МОНІТОРИНГ, ДІАГНОСТИКА ТА КЕРУВАННЯ ЕНЕРГЕТИЧНИМИ ПРОЦЕСАМИ ТА ОБЛАДНАННЯМ
MONITORING, DIAGNOSIS AND MANAGEMENT OF ENERGY PROCESSES AND EQUIPMENT

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OPTIMIZATION OF VOLTAGE CONVERTERS OF MATRIX AND INVERTER TYPES USING SIMULATION MODELLING

The paper presents the results of simulation modeling of functional capabilities of pulse converters of alternating voltage with free circulation of energy of two types: inverter type with intermediate link of pulsating voltage and matrix type with discharge of reactive load energy into the network. With the help of a software package OrCAD, the main modes of operation of these converters are investigated: lowering and increasing the output voltage relative to the input. The simulation results of each mode are presented in the form of diagrams of the control algorithm of the converter keys and diagrams of its electrical characteristics: input and output currents, voltage on the intermediate link (buffer capacitor) and output. On the basis of visual models for lowering and raising modes of work mathematical models and substitute electric schemes of the studied converters on intervals of their invariable structure are created. Simplified formulas for the approximate calculation of electrical parameters with sufficient accuracy for practice are proposed for both modes. Simulation models of the logic unit of the control system and the circuit of the power unit are presented separately for the three-phase matrix converter with energy reset and recovery. On the basis of visual models obtained with the help of the OrCAD software package, mathematical models and alternate electrical circuits of these converters at intervals of their constant structure were created. The conducted simulation allows to determine the most expedient areas of use of such converters and to perform optimization of their power circuits and control systems.

Keywords: reversible rectifier, buffer capacitor, matrix regulator, inverter regulator, simulation model, power switch, reactive power.

Introduction. Pulse modulation DC-DC converters (PMDCDCC) are used in almost all industries, usually as regulators (stabilizers) of consumer voltage and in some cases as adapters between the grid and consumers to ensure their compatibility [1-4]. Due to the spread of PMDCDCC, the efficiency of electricity consumption largely depends on their work. The quality of DC energy conversion is assessed by the harmonic composition of the output voltage and input current, the input power factor, as well as technical and economic indicators. These parameters can be increased by rational construction of transformer-key structures that form the basis of PMDCDCC, and the choice of the optimal algorithm for their management. Currently, the most promising are pulse modulation DC-DC converters with free circulation of energy between the network and the load, which can be built in several directions [5]: matrix type; matrix type with discharge of reactive power of loading in a power supply network; inverter type. As each direction has its advantages and disadvantages, the choice of the perfect structure of the converter is ambiguous and requires object-oriented analysis based on theoretical information and practical experience in the field of conversion technology. In order to optimise the power circuits and control systems of PMDCDCC, it is advisable to carry out their simulation to determine the configuration of equivalent interlocking circuits at intervals of constant structure and to create a mathematical model of the inverter, divided into several simple ones in time and space.

Purpose of work: create visual simulation models and analyse the main modes of operation of pulsed wide-range voltage regulators of two types: inverter with an intermediate link of pulsating voltage; matrix with the discharge of reactive energy load into the network.

Research material. The paper presents the results of simulation modelling of the power circuit and functionality of two different types of single-phase voltage converters, developed and provided for research by specialists of the Institute of Electrodynamics of NAS of Ukraine. The reliability of the simulation results is confirmed by laboratory and production tests of prototypes of these transducers. The simulation was performed using the OrCAD software package and consisted of three stages. The first stage is to test the functionality of the power circuit and control system. At this stage, the elements in the model circuit were simulated by components from the ANALOG libraries (ideal VS switches, capacitors C_1, C_2, inductors L_1, L_2, resistors); DIG_PRIM (real digital elements DD1 – DD5); BREAKOUT (diodes). Key management algorithms were formed from digital signals at the output of Digurlock SOURCE library sources. The second stage is the gradual approximation of the parameters of the model elements to the parameters of the real elements produced by the industry. The third stage is the analysis of possible modes of operation, including emergency.

Modelling and analysis of single-phase regulator-stabilizer of alternating voltage AC of inverter type with intermediate link of pulsating voltage.

