

High-Voltage Generator of Microsecond Pulses

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The objective of the presented work is the engineering design, calculation, computer simulation, elements thermal regimes computation, and estimation of the dimensions, weight, and cost for the High-Voltage generator (HVG) producing output voltage pulses of microsecond duration with rectangular form and high repetition rate.

The electric circuit of the *HVG* is based on employing the magnetic pulse generator (MPG) consisting of capacitors, saturation-core chokes and transformers with ferromagnetic cores. It is suggested to use the original concept for that; the implementation of the successive discharge of several magnetic pulse generator lines through the multi-turn primary winding of the high-voltage transformer (HVT) [1]. In order to maintain a high-voltage rise rate at the HVT, the secondary winding should also have several turns.

1. Introduction

Several Linear Induction Accelerators with magnetic elements (LIA) [2] were developed and produced in the Nuclear Physics Institute (Tomsk, Russia) in recent years. The main difference of the LIA from known designs of accelerators is in the application of magnetic commutators (magnetic switches). Such a switch is capable of commutating a current of hundreds of kiloamperes at a rep-rate frequency of a few kilohertz and has an unlimited lifetime. Another significant advantage is a high stability of generated pulses waveform. Important advantage is the magnetic switch design simplicity; also, there is no need in preventive maintenance and adjustment, problems typical for gas spark gaps.

In addition, systems with magnetic elements have the following advantages:

- Low weight and small overall dimensions.
- High efficiency of the primary storage energy transformation into load energy.
- Small amplitude of reflected pulses.
- Capability of rapid inverting of output pulses polarity.

The main drawback of the known LIA designs with magnetic elements is a short duration of an output voltage pulse (no longer than ~200 ns). This is connected with: 1) the use of forming lines of a limited electrical length; 2) the use of magnetic switches capable of providing 0.5–1 μs duration of forming

lines charging if only the mass of the ferromagnetic material is significant, that means large dimensions and high inductance of winding making the formation of a rectangular output voltage pulse impossible; 3) the use of ferromagnetic induction system, which transforms a voltage pulse during the limited time till the ferromagnetic cores saturation moment. The admissible time interval Δt from the moment of applying a rectangular voltage pulse U till the cores saturation moment is defined by the following formula: $U \cdot \Delta t \approx \Psi$, where $\Psi = \omega \cdot S \cdot \Delta B$ is the flux linkage value of the induction system cores, ω is the number of magnetization turns of ferromagnetic cores of the induction system, S is the cross-section of the ferromagnetic cores steel, ΔB is the induction magnitude in the core steel. The induction systems with a single turn of core magnetization are designed to produce rectangular output pulses. Raising the number of turns up to 2 results in increasing inductance of discharge circuit approximately 4 times (the circuit is formed by the forming line capacitance, magnetic switch winding inductances and inductances of magnetization turns of the induction system). In this connection, the duration of the output voltage pulse increases in 2 times with its amplitude parameters scaling-down (the maximum power in the pulse decreases in 2 times). The output voltage pulse of the induction system gets the bell-shape profile. The increase of the induction system flux linkage is limited by the size of the constructed ferromagnetic cores, and the value of ΔB is limited by the ferromagnetic material characteristics.

We designed the *HVG* producing the output voltage pulse of microsecond duration with rectangular form. It is suggested to use the original concept for that; the implementation of the successive discharge of several MPG lines through the high-voltage transformer.

2. High-Voltage generator structure

The *HVG* consists of the following units (see Fig. 1): **Power supply** containing a primary storage charger, the primary storage C_0 in the form of separate sets of capacitor banks, protector, oscillatory charger, thyristor pulse generator, and demagnetization source; **High-voltage unit** containing pulse transformer and magnetic pulsed generator (MPG) having N stages; the last, N -th stage consists of m parallel lines. The

MPG contains capacitive storages and saturation-core chokes, pulse transformer core demagnetization source, and high-voltage transformer cores demagnetization source;

High-voltage transformer (HVT) containing several inductors with multiple-turn primary and secondary windings.

