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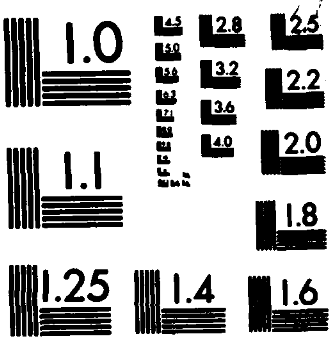
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FOREIGN TECHNOLOGY DIVISION

AIR FORCE SYSTEMS COMMAND

FORMING OF MAGNETIC FIELDS WITH COMPLEX LAW OF VARIATION IN TIME

by

V.V. Ivashin, E.G. Furman

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By: V.V. Ivashin, E.G. Furman

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Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
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О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

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FORMING OF MAGNETIC FIELDS WITH COMPLEX LAW OF VARIATION IN TIME

V. V. Ivashin, E. G. Furman

Magnetic fields which are formed in inductive loads are widely used in physic experiments, in thermonuclear experimental units, in the excitation of electromagnetic accelerators and acculator rings, in supplying power to magnets in bubble chambers, etc. Extremely diverse forms of the magnetic cycle are required. For example, the requirement for a constant magnetic field value in an electrical magnet is a typical problem for most operating and projected accelerators and thermonuclear research units [1-4].

When the electromagnet of an accelerator is excited from a capacitor bank for the purpose of forming a flat elevation (plateau) in the curve of an electromagnetic current and, consequently, a magnetic field, energy losses in the winding of the electromagnet must be compensated on the necessary level of the current and maintained with the required accuracy during the formation of a plateau The stability of the forming field during the duration of the plateau from several to tens of milliseconds can be extremely high and depends on the conditions of the experiment.

The problem of producing a plateau in a magnetic field at maximal energy is extremely difficult from a technological standpoint. It requires the creation of powerful pulsed current, which leads to a substantial increase in the cost of the accelerator, complication of the power supply system, and lower operating reliability on its part. At the present time considerable attention has been directed toward developing effective pulsed power generators - devices with intermediate energy storage in LC-elements, rotating masses, etc., which assure the necessary power at the output during the forming of the plateau and which require a moderate amount of power from the network, determined primarily by the pulsing ratio [duty ratio] of the generator.

In the case of low pulsing ratios and prolonged plateaus it is best to form the plateau directly from the power supply source without the intermediate storage link.

The use of powerful semiconductor devices for purposes of power switching makes it possible to form powerful pulse fields of the required shape in an inductive load and use capacitive energy accumulators [5-7].

Forming of Magnetic Fields of Quasi-Sinusoidal or Similar Shape

If a plateau is required in the curve of a magnetic cycle of short duration, then a system with unipolar current pulses can be used to power the electromagnet [5, 6]. Here, as a result of the artificial, abrupt change in the circuit from the mode corresponding to angle $\frac{\pi}{2} \pm \omega t$, to a regime corresponding to angle $\frac{\pi}{2} \mp \omega t_{к}$, an artificial change in the length of the pulse peak is obtained. Let us look at such a working mode using the excitation of a betatron electromagnet by current pulses of higher frequency as our example [5] (Fig. 1).

In its original state energy storage capacitor C is charged to the required voltage, while buffer capacitor C_1 is charged by a rectifier current switched to terminals 1 and 2. When the pulses reach thyristors T_1 and T_2 the capacitor bank is discharged to the electromagnet and the leading front of the current pulse is formed in it. When the polarity of the voltage on capacitor C changes, diodes $Д_1$ and $Д_2$ open and the direct-current controlable reactor begins to reverse its magnetic polarity. At moment in time T_3 under the effect of voltage

U_{C_1} the thyristors are switched off and the current of the electromagnet is completely drawn into the circuit of diodes $Д_1$ and $Д_2$. Here the direction that the current takes through capacitor C reverses, and it [capacitor] is recharged at the same polarity that it is discharged. At the moment that the current is intercepted or after a slight delay thyristor T_3 in the pulsed energy input circuit is switched on and energy is admitted to the oscillatory circuit from the buffer capacitor and the rectifier through charge reactor L_1. The input of energy is accompanied by certain decrease in the duration of the current drop in the electromagnet.