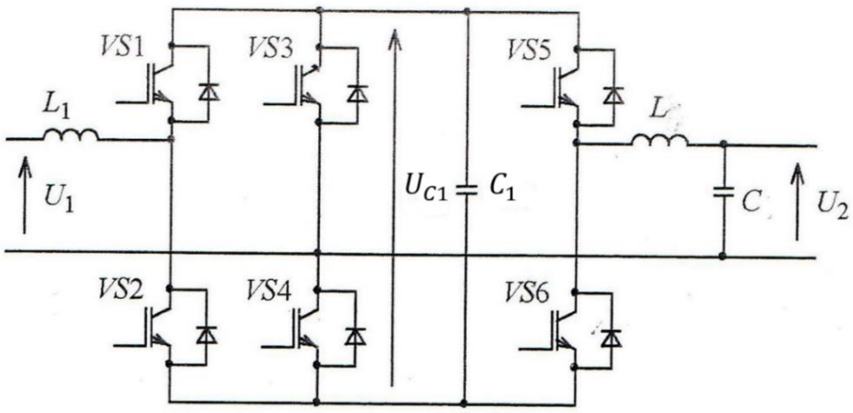


Figure 1 - Scheme of the inverter type regulator with a pulsating voltage link

The regulator in Fig.1 can work in two modes: lowering and increasing the output voltage U_2 relative to the input U_1. In the lowering mode, the keys of the reversible rectifier *VS1, VS2, VS3, VS4* are switched with the mains frequency, and the power switches of the half-bridge *VS5, VS6* - with the increased frequency; in step-up mode, switches VS1, VS2 are switched on alternately with increased frequency, and *VS3, VS4, VS5, VS6* - with network frequency. The intermediate link in the form of a buffer capacitor C_1 briefly absorbs the reactive energy of the load circuit or the input choke L_1, depending on the mode of operation.

Figure 2 shows a diagram of a simulation model of such a converter in the mode of voltage reduction, Fig. 3, Fig. 4 - simulation results.

Fig. 3 shows the plots i_1 and output i_2 currents; current i_{C1} and voltage u_{C1} of input of the buffer capacitor, as well as the voltage on the active load U_{R2}.

Fig. 4 shows diagrams of the key control algorithm VS5; pulsations of output i_2 and input i_1 currents, current and voltage u_{C1} of the buffer capacitor.

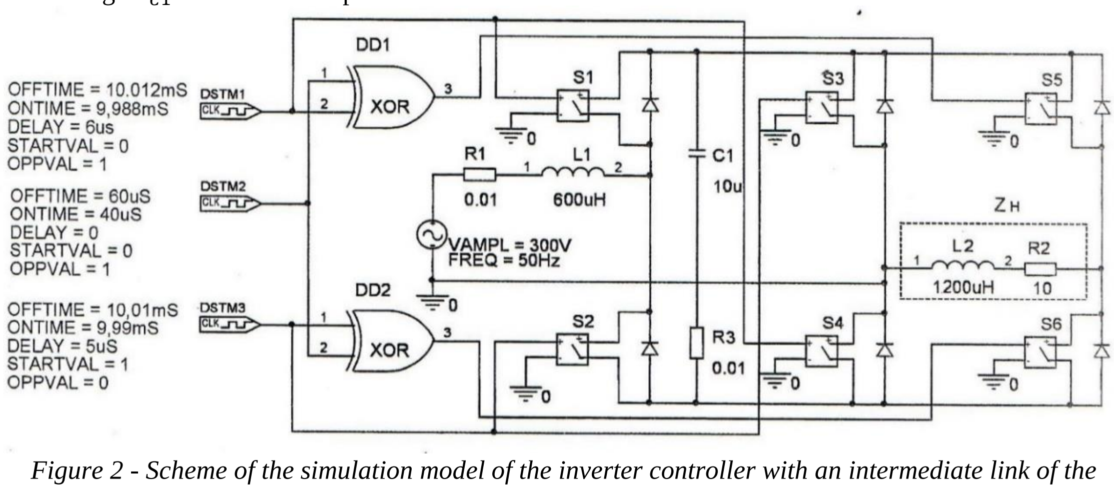


Figure 2 - Scheme of the simulation model of the inverter controller with an intermediate link of the pulsating voltage

