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Power System for Industrial ILU-Type Electron Accelerators

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Abstract—The device and principle of operation of the pulse modulator, which is the power-supply system for the ILU series accelerators, as well as some features that arise during its operation, are described. The modulator is a device that is a nonlinear load for the supply network, as a result of which, in all phases of the supply network, an asymmetry of the current form occurs over the period of the network. This leads to the appearance of a constant current component in the phases of the supply transformer. To solve this problem, current balancing of the start time of modulators was proposed. Using this method, it is also possible to equalize the values of effective currents in phases. Another problem is the possibility of the appearance of higher harmonics in relation to the supply frequency in the phases of the power-supply network. To reduce the values of higher harmonics, it is proposed to install additional inductances in each phase of the power-supply network up to the modulator, which makes it possible to reduce the harmonic coefficient by half.

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1. INTRODUCTION

The Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences, has developed a series of pulsed high-frequency (HF) electron accelerators of the ILU type for an energy of 1–10 MeV, which are used both in the electron irradiation mode and in the bremsstrahlung mode. To power these powerful pulsed accelerator devices, consisting of one or more resonators, generators based on high-power, high-efficiency electrovacuum devices, GI-50A triodes, were used. The anode power supply of the generators is formed by modulators, the basis of which is forming lines with lumped parameters and switching elements from power thyristors. Each modulator contains a low-voltage three-phase rectifier assembled according to a bridge circuit (Larionov's circuit), a storage choke that forms a line, and a pulse transformer that matches the parameters of the modulator and generator; switching elements are thyristors [1]. All accelerators of the ILU series operate with one modulator; only the ILU-14 accelerator with an energy of accelerated electrons up to 10 MeV and a beam current power of up to 100 kW at a beam current pulse repetition rate of up to 50 Hz is powered by three modulators [2]. The impulse is formed due to the capacitive component of the line precharged to a given voltage. The modulator generates a high-voltage voltage pulse to the anode of the RF generator with an amplitude of up to 32 kV and a duration of approximately 500 μs. The forming line is charged from the power supply without transformation to a voltage of 8 kV. The main technical characteristics of the modulator are presented below:

Output pulse amplitude	30 kV
Limits of regulation	0–100%
Pulse duration	500 μs
Pulse repetition rate	1–50 Hz
Power supply: three-phase AC	220 V
Mains operating frequency	50–60 Hz
Total power consumption	150 kW

2. PULSE MODULATOR DEVICE

Let us consider the operation of one modulator designed for pulsed power supply of industrial electron accelerators of the ILU type (accelerators ILU-7, ILU-8, ILU-10, etc., work with one modulator). Each modulator contains the following: controlled three-phase rectifier; linear (with a large air gap evenly distributed along the length of the steel core) accumulation throttle L_1; forming line capacity C_1, equal to 120 μF; and synchronized switch assemblies T_1–T_3, recruited from thyristors type TB333-500-14. The schematic diagram of the modulator is shown in

† Deceased.