The length of the plateau can be assumed equal to $4\omega t_k$ (see Fig. 1b), while stability is determined as

$$\delta = \frac{\Delta I}{I} = 0{,}5(\omega t_k)^2 \exp\left(-\frac{4L}{R} t_k\right), \quad (1)$$

where R is the effective resistance of the circuit.

To increase the stability and length of the formed current pulse peak in the generator system of quasi-trapezoidal current pulses [6], it is possible, using the principles of pulse-width modulation [8] to use the remaining energy of the energy storage capacitor in the capacity of an energy source to compensate losses in the electromagnet. The formation of a highly stable plateau in an induction load is shown schematically in Fig. 2.

In its original state the energy storage capacitor C and switching capacitors C_1 and C_2 are charged to the required voltages (see Fig. 2a). When the necessary current is reached in the electromagnet L, thyristor T_3 is switched on. The discharge current of switching capacitor C_1 cuts off thyristor T_1, the energy storage capacitor is cut off from the electromagnet, and circuit L, T_2, $Д_1$ is shorted. The electromagnet current during time interval T_3-T_2 drops exponentially. At moment T_3 thyristor T_1 is switched on again, diode $Д_1$ is switched off, part of the energy from the energy storage capacitor enters the electromagnet, at moment in time T_4 the accumulator is switched off, etc.

By the end of the formation of the plateau in the electromagnet thyristor T_4 is switched on and switching capacitor C_2 is switched to the first winding of switching transformer Tp. Under the influence of the emf induced on the second winding of the transformer, thyristor T_2 is switched off, while diode D_2 is switched on and the discharged storage capacitor C is connected to the electromagnet. The energy from the electromagnet enters the capacitor bank through the circuit consisting of $L, Д_2, C, Д_1$. The length of the formed plateau depends on the time constant of the electromagnet and the moment in time that the storage capacitor is switched off:

$$t_u = \tau/2\, tg^2 \omega t_\kappa \quad , \qquad (2)$$

where τ is the time constant of the electromagnet.

The stability of the formed plateau is determined by the frequency with which the storage capacitor is switched to the electromagnet during the forming of the plateau and equals

$$\delta = \frac{\Delta I}{I} = 1 - \exp\left(-\frac{\tau - \rho C tg \omega t_\kappa}{2n\tau tg^2 \omega t_\kappa}\right) \quad , \qquad (3)$$

where n is the number of switchings of the storage capacitor to the electromagnet; ω, ρ - circular [sic] frequency and wave resistance of the circuit.

If a short plateau is required at the maximum electromagnet current value, then an auxiliary capacitor bank [3, 9] can be used for this purpose. This capacitor bank is switched to the circuit during the time that the plateau is forming. In such a system (Fig. 3) the plateau is formed as a result of the change in the natural frequency of the LC-circuit, while the energy dissipated in effective resistance of the electromagnet is compensated by the energy of buffer capacitor C_0. The stability of the formed plateau

$$\delta = \frac{\Delta I}{I} = \frac{t_u^2}{8L(C_0+C)} \quad . \qquad (4)$$

These systems for "stretching" the pulse peak of the electromagnet current can be used in formed plateaus of short duration and when stability requirements for the shaped current are not high.

Formation of Highly Time-Stable Plateaus in Electromagnet Current Curve

Figure 4 shows a diagram of a pulsed power generator in which precharged capacitors C_1, C_2, C_3, ..., C_6 with switching devices T_1, T_2, T_3, ..., T_6 are alternately discharged onto the electromagnet through the double integrating element L_1C_0 and L_2C_0 for the purpose of maintaining and shaping the plateau. In this case the voltage on the buffer capacitor C_0 which switches the electromagnet during the shaping of the plateau is held almost constant and equal to the voltage drop on the electromagnet. The pulsed power generator is switched to the electromagnet at an electromagnet current which is either maximal or close to it.

The generator output (terminals A and B) should be switched parallel to one of the diodes, for example, Д_4. In this case no additional gates (rectifiers) are required to protect the low-voltage capacitor bank C_0 from the high-voltage LC-circuit.

