https://doi.org/10.46813/2025-160-059

SELECTION AND COMMISSIONING OF SWITCHES FOR ACCELERATOR MODULATORS

V.O. Mats, V.Yu. Titov, I.O. Chertishchev, O.O. Butenko
National Science Center "Kharkiv Institute of Physics and Technology", Kharkiv, Ukraine
E-mail: certisevigor0@gmail.com.ua

The paper presents the rationale for selecting switches for the modulators of technological accelerators. The reliability of the chosen thyratrons has been evaluated. The process of conditioning and commissioning the switches into operational mode is described.

PACS: 2917+w

INTRODUCTION

Previously developed accelerators "LPE-10" and "LPE-40", as well as a test bench for klystron conditioning, have been restored and commissioned at the NSC KIPT [1, 2]. The accelerators are used for the irradiation of medical and food products, for isotope production, and the test benches are used for conditioning and bringing into operational mode the components of high-voltage modulators (thyratron, klystron, pulse-forming line, charging choke) [3, 4]. High-voltage modulators are among the most important and energy-intensive units of a technological accelerator. The switching rack, in turn, is one of the key components of the modulator [5]. Therefore, the selection of a switch, its connection scheme, and its proper commissioning into operating mode is a very important task. Solving this task will help ensure reliable and high-quality operation of the technological accelerators. This can extend both the lifetime of the accelerator's components and the lifetime of the accelerator as a whole.

The main requirements for switches are compliance with the technical specifications of the accelerator modulator, reliability in operation, replaceability, availability for procurement, relative cost-effectiveness, and ease of maintenance. Several types of pulse thyratrons meet these requirements. Under our conditions, they have advantages over solid-state switches due to their ability to conduct high currents without the need for parallel connection of multiple devices [6, 7]. In addition, they are relatively inexpensive and readily available. The connection scheme for pulse thyratrons is quite simple. Pulse thyratrons have high dielectric strength. The thyratron grid has low permeability, so the anode field practically does not affect the cathode area.

SWITCHING RACK OF THE PULSE MODULATOR

Fig. 1 shows a simplified diagram of the accelerator modulator. In the modulators of the SRC "Accelerator", modulators with full discharge of the energy-storage element – the pulse forming network (PFN) – are used. The storage unit is charged through a charging choke (L) and a diode (VD).

During thyratron (TGI) switching, the pulse-forming line discharges through the primary winding of the pulse transformer (PT) into the load (R). The switching process in a hydrogen thyratron can be divided into the following phases: anode voltage hold-off, triggering, conduction, and the deionization process after the pulse [8, 9].

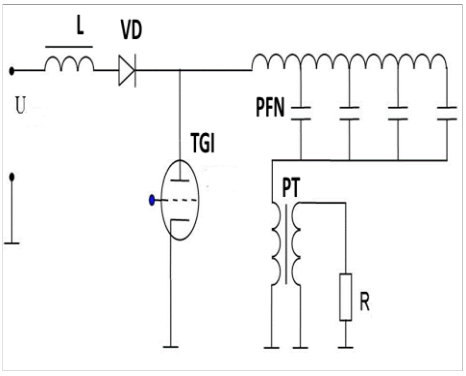


Fig. 1. Simplified diagram of the modulator

The load is typically a "KIU-12 AM" klystron. As a result, the modulator output produces a voltage pulse with a waveform close to rectangular. A pulse thyratron is used as the switch. Fig. 2 shows the thyratron connection diagram to the power supply unit. A high voltage is applied to the anode of the thyratron (TGI). The thyratron is at the threshold of conduction, but a triggering pulse must be applied to its grid. When the triggering pulse is fed to the grid, a glow discharge forms between the grid and the cathode. A voltage pulse with an amplitude of 1000…1500 V is supplied to the thyratron grid from the trigger unit (TU). A limiting resistor (Rl) is added to the grid circuit to limit the grid current; this allows setting the grid current values according to the operating specifications. For galvanic isolation of the grid circuit from the trigger unit, a transformer (ST) is used, and protective diodes (VD) are installed to protect the trigger unit.