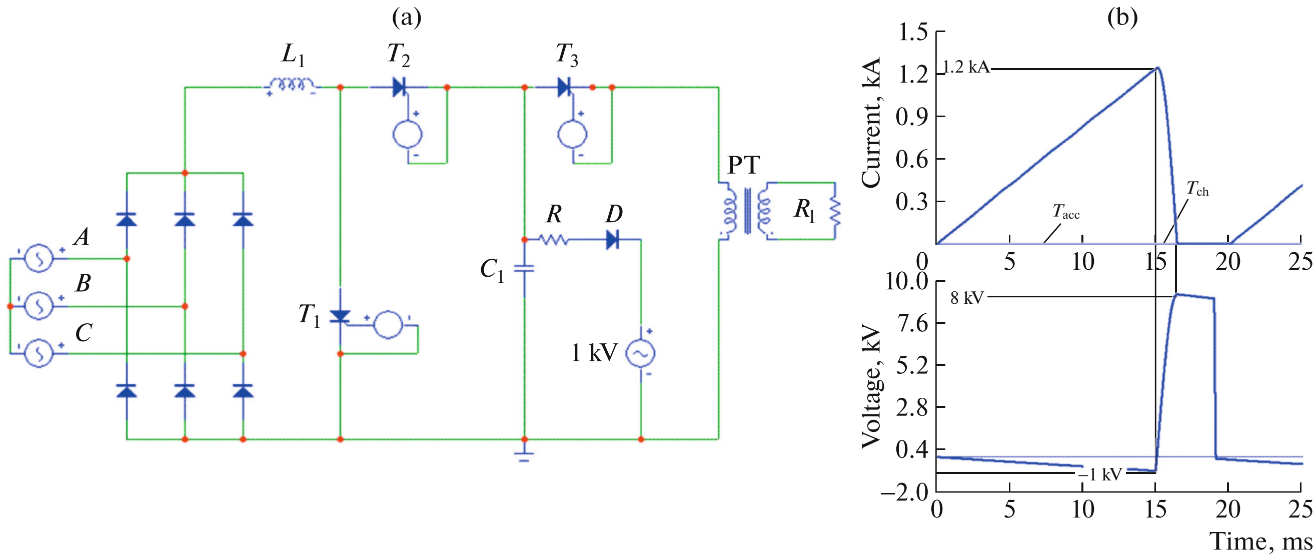

Fig. 1. (a) Scheme of pulsed current accumulation in the inductance and charging of the capacitance of the forming line (T_1–T_3 is synchronized switch assemblies; PT is pulse transformer); (b) timing diagrams explaining the operation of the modulator.

Fig. 1a; Fig. 1b shows timing diagrams explaining the operation of the modulator.

Consider the choice of the main parameters and elements of the modulator. Accumulation time for the operating mode of the electron accelerator T_{acc} equals 16 ms. In this case, the value of the average accumulation current is consistent with the value of the average thyristor current T_1 (500 A). We obtain the amount of inductance L_1 from the following energy ratio: $W_E = \frac{L_1 I^2}{2}$. At $W_E = 4000$ J, $I = 1200$ A, we get $L_1 = 6$ mH. We obtain recharge time T_{ch} from the Thomson formula: $T = 2\pi\sqrt{L_1 C_1}$, where $T_{ch} = T/4 = 1.33$ ms.

A schematic drawing of the accumulation throttle is shown in Fig. 2. Two metal cores, each with four sections, are stacked with plates of electrical steel 0.35 mm thick and with a cross section of 16 × 16 cm^2, and the height of the cores is 50 cm. The cores are connected above and below by steel plates 50 cm long. The total length of the air gap separating the sections of the cores and the slab is 28 cm: three gaps of 2 cm between sections as well as top and bottom gaps of 4 cm.

Uniform distribution of air gaps along the perimeter of the magnetic circuit ensures that there is no large leakage of magnetic flux in the gaps and minimizes possible eddy losses from induced currents in the metal elements of the inductor design. The picture of the distribution of the inductor's magnetic field is shown in Fig. 2. Accumulation choke coils w_1 and w_2, located on the cores, are wound with OF-OK hollow copper bar with a section of 12.5 × 12.5 mm^2 with a round hole with a diameter of 7 mm; each coil consists of three sections of 30 turns.

The calculated effective current for an accumulation time of 16 ms and a pulse repetition rate of 50 Hz is 670 A. The value of the magnetic induction in the gland of the inductor is approximately 1 T. The total active losses in six windings reach 8 kW. The effective currents in the phases of the power-supply network up to the rectifier reach 570 A and impose a limit on the length of the cables connecting the modulator to the supply transformer. Thus, using a 100-m-long three-phase copper cable (section 150 mm^2, resistance 0.1 Ω/km) for connection, approximately 10 kW can be lost.

3. OPERATING CYCLE OF THE MODULATOR

When starting the thyristor assembly T_1 in inductance L_1, current begins to increase linearly and energy accumulates (accumulation time T_{acc} in Fig. 1). For the case of turning on the inductor without active losses for direct EMF, the current in the inductor increases linearly with time: $i(t) = \frac{E}{L_1}t$. The calculation gives the value $T_{acc} = 14$ ms for stored energy up to 4.3 kJ and current up to 1.2 kA. The value of the output voltage of the rectifier is equal to the amplitude value of the linear voltage of the network: 537 V. Experimentally, these operating parameters (taking into account active losses) are achieved with an accumulation time of approximately 15 ms. When starting the key T_2, key thyristor T_1 restores the isolating state (key T_1 opens), while the accumulation process stops, and all the energy stored in the inductance L_1 is resonantly transferred to the capacitance of the forming line C_1 (charge time $T_{ch} = 1.33$ ms in Fig. 1).

