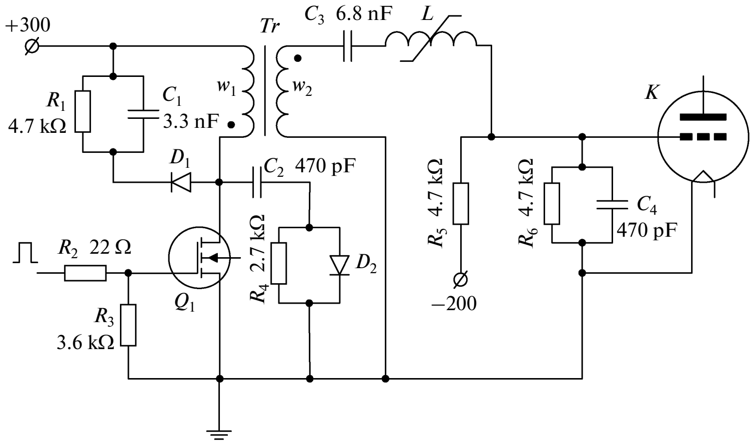

Fig. 4. Circuit diagram of the device for forming a positive voltage pulse at the thyratron grid: (*K*) ТГИ1-1000/25, (Q_1) 2SK1357, (D_1, D_2) FR207, and (*Tr*) ETD39.

mens + Matsushita firm, $w_1 = 20$ turns and $w_2 = 40$ turns).

CONCLUSIONS

The performed investigations allowed us to establish the causes of the appearance of a jitter in pulse hydrogen thyratrons and to develop devices for their triggering, which allow control of the anode-current delay time at a thyratron jitter of ~1 ns. These studies were initiated by the necessity of practically realizing the master oscillator–amplifier system in a single gas-discharge tube at a two-pulse excitation of the active medium [7], when the first excitation pulse forms a light field in the resonator and the second pulse provides its amplification. Under these pumping conditions, the thyratron jitter determined a substantial instability in the copper-vapor-laser pulse energy.

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