In a thyratron, the grid can only ignite the tube, but cannot control the anode current; after breakdown occurs, the grid loses control, and the tube can be turned off only by reducing the anode voltage to zero. A number of thyratrons are manufactured with two grids. In such thyratrons, the control grid is the second grid, which is farther from the cathode.

Ignition of the thyratron is accompanied by a sharp increase in anode current to a value determined by the anode voltage and the load resistance. After the pulse ends, the discharge through the thyratron stops. For more reliable turn-off of the thyratron, it is desirable that the voltage pulse includes a small-amplitude (a few kiloelectronvolt) reverse-voltage component. This must be taken into account when adjusting the pulse-forming lines.

Voltage is supplied to the hydrogen reservoir (HD) and the thyratron heater (GV) through a transformer. These voltages are typically adjusted depending on the stability of thyratron triggering, usually within the range of 6.0…6.6 V, and sometimes over a wider range when necessary.

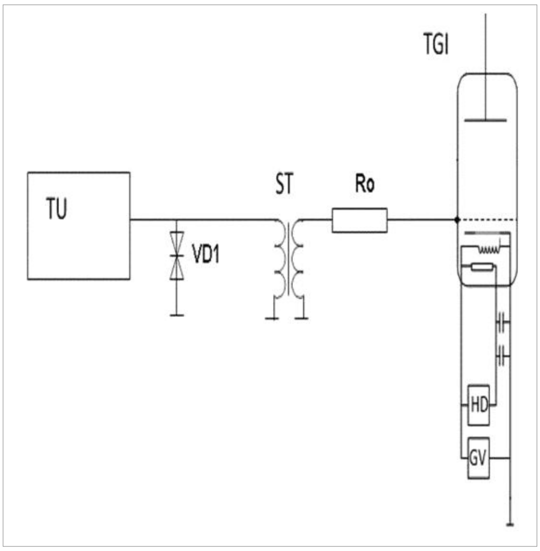


Fig. 2. Connecting the switch to the power supply

USE OF DIFFERENT TYPES OF THYRATRONS IN PULSE MODULATORS

At various times, different types of switches were used in the modulators of technological accelerators. Each type had its own operational advantages and disadvantages. The selection of a thyratron was based on its compliance with the technical parameters of the technological accelerator, operational reliability, the need to minimize the number of connections in the modulator circuit, and the availability of the device for purchase.

Thus, in technological accelerators operating at a pulse repetition rate of 300 Hz, TGI 1-5000/50 thyratrons were used. However, as these devices gradually reached the end of their service life and new units of this type could no longer be acquired, a decision was made to reduce the modulator repetition rate to 250 Hz. At this pulse frequency – while keeping the parameters of the pulse-forming line and pulse transformer unchanged – the average current of the switch does not exceed 4 A. Among the thyratrons available at that time, the CX1525A and TGI 1-2500/50 met these requirements.

Deuterium-filled thyratrons such as the CX1525A are expected to be more stable compared to conventional tubes. This thyratron has two grids (G1 and G2) as well as a gradient grid for distributing the anode potential across its surface. Thyratrons of this type were operated in the modulators of technological accelerators for 2,000 to 6,000 h. However, the use of CX1525A thyratrons had several disadvantages: they required a special dedicated trigger unit or the use of two standard trigger units available at the SRC “Accelerator”, which complicated the thyratron connection scheme and made rapid replacement difficult. In addition, surface breakdowns between the cathode and the first grid occasionally occurred, reducing the operational lifetime of this type of thyratron.

Other thyratrons were also used in the modulators of technological accelerators, including TGI1-2500/25 and L4147. Some of them, such as the TGI1-2500/25, have nearly exhausted their service life and can now be used only on individual test benches, while others, such as the L4147, were purchased in very limited quantities, making their use in switching racks economically impractical.

As a result of long-term operational experience with pulse modulators of technological accelerators and experimental studies on test benches, several types of thyratrons have been selected and continue to be used in working installations.

COMMISSIONING OF TGI1-2500/50 AND TGI1-1000/16 THYRATRONS INTO OPERATIONAL MODE

When selecting a thyratron for a pulse modulator, the operating conditions of the accelerator must be taken into account. For the switch, the key parameters are the maximum anode voltage and maximum current through the switch, as well as the average current through it.