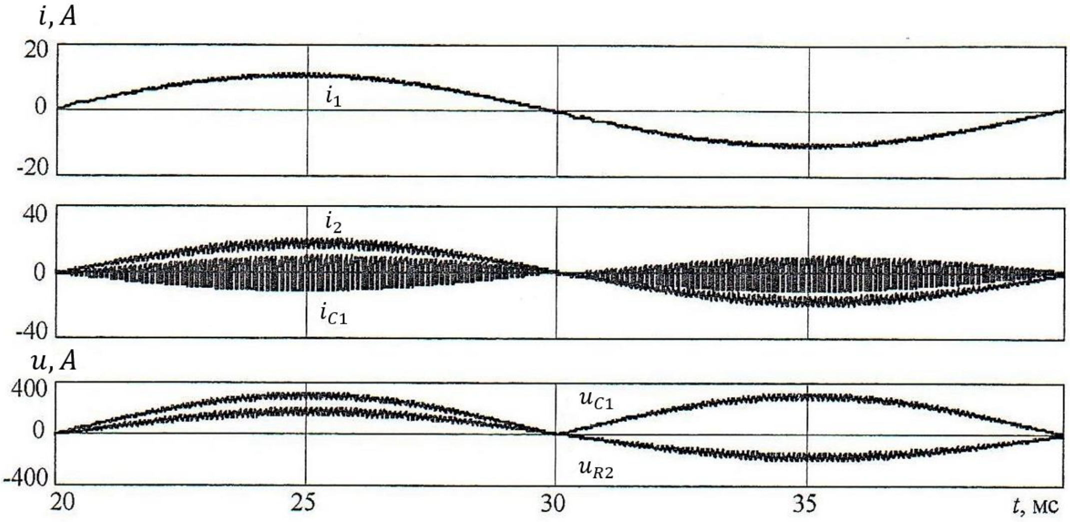


Figure 3 - Diagrams of currents and voltages of the inverter type regulator in the step-down mode

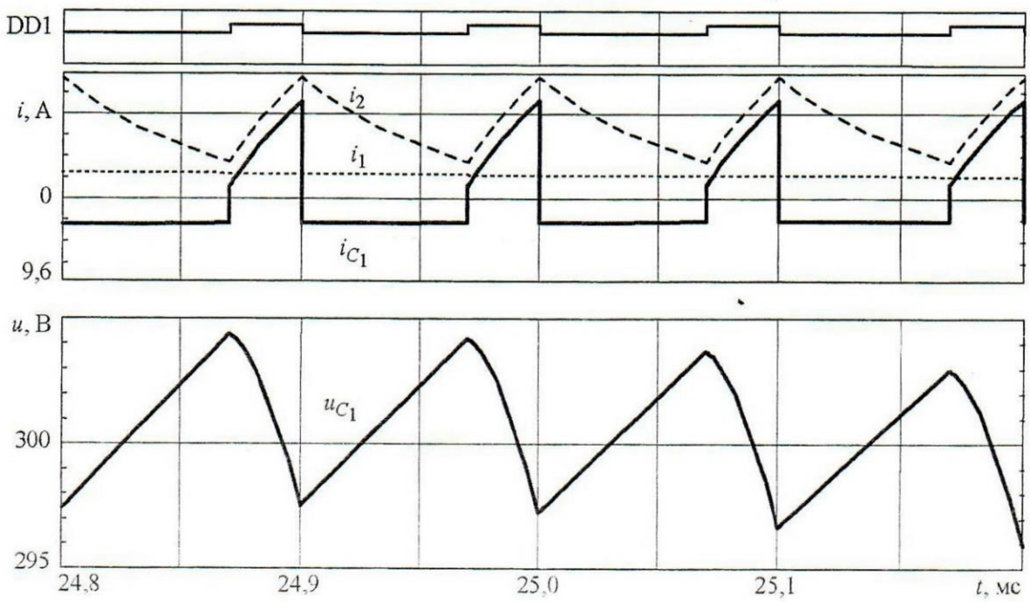


Figure 4 - Diagrams of the algorithm for controlling the key VS5 and ripple currents and voltages of the intermediate link of the inverter controller in the step-down mode

From the diagrams it follows that when the transistor VS5 is switched on, the output current i_2 is the sum of the input current i_1 and the capacitor current, the passage circuits of which are shown in Table T1 (interval 1). The capacitor C_1 of the intermediate link is discharged to the load, and a voltage pulse is formed at the output of the converter.