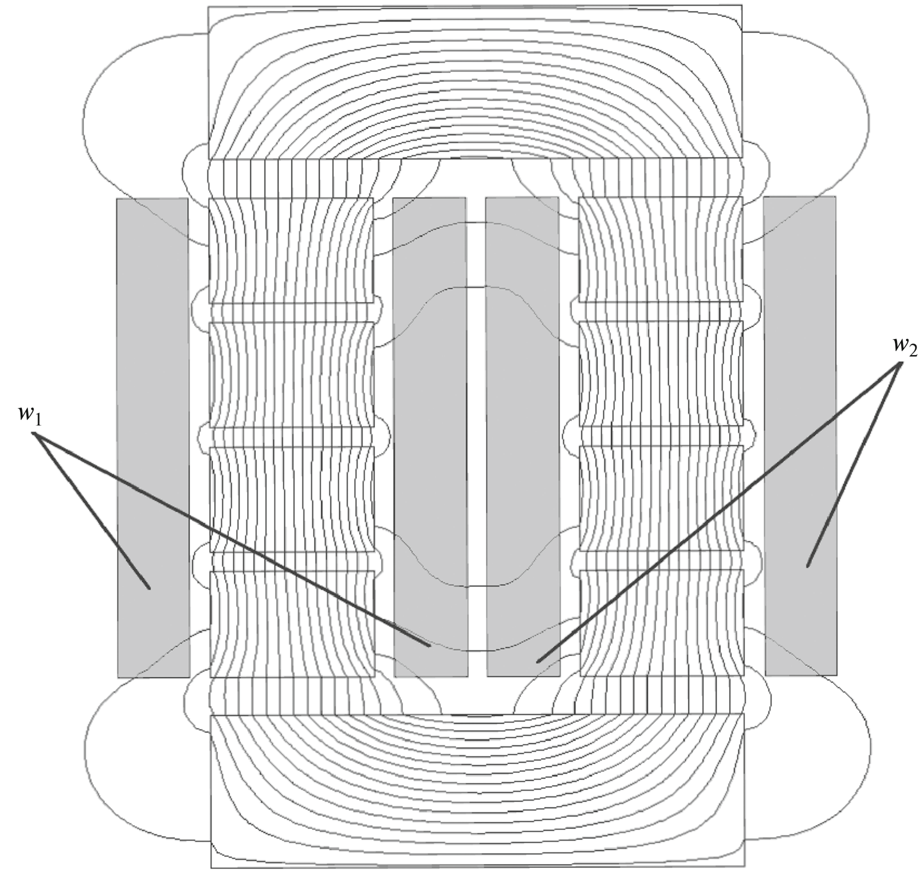

Fig. 2. Estimated picture of the distribution of the magnetic flux along the magnetic circuit of the modulator accumulation inductor.

Stopping the rising current in the choke or forced shutdown of T_1 is achieved by the ability of the circuit to be connected to the anode of a conductive thyristor T_1 precharged capacitor C_1 forming line. Negative polarity up to a voltage of −1 kV on the working capacitance is preliminarily formed by an additional source through the elements *R* and *D* in Fig. 1. Thyristor key T_2 connects C_1 (practically EMF) to a conductive thyristor T_1. The time of action of the reverse voltage is determined by the recharge time of this capacitance and storage inductor from −1 to +8 kV. Recharge time from −1 kV to 0 when a negative voltage is applied to T_1 under the action of which the thyristor blocking ability is restored, which is equal to at least 100 μs (the turn-off time of the TB333-500 thyristor according to the passport is less than 50 μs). In this way, the capacitance is charged with smooth adjustment of the voltage value by the charge accumulation time T_{acc}.

After the end of the process of charging the capacity, the thyristor key T_2 is locked since the current in the inductor becomes equal to zero (current through T_2 is absent), the controlled thyristor key T_3 is triggered, and the forming line is connected to the load R_l. In this case, the time of energy accumulation in the choke and its transfer to the tank, as well as the time of formation of the working pulse (up to 1 ms), determine the pulse repetition frequency up to 50 Hz (T_{slave} = 20 ms in Fig. 1), with which the device operates, and the magnitude of currents and voltages for selecting the elements of the above circuit. Structurally, all elements of the modulator are placed in steel electrical cabinets (Fig. 3).