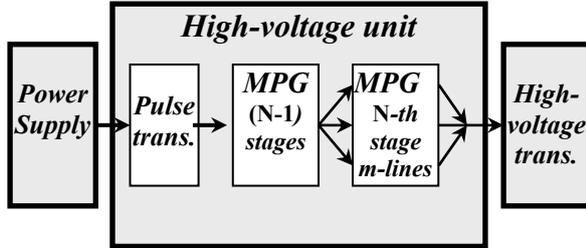


Fig. 1. *HVG* block-scheme.

Of course, *HVG* should include the high-voltage insulator, system of parameters diagnostics, cooling system (thyristors and diodes of the power supply are cooled by the liquid), and control system that makes possible powering-up, setting the characteristics (pulse repetition rate, duration of the pulse packet, duration of the pause between the pulse packets), and warning of pre-fault and emergency conditions. These systems are not indicated in the figure.

3. High-voltage unit of the *HVG*

It is the main unit of the *HVG*. Fig. 2 presents the high-voltage unit diagram. The unit employs the magnetic pulse generator containing several *LC*-compression stages connected in series (depending on the compression degree) and in parallel (depending on the output pulse duration). Unlike earlier designs of LIA with magnetic elements, the last, *N*-th stage 3, 4, 5 of the MPG is divided into several (*m*) parallel lines. Output terminals of the last compression stages of all MPG lines are connected in parallel to the primary winding 2 of the high-voltage transformer 1 (the structure of the HVT is similar to pulse linear transformer and LIA induction system).

The MPG consists of capacitors $C_1, C_2, \dots, C_{N-1}, C_{1N}, C_{2N}, C_{mN}$ and saturation-core chokes $L_1, L_2, \dots, L_{1N-1}, L_{2N-1}, L_{mN-1}, L_{1N}, L_{2N}, L_{mN}$. The last stage of the MPG is divided into *m* parallel lines (3,4,5), which are formed by the elements $L_{1N-1}-C_{1N}-L_{1N}, L_{2N-1}-C_{2N}-L_{2N}, \dots, L_{mN-1}-C_{mN}-L_{mN}$. The chokes $L_{1N-1}, L_{2N-1}, L_{mN-1}$ have the common ferromagnetic core, at which *m* identical windings are positioned.

The first compression stage of the MPG is connected to the secondary winding of a pulse transformer (not shown in the figure), all MPG lines are connected to the common high-voltage transformer inputs 2 of the primary winding.

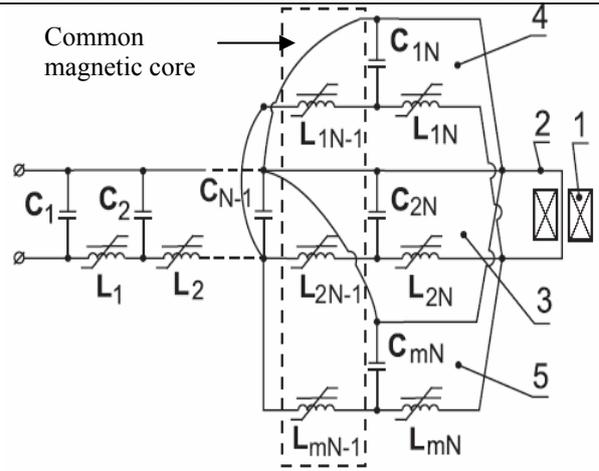


Fig. 2. High-voltage unit diagram.

The HVT secondary winding is connected to the load and is not shown in Fig. 2. Unlike the known LIA designs, there is no forming line in the unit, which function is performed by the capacitors of the MPG lines C_{1N}, C_{2N}, C_{mN} . The parameters of the windings of the saturation chokes $L_{1N-1}, L_{2N-1}, L_{mN-1}$ should be identical in order to ensure equal time interval of the charge-discharging operations and equal amplitude of the charging voltage of the capacitors C_{1N}, C_{2N}, C_{mN} .

