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ESTIMATION OF PARAMETERS OF HIGH-VOLTAGE MODULATORS ELECTRON ACCELERATOR

I.O. Chertishchev, O.I. Kosoy, V.O. Mats, Yu.O. Titarenko
National Science Center "Kharkiv Institute of Physics and Technology",
Kharkiv, Ukraine
E-mail: V_Mats@kipt.kharkov.ua

The paper considers the main parameters and technical characteristics of high-voltage pulse modulators electron accelerators in operating modes. Calculations of the pulse shape on the main units of the setup have been carried out. An assessment of the influence of the parameters of the installation units on the output signal was carried out.

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INTRODUCTION

For scientific and applied problems, various electron accelerators were created and operated at the NSC KIPT [1]. Accelerators "LUE-10", "LUE-40", "KUT-1", "KUT-30", "EPOS", as well as various test stands. Most of the accelerators were assembled on the old element base. Subsequently, when some elements of the accelerators (klystrons) were no longer produced, others (thyratrons) were produced in limited quantities, the task was to develop methods and techniques for optimizing the operating parameters of the equipment and its restoration in order to extend the service life. A separate stand was created for training and restoration of klystrons [2]. The existing team also carried out repairs and commissioning of pulse transformers (PT) and forming lines (PFN). In 2022, due to Russian aggression, the material base of the SRE "Accelerator" was damaged. However, the remaining team managed not only to keep some equipment, but also to put a number of accelerators into operation. The stand for the restoration of klystrons has been restored. It is of interest to investigate the influence of the parameters of the modulator nodes, such as the forming line and the pulse transformer, on the klystron voltage output signal. This will allow, based on the shape of the voltage at the output of the pulse modulator, to make an assessment of a possible malfunction or incorrect setting of one of the modulator nodes. Also, by the shape of the pulse at the output, one can judge the performance of the klystron. In [3], the possibility of tuning the forming line at low voltages by correcting the voltage pulse was considered. A correct and timely assessment of possible malfunctions in the modulator will make it possible to carry out timely repairs and adjustment of equipment without bringing the accelerator to an emergency state. This can extend the life of the accelerator units. At present, the NSC KIPT has put into operation the "LUE-10" and "LUE-40" accelerators. The main requirements for accelerator units are compliance with technical characteristics and reliability in operation. In connection with the circumstances that have arisen, the possibility of replacement, the possibility of acquiring the necessary equipment, relative cheapness and ease of operation are added to the technical requirements.

PULSE MODULATOR

The high-voltage pulse modulator consists of the following components: storage element (forming line), pulse transformer (PT), charging circuit (rectifier, choke, thyristor controller), commutator (thyratron), load (klystron).

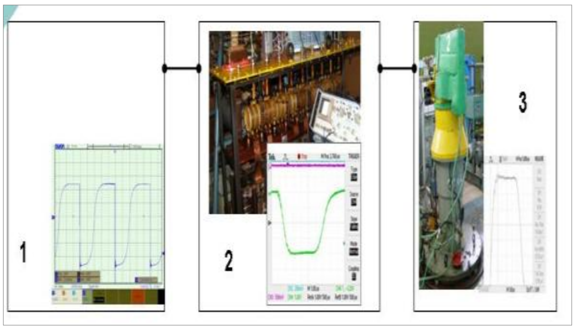


Fig 1. Simplified block diagram of a pulse modulator: 1 – charging circuit; 2 – storage element and discharge circuit; 3 – load (klystron)

Fig. 1 shows a simplified block diagram of the modulator. Three-phase alternating voltage is supplied to a step-up transformer with a three-phase rectifier. The transformer is the power source for the modulator. The voltage from the step-up transformer is fed to a single-phase charging choke with charging diodes. The step-up transformer and charging inductor are the charging circuit of the modulator. Requirements for the charging circuit - no leakage current in the charging diodes, the value of the inductance required for a full charge, a short pulse duration in static mode. Ideally, to optimize the parameters of the charging circuit, it is necessary to calculate and select the value of the inductance of the charging inductor for each accelerator separately. For operating accelerators, the value of the inductance of the inductor will be L=3…8 H. Voltage is supplied through the charging choke to the storage element – the forming line. Two types of forming lines are used in operating accelerators: a single forming line with a wave impedance of 8 Ω for modulators with a pulse transformer, the transformation ratio of which is 14 (for the "LUE-10" accelerator) and a double forming line of 60 Ω with a transformation ratio of 5 (for the "LUE-40" accelerator).