4. CURRENT CALCULATIONS IN POWER MAINS PHASES

Consider the timing diagrams of all currents (Fig. 4) for various schemes of switching on modulators. When one modulator is turned on (see Fig. 4a), a significant asymmetry of the current signal waveform over a period of the network is visible, as evidenced by the shape of the growth curves of the average current over one period in phases. This leads to the appearance of a constant current component in the phases of the supply transformer during the operation of one modulator. Because of this, in the current of the secondary windings supplying the modulator, in each of the three cores of the transformer magnetic circuit (included in

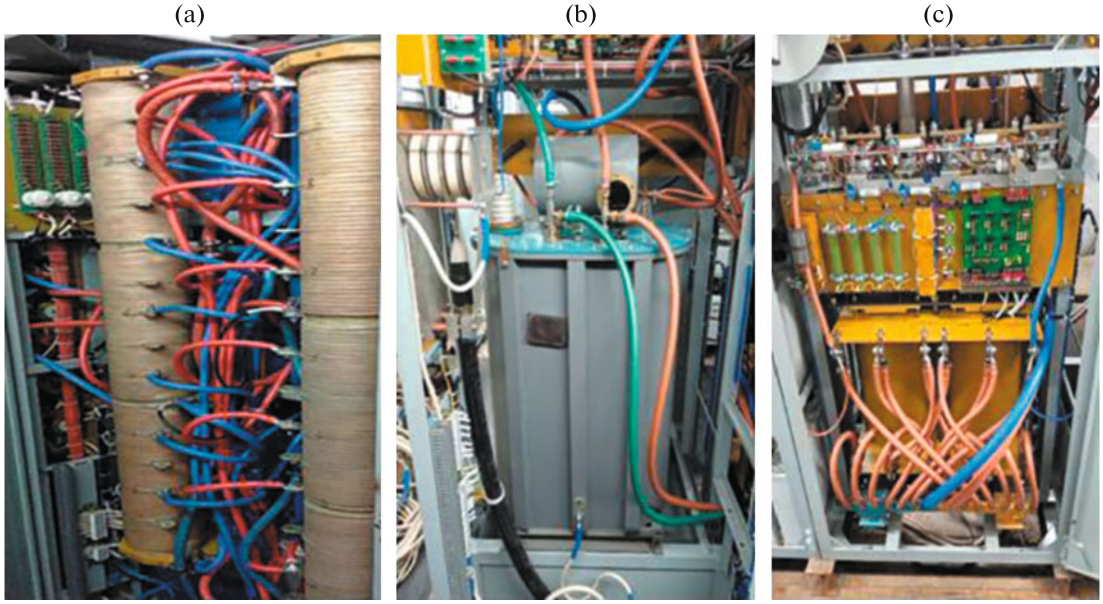

Fig. 3. Cupboard: (a) with forming line C_1; (b) with pulse transformer; (c) with accumulative choke L_1.