In their original state the cells of capacitors C_1 and C_2 are charged from the rectifier to the required voltage. The moment that thyristor T_1 of the first cell of the capacitors is engaged is assigned by the condition that the discharge current of capacitor C_1 must be approximately equal to the electromagnet current by the moment that the maximum electromagnet current is attained. During time t_3-t_2 the discharge current of the capacitor flows through the circuit consisting of C_1, T_1, L_1, L, R with parallel-switched buffer capacitor C_0, through which the current difference between the electromagnet and the pulsed power generator passes.

With a complete discharge of the capacitor diode $Д_1$ is switched on, and in the course of time t_6-t_3, under the influence of voltage U_{c0}, the current and choke L_1 drops to zero. At moment in time t_4 thyristor T_2 is switched on and switches the capacitor C_2 of the other generator pole to the electromagnet through conductor L_2. At the moment in time at which inductance L_1 drops to a zero value, capacitor C_3 is connected through thyristor T_3 to the load, whereupon thyristor T_4 responds and switches capacitor C_4, etc., until the formation of the plateau is complete.

The frequency with which the thyristors in the capacitor cells open must be such that the average load discharge energy of the capacitors is equal to the energy dissipated on effective resistance of the electromagnet winding. Such alternative switching of the cells of capacitors C_1, C_2, C_3 ... through a dual integrating component makes it possible to substantially improve the shape of the applied voltage $E \approx U_{c0}$ to the electromagnet as compared to the working systems [2, 10], to obtain a satisfactory working mode for the control devices, and to utilize their average current more effectively.

The laws of change in current and voltage during discharge of a capacitor of any of the cells can be written as

$$U_c = E[1 + (K-1)\cos\omega t]\ ; \tag{5}$$

$$i_c = \rho E(K-1)\sin\omega t\ , \tag{6}$$

where ω and ρ represent the circular [sic] frequency and wave resistance of the circuit consisting of C_1L_1 and C_2L_2; K - dimensionless coefficient which indicates the number of times that the initial voltage on the capacitor cells exceeds the average value of the voltage applied to the electromagnet.

The discharge time of the capacitor of one of the cells into circuit C_0LR is determined as

$$\Delta t_1 = \frac{1}{\omega}\left(\pi - \arccos\frac{1}{K-1}\right) , \qquad (7)$$

while the time during which the current flows into inductors L_1 or L_2 after the discharge of the capacitor is determined as

$$\Delta t_2 = \frac{(K-2)}{\omega} . \qquad (8)$$

Figure 5 is a graphic representation in relative unit of some of the working characteristics of the generator.

Curve 1 is a dependence representing the relationship of the amplitude of the current formed in the electromagnet to the amplitude of the discharge current of the capacitor cells.

Curve 2 represents the ratio of maximal energy stored in the choke to the originally accumulated energy of one cell of the capacitors as a function of the ratio of voltage on the capacitor cells to the average voltage on the buffer capacitor.

Curve 3 represents the dependence of the ratio of the period of the main harmonic to the pulse length of the current through inductor L_1 or L_2.

Curve 4 represents the dependence of the ratio of the amplitude of the main harmonic of the current and the output spectrum current of the generator to the amplitude of the electromagnet current.

The stability of the formed plateau in this variant of the pulsed power generator can be determined, when K is known as

$$\delta = \frac{(I_{\sim}/I_m)\left[(T_{\sim}/t_u)\cdot t_u\right]^2}{2\pi C_0 L} . \qquad (9)$$

Formula (9) enables us to select the buffer capacitance value and the number of cells in the capacitors which will assure the required stability of the formed plateau.

This pulsed power generator makes it possible to produce magnetic fields in an inductive load with a plateau which slowly increases, decreases, or changes according to a certain law. This is achieved by regulating the moment that the controlled devices in the capacitor cells are engaged [ignited], i.e., by changing the value of the energy which enters the circuit LRC_0. For example, on the oscillogram (Fig. 6) the current in the electromagnet drops at the moment that the pulse peak is formed.

If the pulse repetition rate of the formed plateau is close to one, then the intermediate accumulation of energy in the LC-elements is not rational, and a direct current source should be used to shape the plateau.