4. Operation principle of the high-voltage unit

Let us consider an operation principle of the *HVG* containing the MPG with two compression stages ($N=2$) and three parallel lines in the last compression stage ($m=3$). (This example can be regarded as work of two last compression stages of the multi-stage MPG). First, the required current is set in the MPG circuit determining the magnetic state of the core of the saturation chokes and HVT. Demagnetization current is formed by the demagnetization source connected through the decoupling inductance to the secondary winding of the pulse transformer. While C_0 discharges, the voltage at C_1 increases and, when $t = t_1$, it reaches maximum (Fig. 3). By that moment, the process of the energy transfer to the capacitor C_1 can be finished. The inductance in the core of the saturation chokes grows and, at the time t_1 , the inductance reaches the value B_s , the core of the chokes is saturated, and the discharge of the capacitor C_1 through its winding to the capacitors C_{12}, C_{22}, C_{32} starts. Upon saturation, the inductance of the saturation chokes L_{11}, L_{21}, L_{31} windings decreases abruptly in consequence of $\mu \rightarrow 1$.

The duration of C_0 discharging must correspond to the duration of magnetization reversal of the saturation choke $L_{11} (L_{21}, L_{31})$:

$$t_1 - t_0 = \pi \sqrt{L_0 C_0 / 2} \approx \Psi_{11} / \langle U_{C_0} \rangle, \quad (1)$$

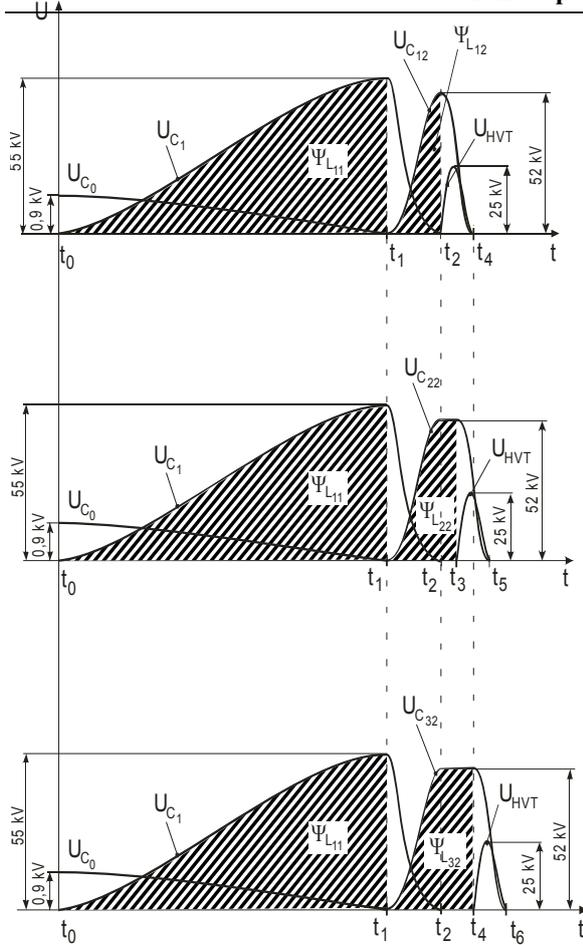


Fig. 3. Voltages at the *HVG* high-voltage unit elements versus time.

where L_0 is the inductance of the discharge circuit formed by the primary stage, pulse transformer primary winding, and connecting conductors, $\Psi_{L11} = \Psi_{L21} = \Psi_{L31} = \omega_{11} S_{L11} AB$ is the linkage of L_{11} , L_{21} , L_{31} , ω_{11} is the number of turns in the windings, S_{L11} is the steel cross-section, $AB = 2B_s = 2.5$ T is the induction magnitude in steel for Permalloy 50 NP, $\langle U_{C0} \rangle \approx U_{C0}/2$ is the average operating voltage at the turns of the saturation chokes, and $U_{C0} = 0.9$ kV is the amplitude of the C_0 charging voltage.

From the equation (1), it is possible to determine the required cross-section of the core steel of the saturation chokes L_{11} , L_{21} , L_{31} for the given number of turns of the winding.