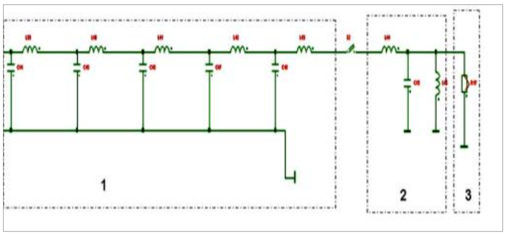
The wave impedance of the forming line is matched with the klystron beam resistance ~ 1.7 kΩ. The momentum transfer coefficient in this case is 0.5 – this can be attributed to the disadvantages of this scheme from the point of view of energy. The advantages of the matched mode are the ease in setting the pulse shape and the absence of transients after the pulse. The number of cells in the line is chosen so that it can be adjusted and the line parameters are much larger than the parasitic parameters of the circuit. A pulsed thyratron is used as a switch. Currently, water-cooled thyratrons of the "TGI1-2500/50" type are used in the modulators of the "LUE-10" accelerator, and air-cooled thyratrons of the "TGI1-1000/16" type in the modulators of the "LUE-40" accelerator. When switching thyratrons, the forming line is discharged through the primary winding of the pulse transformer to the load (klystron "KIU-12 AM"). As a result, at the output of the modulator, a voltage pulse is formed that is close to rectangular in shape. The pulse transformer distorts the shape of the pulse – the front is delayed, the bevel of the peak of the pulse increases. This must be taken into account when setting the forming line at low voltages. In work [3] it is shown that with the correct setting of the line, it is possible to form a voltage pulse with a squareness factor of up to 0.8.

CALCULATION OF THE STORAGE ELEMENT OF THE CHARGING CIRCUIT

On Fig. 2,a,b shows a diagram for calculating the shape of pulses in various elements of the discharge circuit. The discharge circuit consists of a forming line (1), a pulse transformer (2) and a load – a klystron (3). For the calculation, a forming line with a resistance of 8 Ω was selected, the parameters of the cells are inductance 2…3 μH, the cell capacitance is 0.03 μF, the number of cells is 10. The equivalent circuit of a pulse transformer can be represented as a leakage inductance together with the inductance of the supply ends, connected in series with the load, as well as the magnetizing inductance and dynamic capacitance of the transformer connected in parallel with the load. The leakage inductance mainly affects the front of the pulse. The leakage inductance, together with the dynamic capacitance of the pulse transformer, constitutes an oscillatory circuit. Thus, with an inconsistent load, a surge can form at the front of the pulse. The leakage inductance for the used transformers is 8…10 μH, for the design scheme it is a continuation of the inductance of the first cell of the line. The klystron beam resistance, as a rule, does not change during the pulse, therefore, for simplicity, it is proposed to consider it as an active load of 1.7 kΩ.

Fig. 2,b shows that the load voltage and current pulses are matched and have a uniform top. It should be noted that for the evaluation calculation, parasitic parameters of the circuit, such as the inductance of the capacitor, the capacitance of the forming line arising due to grounding, and the dielectric loss tangent of the capacitors, were neglected. Nevertheless, a good agreement between the calculated and real pulses is observed.

Thus, it is proposed to accept the design scheme as a working one and, on its basis, consider some processes occurring in a pulse modulator, consider the dependences of the parameters of the voltage pulse on the load on the parameters of the modulator circuit. The following parameters were introduced in the calculation scheme: leakage inductance and inductance of the supply contacts of the pulse transformer 8 μH, demagnetization inductance 1 mH, dynamic capacitance of the transformer 5 nF.



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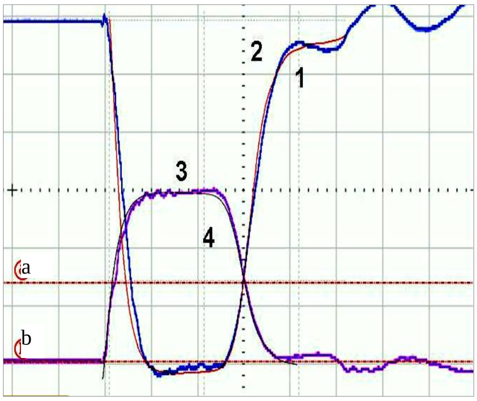
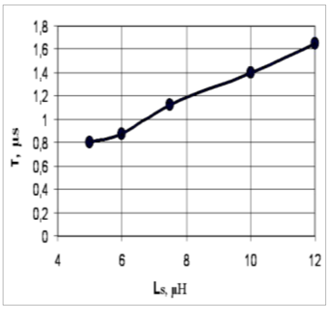


b

Fig. 2. A simplified diagram of the discharge circuit of the pulse modulator: 1 – forming line; 2 – pulse transformer; 3 – klystron (a); voltage pulses calculated 1 and measured, 2 and current calculated 3, and measured 4 on the load (b)