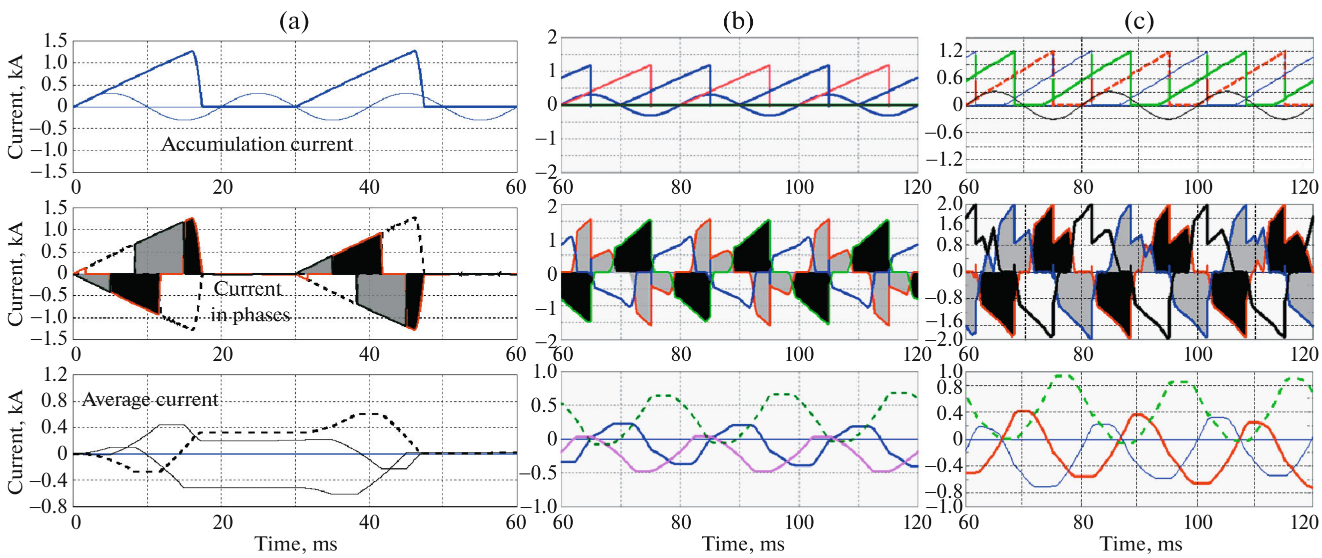

Fig. 4. Curves of accumulation currents, total currents by phases (each phase is highlighted in its own color), and average currents in each phase of the power supply for (a) one, (b) two, and (c) three modulators. In the upper figures, a sinusoid of the mains voltage (50 Hz) is shown for clarification.

the installation circuit or at the substation), a unidirectional transformer bias flux occurs, which reduces the allowable range of changes in the induction in the core. In this case, the transformer can be magnetized (the magnetic resistance of the core increases), and the magnetic fluxes are closed through the air and structural elements of the transformer. This leads to the occurrence of emergency currents and overheating of the transformer.

To solve this problem, current balancing of the start time of accumulation in devices for charging capacitive loads was proposed [3]. When three modulators are turned on to obtain a symmetrical system of nonsinusoidal currents, the modulators are each started after 6.67 ms, and when two modulators are turned on, it is after half a period of the network [4]. Using this method, it is possible to equalize the values of effective currents in phases. Symmetrization of currents by

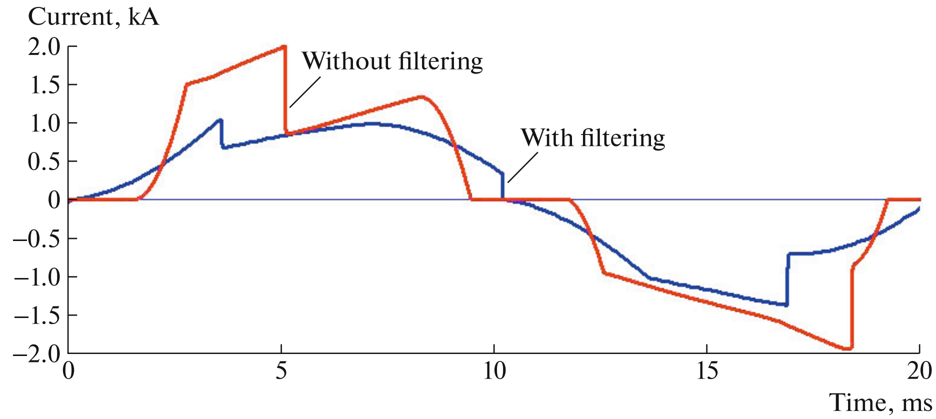

Fig. 5. Influence of filtering chokes on the shape of the period of phase *A* current.

phases of one modulator is not achieved during the network period, and it is necessary to skip one more network period to reset the average current. The next accumulation cycle should be started in 10 ms (pulse repetition frequencies are equal to 33.3, 20, 14.3, 12.5 Hz, etc.). An analysis of the shape of the average currents by phases (see Fig. 4a) shows that, for one modulator, the complete demagnetization of the transformer rods in the supply phases occurs only on the second accumulation pulse, when the phase currents change polarity. Taking into account the constant component in the current, it is necessary to double the power of the transformer. Effective phase currents also have to be symmetrical. The convenience of monitoring the magnetization of the transformer rods according to the curves of average currents in the phases should be noted.