The inductance of the winding of the saturation chokes upon cores saturated state ($\mu \rightarrow 1$) equals:

$$L_{11} = \sqrt{\frac{\mu_0}{2\pi}} l_{11} \omega_{11}^2 \ln \frac{D_{11}}{d_{11}}, \quad (2)$$

where D_{11} , d_{11} , l_{11} are the outer and inner diameters and the length of the winding.

At the time t_1 , the core of the saturation choke of the first stage of the MPG is saturated, and the capacitors C_1 begin to discharge to the capacitors C_{12} , C_{22} , C_{32} , connected in parallel. For effective energy trans-

fer, the following proportion between the capacitances of the capacitors should be implemented: $C_1 = C_{12} + C_{22} + C_{32}$.

Within the time period between t_1 and t_2 , magnetization reversal of the core of the saturation choke (magnetic switch) L_{12} occurs. The value of the linkage of the saturation choke L_{12} should be sufficient for complete discharge of the capacitor C_1 to the capacitors C_{12} , C_{22} , C_{32} , i.e., meet the following condition:

$$\Psi_{L12} = U_{C12}(t_2 - t_1)/2, \quad (3)$$

where U_{C12} is the amplitude of the charging voltage of the capacitors C_{12} , (C_{22} , C_{32}) (the voltage amplitude reduction from 55 kV to 52 kV seen in Fig. 3 is conditioned by the losses at the energy compression, which were estimated by computer simulation), and

$$t_2 - t_1 = \pi \sqrt{\frac{L_{11} C_1 (C_{12} + C_{22} + C_{32})}{C_1 + C_{12} + C_{22} + C_{32}}}. \quad (4)$$

The capacitances of the capacitors should be identical $C_{12} = C_{22} = C_{32}$ in order to ensure high efficiency of the energy transfer from the first compression stage of the MPG to the last one and equality of the amplitude of charging voltages and the duration of charge-discharging processes.

The inductance of the magnetization turns of the saturation choke L_{12} at the saturated state of the core is determined by the formula similar to (2). In order to provide the long duration of the flat part of the *HVG* output pulse $\tau \sim 1$ μ s, it is necessary to form 3 pulses with ~ 0.7 - 0.8 μ s duration each on the high-voltage transformer input. The time delay between the first and second pulses is $\tau/3 \sim 0.35$ μ s and that between the first and third ones is $2\tau/3 \sim 0.7$ - 0.8 μ s. The output pulse delays of the second and third lines of the MPG can be achieved by increasing the linkage of the saturation chokes L_{22} and L_{32} .

Thus, the following conditions should be satisfied:

$$\Psi_{L22} = U_{C22}(t_2 - t_1 + \tau/3)/2. \quad (5)$$

$$\Psi_{L32} = U_{C32}(t_2 - t_1 + 2\tau/3)/2 \quad (6)$$

The linkage increase is achieved by the increase of steel cross-section, quantity of winding turns, by using a material with different AB , and by combination of the said methods.

Between the moments t_1 and t_2 , the core magnetization reversal for the switch L_{12} occurs, and C_{12} discharges in the time interval ($t_4 - t_2$) through the HVT primary winding and shapes a high-voltage pulse at the load. The discharge of the second line of the MPG (the capacitor C_{22}) should be implemented at the moment t_3 (the core magnetization reversal for the switch L_{22} occurs) that corresponds to half duration of the output pulse of the first line of the MPG. The third line of the MPG (the capacitor C_{32}) is enabled at the moment t_4 (the core magnetization reversal for the switch L_{32} occurs) that corresponds to the end of discharge of the first line of the MPG and to half duration of the discharge pulse of the second line of the MPG.

The total duration of pulses created by three lines of the magnetic pulse generator of the high-voltage unit at the primary winding of the high-voltage transformer equals to the time interval (t_6-t_2). The superposition of the output bell-shaped pulses of the three lines of the MPG (U_{HVT} in Fig. 3) enables the formation of the output rectangular pulse of microsecond duration and required amplitude at the load.