In the interval when the transistor VS5 is turned off, the buffer capacitor C_1 is charged by the current generated by the EMF of the network and the EMF of the induction choke L_1. The output of the converter is closed by a short open transistor *VS6*, and the output of the regulator is formed zero shelf (pause) in the output voltage (table T1 interval 2).

Table T1 shows the replacement circuits for the down-mode of operation of the regulator and the positive polarity of the mains voltage. Bold lines show the circuits with currents in the case of coincidence of current and mains voltage, thin - otherwise. As the polarity of the mains voltage changes, the substitution schemes become symmetric with respect to the tables.

Schemes of the simulation model of the inverter-type regulator in the modes of voltage increase and decrease differ only in that the algorithms for controlling the rectifier keys *VS1, VS2* and half-bridge keys *VS5, VS6* mutually change.

Table 1. The replacement circuits for the down-mode of operation of the regulator and the positive polarity of the mains voltage

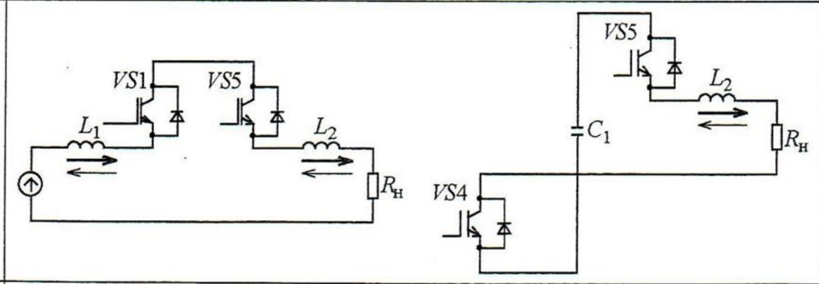
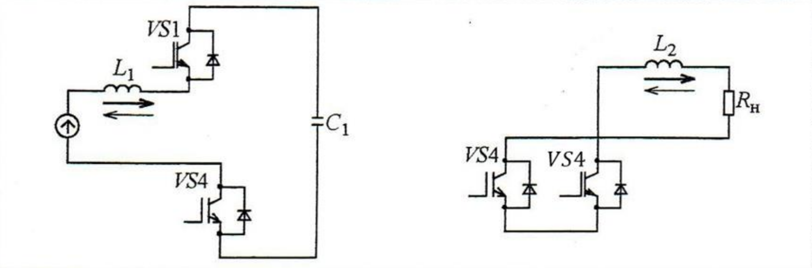
Interval	Substitute schemes
1	
2	

Fig. 5 shows the results of simulation of the converter in the ascending mode: diagrams of the algorithm of the key *VS1*, the ripple of the input current i_1, current i_{C1} and voltage u_{C1} of the buffer capacitor.

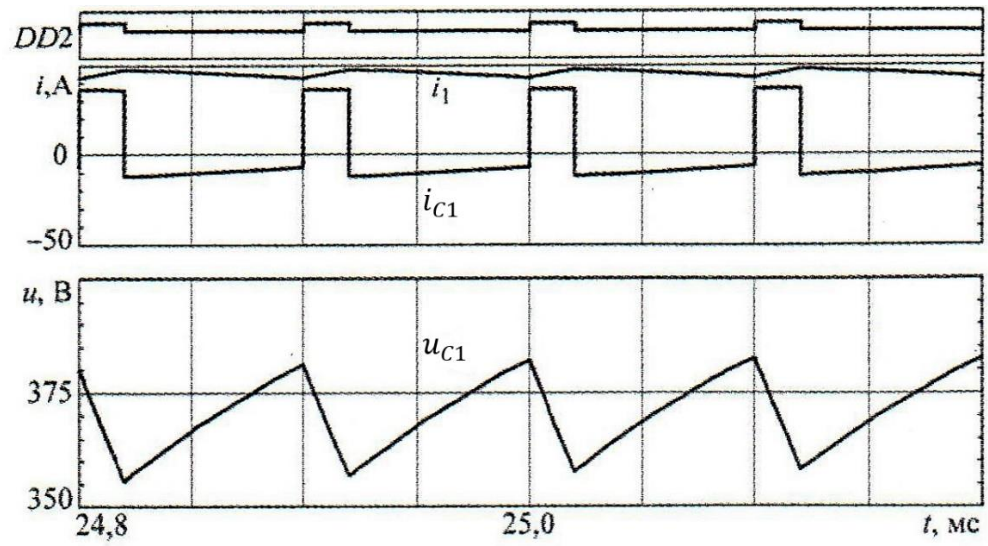


Figure 5 - Diagrams of the algorithm for the operation of the key VS2 and current and voltage ripples of the intermediate link of the inverter controller in the ascending mode