The average currents for the period of the network for the variants of switching on two (Fig. 4b) and three (Fig. 4c) modulators are zeroed for the period, and, consequently, there are no magnetizing currents in the network supplying the accelerator. For the variant in Fig. 4c, the effective currents are the same in phases.

5. HIGHER HARMONICS OF THE POWER MAIN'S FREQUENCY

The modulator is a device that consumes nonsinusoidal current (i.e., it is a nonlinear load). Let us consider the spectra of harmonics generated by the currents of a six-pulse rectifier in three-phase networks for the case of three modulators (Fig. 4c). The power-supply circuit uses a three-phase bridge rectifier, which generates and distributes pulsed currents over the phases. The main generator of higher harmonics is not the load but the rectifier (inductive load is linear). To reduce higher harmonics, it is proposed to install additional inductances (filtering chokes) of 0.5 mH in each phase before the rectifier. Figure 5 shows the curves of the currents of one phase of the network without inductances and with filtering chokes.

Using the Fourier expansion, we obtain a representation of the current period function as a trigonometric series of the sum of 15 harmonics. The correspond-

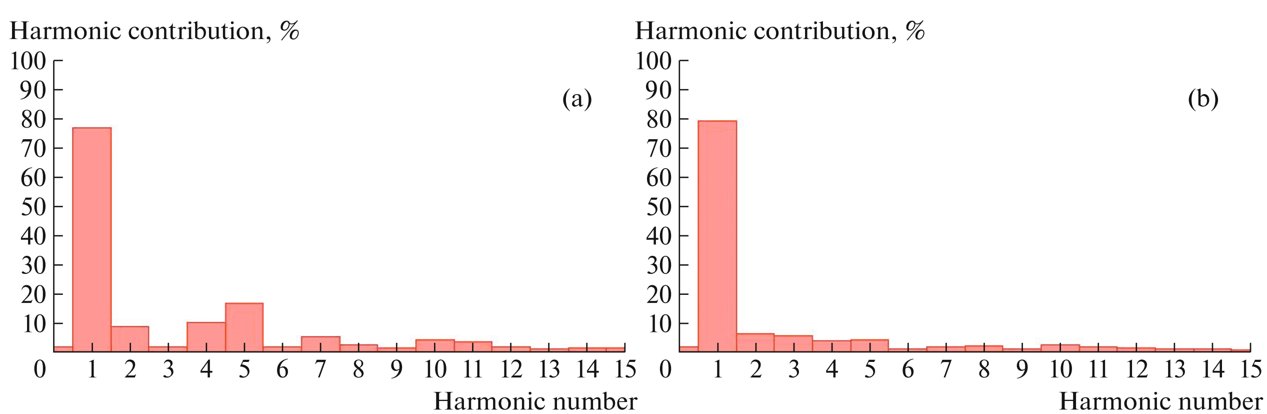

Fig. 6. Phase *A* current expansion in terms of harmonics: (a) without additional inductances and (b) with filter chokes.

ing histograms are shown in Fig. 6. Harmonic distortion K_U in GOST 13109-97 is defined as the distortion factor of the sinusoidality of the voltage curve and is calculated by the formula

$$K_U = \frac{\sqrt{\sum_{k=2}^{15} (U_K/\sqrt{2})^2}}{U_1} 100,$$

where U_K is the effective value of the interfacial voltage of higher harmonics, multiples of the frequency of the fundamental harmonic.

The maximum allowable value of the harmonic coefficient K_U, according to GOST 13109-97, is 12%, the calculation without additional chokes in the phases of the power supply gives a value of 21.2%, and that when calculating current harmonics with filtering chokes is 10%.

6. CONCLUSIONS

The power of modern industrial accelerators has grown to hundreds of kilowatts, and the devices used to power them, which consume nonsinusoidal current, can distort the entire supply network. To eliminate undesirable effects associated with the operation of power systems with linear charging of an inductive storage and capacitive load, several methods have been proposed to improve their operation. These make it possible to achieve balancing of effective currents in the phases of the supply network as well as to reduce harmonic distortions in the power-supply network. In particular, the installation of linear 0.5 mH chokes in the network phases makes it possible to reduce harmonic distortions to the values required by GOST 13109-97, and the launch of three modulators after 6.67 ms makes it possible to equalize the effective currents by phases.

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