In Fig. 7 we see one possible system which would enable us to obtain long, highly stable plateaus. In its original state energy storage capacitor C is charged, and a direct current flows through the winding of the electromagnet from a direct current source, which is connected to the midpoint of the winding through the thyristors and diodes. At the moment in time t_1 thyristor T_3 is switched on and connects the recharge switching capacitor C_1 to the first winding of the switching transformer. Under the effect of the voltage induced on the second winding the thyristors are switched off, and the energy storage capacitor is series-connected through the diodes to the following circuit: dc source, electromagnetic. The energy from the electromagnet enters the capacitor, while the current in it drops to zero.

At moment in time t_3 thyristors T_1 and T_2 are switched on and capacitor C discharges onto the electromagnet. Upon complete discharge of the capacitor the diodes are switched on, the current in the electromagnet is maintained for the required time, etc. The dc power supply source must provide at the output the power required for the effective resistance of the electromagnet winding at the output voltage, which is equal to the voltage drop on this resistor.

The power supply system makes it possible in an inductive load to form magnetic fields which have different shapes in time: sinusoidal, stepped, triangular, etc. This is possible because of the artificial switching of the current from the thyristors to the diodes and vice versa at the necessary moments by familiar methods [5, 6, 8].

Conclusion

The examined shaping systems use the most effecient working modes: capacitors - unipolar with respect to voltage, electromagnets - unipolar with respect to current, and this makes it possible to substantially increase the technical and economic indicators of these systems [5, 7] and achieve programmed control of the shape of the magnetic cycle of the electromagnet in time.

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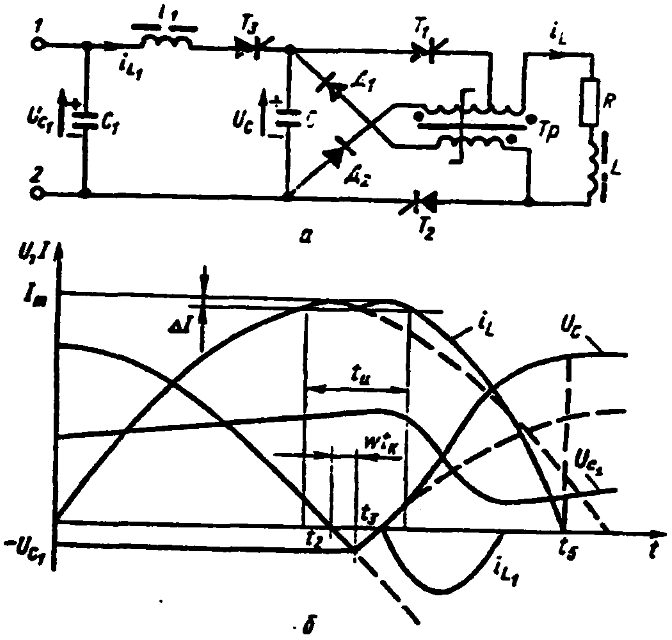

Fig. 1. Excitation of electromagnet by unipolar current pulses.