The synchronization of several lines at the MPG operation is possible because the common saturation choke core is used (the time moment t_1 is strictly determined for all MPG lines. During the adjustment of the *HVG*, it is possible to smoothly change the level of the linkage of the saturation chokes (the moment of connecting the lines of the MPG to the HVT primary winding). For that, the additional circuits of demagnetization of the saturation chokes L_{12} , L_{22} , L_{32} should be implemented.

5. *HVG* computer simulation results

Since *HVG* is an expensive and labor-intensive system, the stage of computer simulation is very important. The system elements are sophisticated equivalent circuits; therefore, calculation of the *HVG* is possible only by applying computer means, which allow for considering practically every physical effect upon energy compression. The work objective is to create a computer model to calculate the processes occurring within the high-voltage unit of the *HVG* and to choose effectively the elements parameters for maximizing the output power and efficiency and to form the pulse with the required waveform.

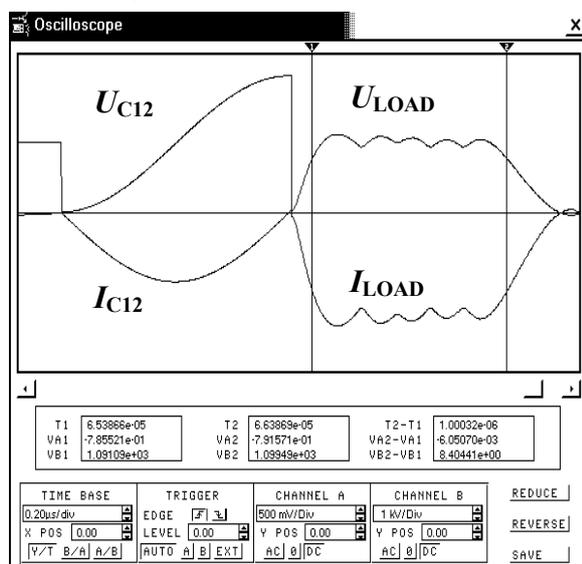


Fig. 4. Output pulse at the ohmic load, charging voltage and current at the capacitor C_{12} . The voltage on the load is 477 kV; the current is 1060 A, 1.0 μ s long at the level of 0.9 kA.

In order to solve the problem, a real electric circuit (Fig. 2) is introduced as an equivalent circuit, for which the parameters of elements are defined. Then, a calculation design is drawn up by means of the software product «Electronic Workbench». Some results of the computer simulation can be seen in Fig.4.

It should be noted that oscillations at the pulse tops can be eliminated by application of antiresonant circuits.

6. Conclusion

The original ideas are realized for the *High-Voltage Generator*. The formation of the output pulse is executed by the discharge of several (three in this case) synchronized magnetic pulse generator lines. The synchronization of the MPG lines operation is possible, because the common saturation choke core is used (the time moment t_1 is strictly determined for all MPG lines). The application of the saturation chokes with increased linkage values in the several lines of the MPG last compression stage makes possible the delay in switching on to the winding of the high-voltage transformer.

The superposition of the output pulses of the several lines of the MPG enables the formation of the output rectangular pulse of required duration and amplitude at the load. In order to reduce the discharging inductance for getting a steep pulse front, to decrease the weight and dimensions and the cost value, the high-voltage transformer is designed according to the principle of LIA induction system with multiple-turn windings. Application of magnetic elements allows one to achieve high pulse repetition rate.

Conducted simulation allowed us to determine the elements that limit the output parameters, to correct their characteristics, and to adjust the *HVG* elements for obtaining the pulses of required output characteristics: voltage, current, pulse duration. The proposed concept of the *High-Voltage Generator* makes possible the realization of up to 1 MV, 1-5 kA, 1 μ s, 1 kHz pulse parameters. Such parameters are unique and obtained at relatively low weight, size, and cost characteristics. The proper choice of elements parameters in the last MPG stage allows creating output pulses of special forms: linearly increasing or linearly falling down.

References

- [1] I.I. Vintizenko, *Patent RU 2265973*, 2005.
- [2] L.D. Butakov, V.V. Vasilev, I.I. Vintizenko and E.G. Fourman, *Instruments and Experimental Techniques*, 5, 105 (2001).