The total current through the thyratron can be calculated using expression (1):

$$I_{\Sigma} = nI_b + \frac{U_1 \tau_{0.5}}{L_{\mu}}, \qquad (1)$$

where I_{Σ} – the total current through the thyratron; n – the transformer turns ratio; I_b – the beam current; U_1 – voltage on the primary winding of the pulse transformer; $\tau_{0.5}$ – the pulse duration at half-maximum; L_{μ} – the magnetizing inductance of the pulse transformer.

The average current through the thyratron can be determined from expression (2):

$$I_0 = I_{\Sigma} f, \qquad (2)$$

where I_0 – the average current through the thyratron; I_{Σ} – the total current through the thyratron; f – the accelerator pulse repetition rate.

Based on formulas (1), (2), and additional operational factors, the thyratrons TGI1-2500/50 with water cooling were selected for the LPE-10 accelerator, and TGI1-1000/25 with air cooling for the «LPE-40» accelerator. These thyratrons meet several important requirements: high operational reliability, a relatively simple connection scheme, a well-developed procedure for inspection and replacement when necessary, and established methods for conditioning and commissioning into the accelerator’s operating mode.

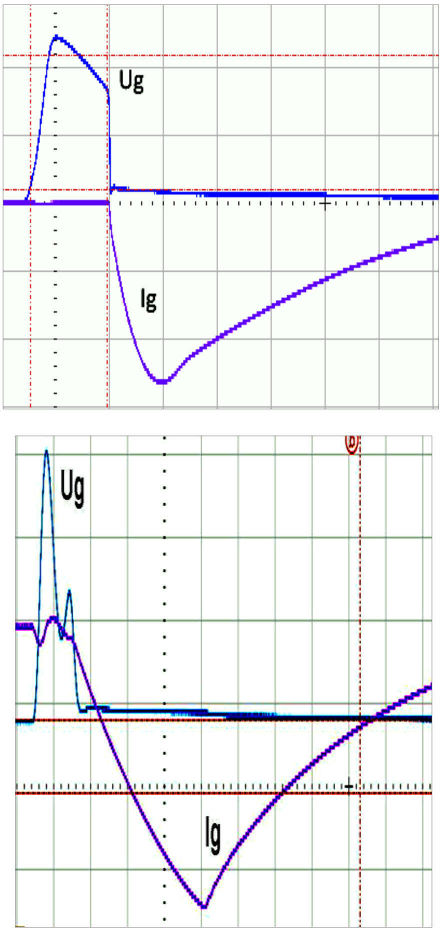
The behavior of the thyratron discharge can be described by Paschen's law (3):

$$U = \frac{a(pd)}{\ln(pd)+b}, \quad (3)$$

where U – the breakdown voltage; p – the gas pressure; d – the electrode spacing; a, b – the coefficients depending on the gas filling

From (3), it follows that a thyratron achieves optimal operating characteristics at the highest permissible hydrogen pressure. However, sufficiently high hydrogen pressure also reduces the thyratron's dielectric strength. Therefore, it is necessary to determine a rational and balanced operating point for reliable triggering.

To bring newly acquired thyratrons into operational mode, conditioning is first performed in the heater-only mode, without applying anode voltage. Fig. 3 shows the voltage and current pulses on the grid of a TGI1-2500/50 thyratron at the initial stage of conditioning. To ensure optimal operating conditions, minimize jitter, and maintain temporal stability of the modulator, the thyratron should trigger on the leading edge of the trigger pulse. As seen in Fig. 3, at the initial stage of conditioning it is not yet possible to obtain the optimal triggering mode, which makes further conditioning necessary.



a

b

Fig. 3. Trigger pulses on the thyratron grid when using different trigger blocks: a – thyristor; b – based on IGBT transistors. Voltage pulse (Ug) 500 V/div, current pulse (Ig) 3A/div