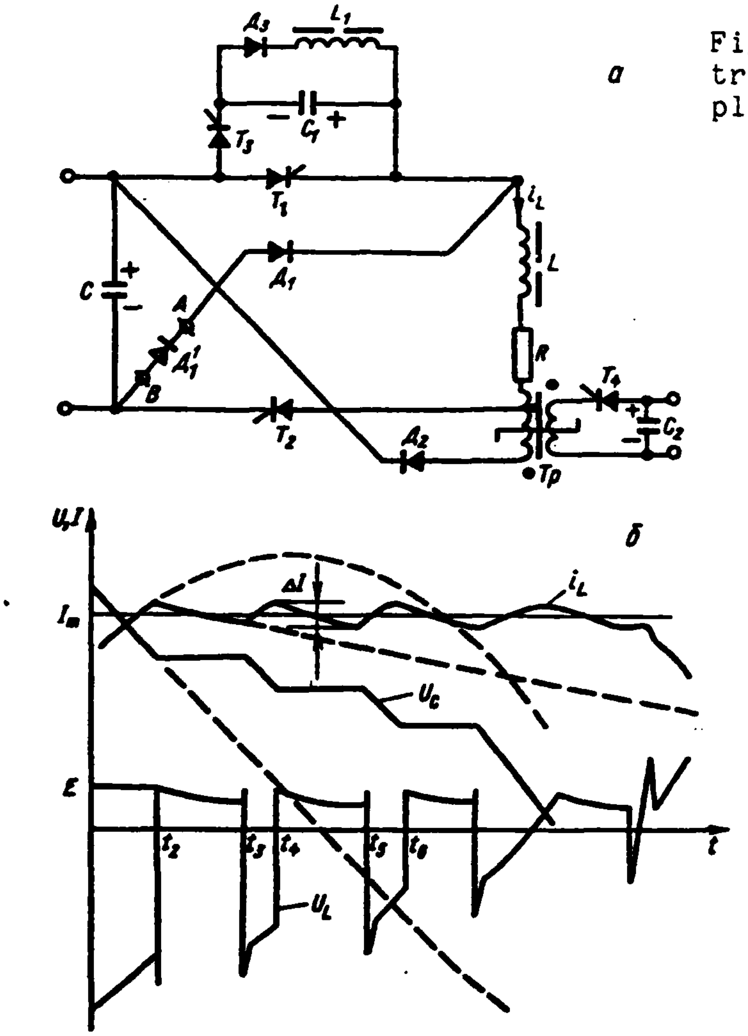

Fig. 2. Formation of quasi-trapezoidal current pulses with plateau.

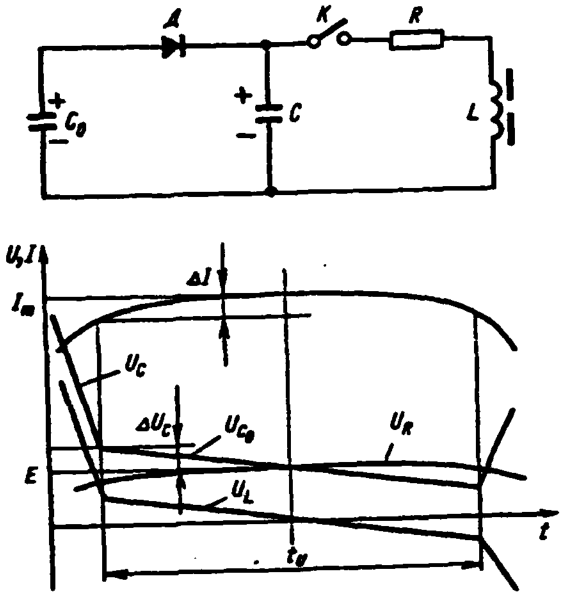

Fig. 3.

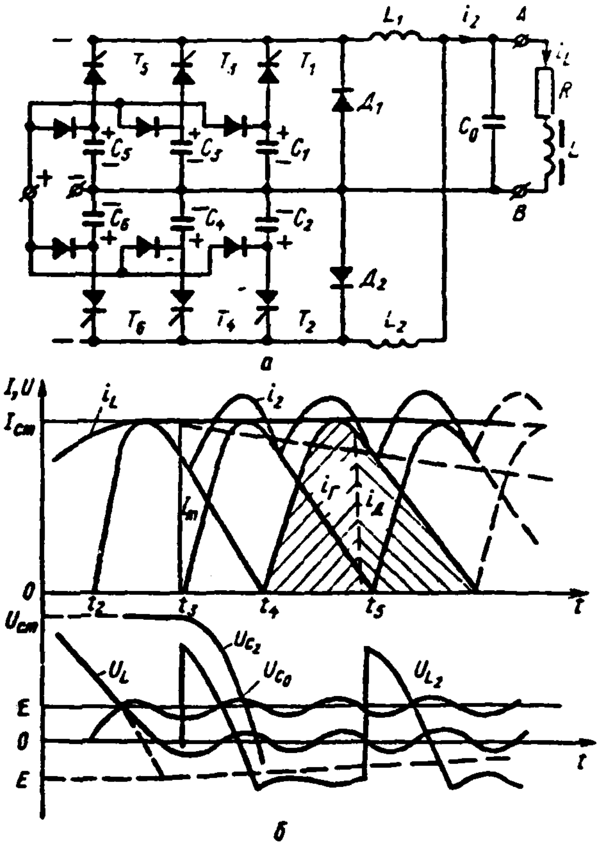

Fig. 4.