The influence of the parameters of a pulse transformer on the pulse shape is considered. Fig. 3,a,b shows the dependence of the rise time of the voltage pulse on the magnitude of the leakage inductance and the peak bevel on the demagnetization inductance of the pulse transformer. It can be seen from the figure that with increasing leakage inductance, the front of the pulse is delayed. The real duration of the pulse front will be 1.2…1.5 μs. It is also seen that with a decrease in the demagnetization inductance, the bevel of the top of the pulse increases. With a demagnetization inductance value above 1 mH, the transformer operates in a linear mode and the change in inductance does not significantly affect the parameters of the voltage pulse. The value of the demagnetization inductance of the pulse transformer affects the bevel of the top of the voltage pulse. When setting up the forming line for an active load, this effect must be taken into account.

Fig. 4 shows the calculated and experimental voltage pulses at low voltages on the active load and on the secondary winding of the pulse transformer in the operating mode of the accelerator. It can be seen from the figure that the pulse transformer distorts the voltage pulse, the front and the bevel of the peak of the pulse increase. Analyzing the change in the bevel of the top, it is possible to estimate the magnitude of the magnetization inductance of the pulse transformer. In the modulators under study, it is ~ 1 mH.



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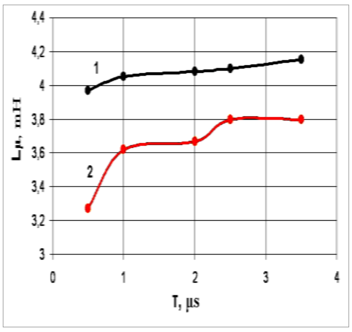
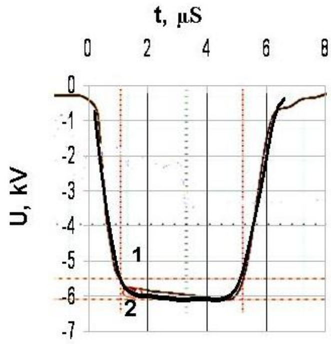


b

Fig. 3. Dependence of the rise time of the voltage pulse on the leakage inductance of the transformer (a); dependence of the duration of the voltage pulse at the level of 0.9 (1) and 0.95 (2) on the demagnetization inductance of the pulse transformer(b)

Calculations and experiments on tuning the forming lines showed that by changing only the values of the cell inductances within acceptable limits, it is possible to compensate for the bevel of the pulse top. In [3], the correction of voltage pulses with sufficiently large dips at the top of the pulse was considered. Since there are 10 cells in the lines used, the correction of the pulse shape is quite simple and is possible in any section of the pulse. In practice, in the modulators of operating accelerators, pulse correction is used in the range of 7…10%.

On Fig. 5 shows the dependence of the bevel of the top of the pulse on the value of the demagnetization inductance. It can be seen from the figure that an increase in inductance above 1 mH does not significantly affect the pulse shape. Reducing the demagnetization inductance below 0.5 mH will lead to a sharp distortion of the pulse shape, the pulse transformer goes into core saturation mode. This phenomenon consists in a sharp change in the magnetic properties of the core material and occurs when the current in the primary winding exceeds a certain value. The value of the magnetization inductance when saturation is reached drops sharply by several orders of magnitude. This will lead to a rapid and significant increase in the current in the primary winding of the transformer, the current through the switch. This mode of operation is an emergency and must not be allowed to work. It is possible in the absence of a demagnetizing current of the core or with a sharp mismatch between the wave resistance of the forming line and the resistance of the klystron beam.



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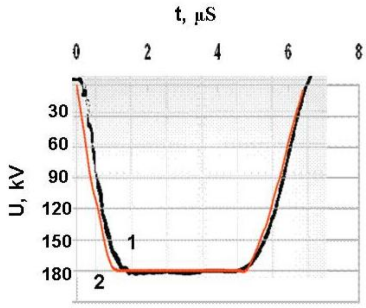

b

Fig. 4. Experimental (1) and calculated (2) voltage pulses at low voltages (a) and on the secondary winding of the pulse transformer in the operating mode of the accelerator (b)

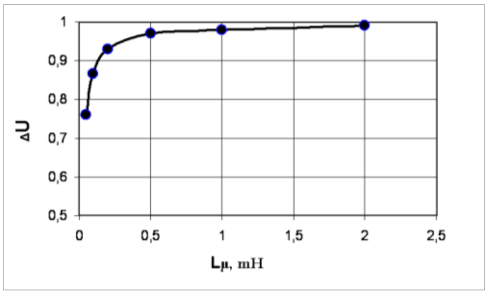

Fig. 5. Dependence of the bevel of the top of the pulse on the demagnetization inductance