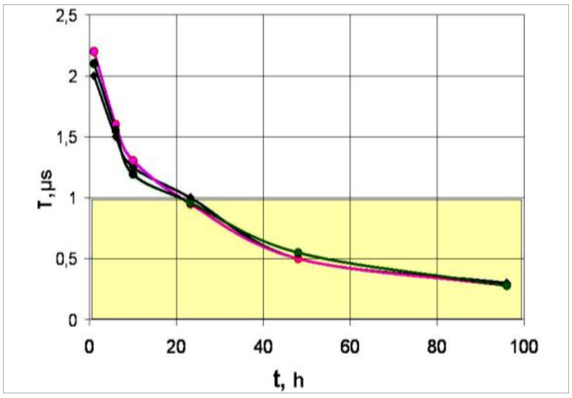


Fig. 4. Dependence of thyratron operation time on training duration

Fig. 4 shows the thyratron TGI1-2500/50 triggering time as a function of conditioning duration. Conditioning is carried out with the heater voltage (6.3 V) and the hydrogen reservoir power supply (6.3 V) switched on. From Fig. 4, it follows that as the conditioning time increases, the triggering time of the thyratrons decreases. After approximately 20 h of conditioning, the triggering time reaches about 1 μs; thus, the thyratron triggers on the leading edge of the pulse and can be considered fully conditioned in terms of its timing characteristics. Afterward, the thyratron must be commissioned into operational mode by gradually increasing the anode voltage; upon successful conditioning, it can be accepted for regular operation.

It should be noted that Fig. 4 presents standard timing characteristics of thyratron conditioning; therefore, the curves shown exhibit close agreement. Occasionally, when a thyratron cannot be activated under standard conditions or when conditioning proceeds slowly, the conditioning algorithm must be adjusted. If triggering occurs on the falling edge of the trigger pulse, a higher heater voltage (up to 7.5 V) may be applied, and the grid voltage may be increased (up to 2 kV). Once the thyratron reaches stable operating conditions, these voltages should be returned to their nominal values during regular operation. To accelerate conditioning, anode voltage up to two-thirds of the operational value may be applied. Operational experience shows that such thyratrons eventually reach stable operating conditions and can be used in pulse modulators of technological accelerators just as reliably as those conditioned using the standard algorithm.

Fig. 5 shows the dependence of the thyratron grid current on triggering time. As seen in Fig. 6, earlier triggering of the thyratron results in an increase in grid current, which creates the need to reduce the grid current during normal operation. The grid current is reduced by introducing a limiting resistor into the grid circuit. According to the technical specifications for the TGI1-2500/50 thyratron, the grid current must not exceed 20 A.

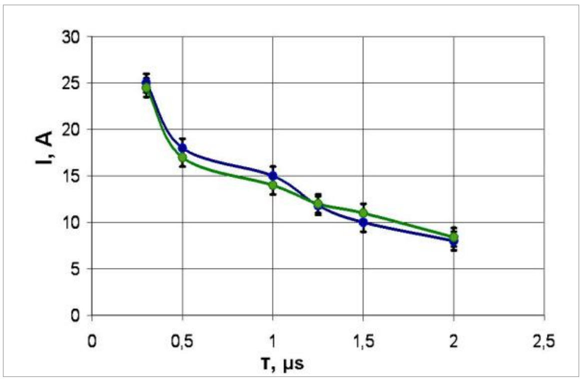


Fig. 5. Grid current of the thyratron TGI 1 2500/50 depending on the operating time without using a limiting resistor

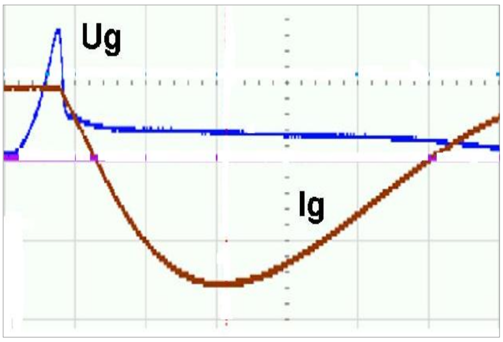


Fig. 6. The voltage (Ug) and current (Ig) pulse on the grid of a trained thyratron. 500 V/div, 6 A/div

Fig. 6 shows the voltage and current pulses on the grid of the TGI-1 2500/50 thyratron in a fully conditioned state. The figure demonstrates that the thyratron is triggered on the leading edge of the control pulse. At the same time, the grid current reaches 15 A, which fully meets the operational requirements.