Fig. 3. Equivalent formation scheme of plateau from additional buffer capacitor bank.

Fig. 4. Pulsed power generator system.

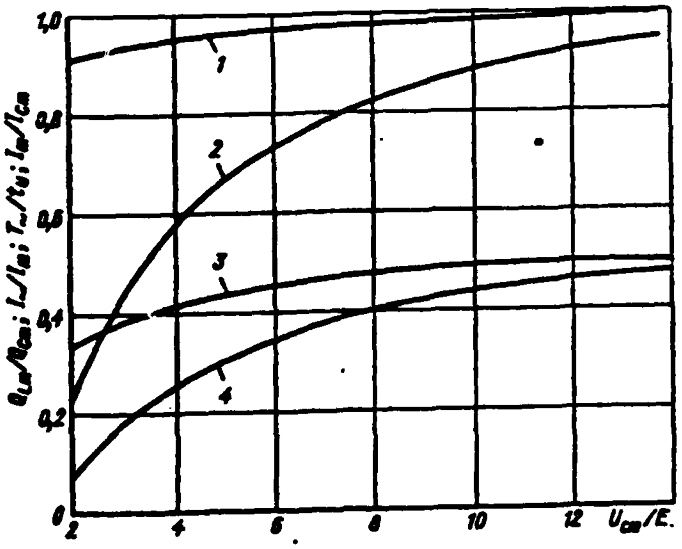

Fig. 5. Working characteristics of generator.

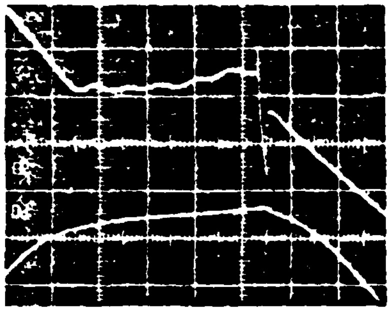

Fig. 6. Oscillogram showing voltage (top beam - 10 V/mm) and current (lower beam - 8 A/mm) of inductive load during forming of plateau which increases in time. Scanning period is $2 \cdot 10^{-3}$ s/cm.

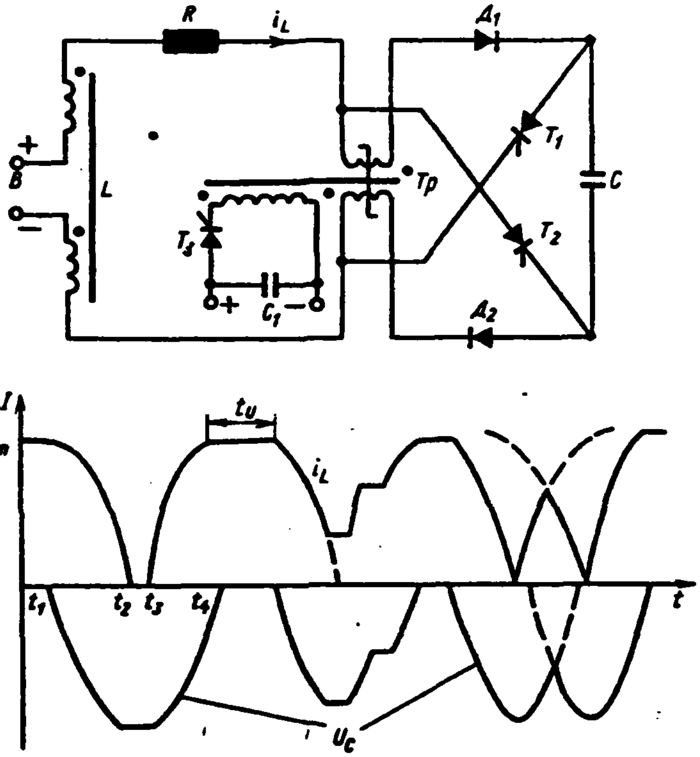

Fig. 7. Generator system for formation of current pulses of different shapes with respect to time.