The total current through the thyratron in the linear mode can be calculated from the expression:

$$I_t = n \cdot I'_n + I_n,$$

$$I'_n = U_1 \cdot \frac{\tau_n}{L_\mu},$$

where I'_n is the beam current, is the magnetizing current in the primary winding of the PT. Magnetizing current in the primary winding PT:

$$I_n = \frac{U_1 \iint \circ\tau_u}{L_\mu},$$

where L_μ is the dynamic inductance of the primary winding PT.

Thus, in the linear mode of operation of a pulse transformer, the contribution of the magnetization current to the total current through the thyratron is small. In the saturation mode, the magnetization current increases sharply, the total current through the switch and the forming line can reach the limit values and even higher. This limits the resource of the equipment and can disable it.

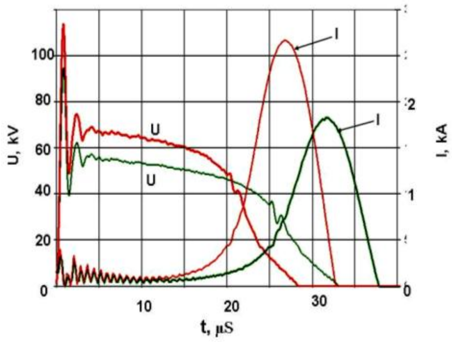

Fig. 6. Experimental pulses of voltage (U) and current of the primary winding (I) at a sharply mismatched load (R = 4 kΩ)

On Fig. 6 shows the current pulse through the thyratron and the voltage pulse on the secondary winding of the pulse transformer on the test bench. These pulses were obtained in a strongly mismatched mode. The current of the primary winding, which sharply increases in saturation mode, can damage the switch and the forming line. Knowing the value of the maximum amplitude of currents through the thyratron, it is possible to estimate the value of the magnetization inductance in the core saturation mode. It will be 40…50 μH.

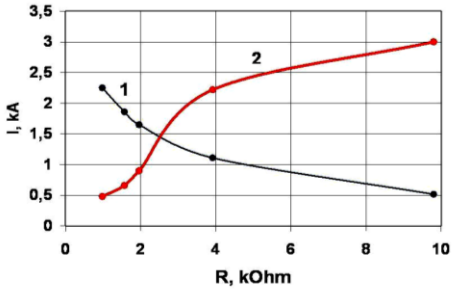

Fig. 7. Calculated dependence of the primary winding current in the linear mode (1) and in the saturation mode (2) at various values of the load resistance in the operating mode of the accelerator

On Fig. 7 shows the calculated dependence of the current of the primary winding in the linear mode and in the saturation mode at various values of load resistance. It can be seen from the figure that with an increase in the load resistance, the value of the primary winding current in the core saturation mode increases, reaching the maximum allowable values. To prevent this mode, it is necessary to introduce the demagnetization current of the pulse transformer. In the absence of the demagnetizing current or in its opposite direction, the incorrect operation of the pulse modulator can be identified by a sharp bevel of the pulse top.

CONCLUSIONS

The paper considers the influence of the elements of the forming line and the pulse transformer on the shape of the pulse. A working scheme for calculating the discharge circuit of a pulse modulator has been compiled. A good agreement between the calculated and real pulses is obtained. The influence of various elements of the modulator on the voltage pulse at the load has been evaluated. Using the calculation scheme, it is possible to analyze the amplitude and time parameters of pulses on various elements of the circuit. By the shape of the pulse on the load, one can judge the elements of the pulse modulator, carrying out timely adjustment and, if necessary, repair. Pulse shape adjustment is possible at low voltages and in operating mode. Acceptable forms of load voltage and klystron current pulses for operating accelerators are obtained. The operation of the pulse modulator in the linear mode of operation and in the saturation mode of the transformer core has been studied.

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ОЦІНКА ПАРАМЕТРІВ ВИСОКОВОЛЬТНИХ МОДУЛЯТОРІВ ПРИСКОРЮВАЧІВ ЕЛЕКТРОНІВ

І.О. Чертіщев, О.І. Косой, В.О. Мац, Ю.О. Тітаренко

Розглянуто основні параметри та технічні характеристики імпульсних модуляторів прискорювачів електронів у робочих режимах. Проведено розрахунки форми імпульсу на основних вузлах установки. Проведено оцінку впливу параметрів вузлів установки на вихідний сигнал.