One of the advantages of using the TGI-1 2500/50 thyratron in the modulators of the "LPE-10" industrial accelerators is the possibility of employing only a single switching device in the rack. This significantly simplifies the connection scheme and enables rapid replacement of key components when necessary. In addition, thyratrons of this type are reliable in operation and readily available.

For the modulators of the «LPE-40» industrial accelerators, which operate at a frequency of 50 Hz with a load voltage amplitude of 200 kV, TGI-1 1000/16 thyratrons were selected as switching devices. These units also exhibit high operational reliability and a simple connection configuration. The grid power supply for these thyratrons can be provided by the standard trigger unit developed at the "Accelerator" R&D Center. Another advantage is the ease of acquiring these devices.

However, a drawback of the TGI-1 1000/16 in existing modulators is the necessity of connecting three thyratrons in series within the rack. This configuration is required to increase the permissible total voltage of the switching circuit, since a single device cannot withstand the required operating voltage. Series connection requires additional circuit components – particularly equalizing resistors, which ensure proper voltage distribution, especially during switching, as uneven distribution may result in premature failure of one of the thyratrons.

Furthermore, it is necessary to supply a separate control signal to each grid, and all three thyratrons must trigger reliably, preferably simultaneously and on the leading edge of the control pulse. This complicates both the circuit design and the diagnostics of the switching rack as a whole.

Fig, 7,a and b show the grid voltage pulses of TGI-1 1000/16 thyratrons during the initial stage of operation and after completion of conditioning. From Fig. 7,a, it is evident that the thyratrons trigger at different time intervals, which may negatively affect the timing stability of the output voltage pulses of the modulator and the klystron current, as well as reduce the lifetime of the switching devices.

Therefore, reliable operation of the switching racks requires preliminary conditioning of the thyratrons and individual selection of limiting resistors in each grid circuit. The conditioning procedure for the TGI-1 1000/16 is similar to that of the TGI-1 2500/50; however, experimental studies have shown that the conditioning process for the TGI-1 1000/16 is somewhat faster.

Fig. 8,b shows the grid voltage pulses of fully conditioned thyratrons. The figure demonstrates that all three devices trigger on the leading edge of the control pulse. Such a switching rack can be considered suitable for use in accelerator modulators.

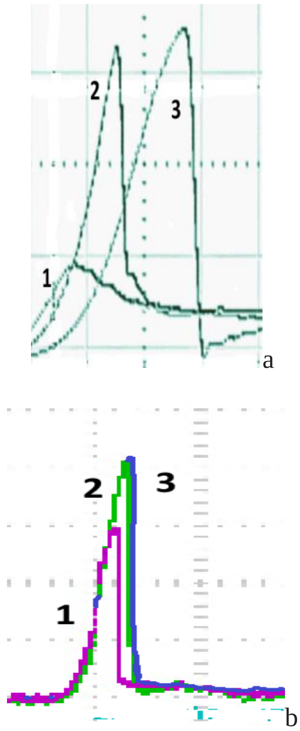


Fig. 7. The voltage pulses on the grids of thyratrons TGI11000/16. 1, 2 ,3 – current pulse on the grid. 100 V/div, 1 μS/div

CONCLUSIONS

The paper examines the conditioning process and commissioning of switching racks for industrial accelerators based on several types of pulse thyratrons.

The selection of these switching devices is presented and justified. The operational stability of modulators equipped with different switching rack configurations has been investigated. It has been shown that with proper adjustment and correct commissioning procedures, pulse thyratrons can operate reliably within their guaranteed service life and may even exceed it. The team of authors expresses gratitude to Viktor Skuryatin for technical support during the research process.

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Article received 20.11.2025

ВИБІР ТА ВИВЕДЕННЯ В ЕКСПЛУАТАЦІЙНИЙ РЕЖИМ КОМУТАТОРІВ У МОДУЛЯТОРАХ ПРИСКОРЮВАЧІВ

В.О. Мац, В.Ю. Титов, І.О. Чертіщев, О.О. Бутенко

Наведено підстави для вибору комутаторів модуляторів прискорювачів, а також оцінку надійності роботи обраних тиратронів. Описано процес тренування та вивід комутаторів у робочій режим.