Table T2 shows the alternate circuits for the two intervals of the converter in the uplink mode with a positive polarity of the mains voltage. The first (working) interval starts with *VS2* on and *VS1* off. In this interval there is an accumulation of energy in the choke L_1 and the return of the buffer capacitor C_1 in the energy load, the accumulation of energy during the previous interval. In the second interval (*VS1* on, *VS2* off) the capacitor C_1 accumulates energy coming from two sources - mains and choke L_1. At both intervals, the output circuit $L_2 - R_H$ is connected to the buffer capacitor C_1, so the output voltage u_2 almost repeats the voltage u_{C1} (voltage drop on public switches is negligibly small).

With the help of diagrams and substitution diagrams, it is possible to calculate the characteristics and analyse in detail the electromagnetic processes in both modes of such a converter, using the method described in [6].

An approximate calculation sufficient for practice is possible according to formulas known from the theory of pulse-width control [5] and simplified by replacing the exponential sections of the curves with linear ones and taking into account the symmetry of pulsations relative to the amplitude of the fundamental harmonic curve.

Simplified formulas are summarized in table T3, where $t_{ВКЛ}$ - the duration of the working interval; τ - regulation period; $\gamma = t_{ВКЛ}/\tau$ - coefficient of filling of control pulses; $f_k = 1/\tau$ - frequency of regulation.

Table 2. The alternate circuits for the two intervals of the converter in the uplink mode with a positive polarity of the mains voltage

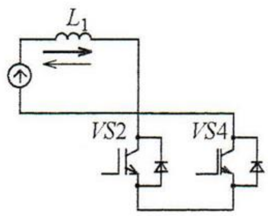
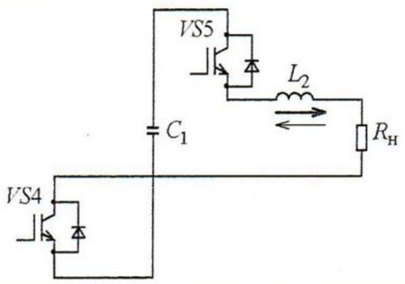
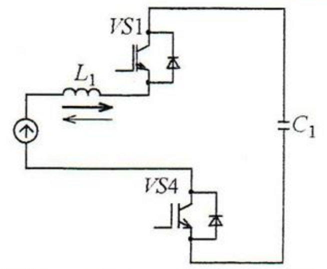
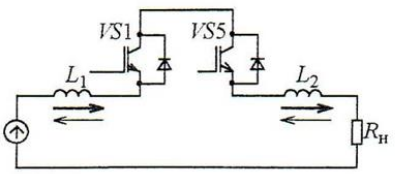
Interval	Substitute schemes	
1		
2		

Table 3. Simplified formulas

Inverter-type converter with pulsating voltage link	Down-mode	Ascending mode
The main harmonic of the output voltage	$U_2 = \gamma * U_1$	$U_2 = \frac{U_1}{1-\gamma}$
The main harmonic of the input current	$I_1 = \gamma * I_2$	$I_1 = \frac{I_2}{1-\gamma}$
The maximum range of voltage pulsations on the capacitor	$\Delta U_{C1max} = \frac{U_{1max} * \gamma^2 (1-\gamma)\tau}{R_H * C_1}$	$\Delta U_{C1max} = \frac{I_{2max} * \gamma}{f_k * C_1}$
Maximum amplitude of input current pulsations	$\Delta I_{1max} = \frac{\Delta U_{Cmax}}{2\pi f_k * L_1}$	$\Delta I_{1max} = U_{1max} * \gamma (f_k * L_1)$

Modelling and analysis of single-phase regulator-stabilizer of alternating voltage of matrix type with discharge of reactive load energy into the network (Fig. 6)

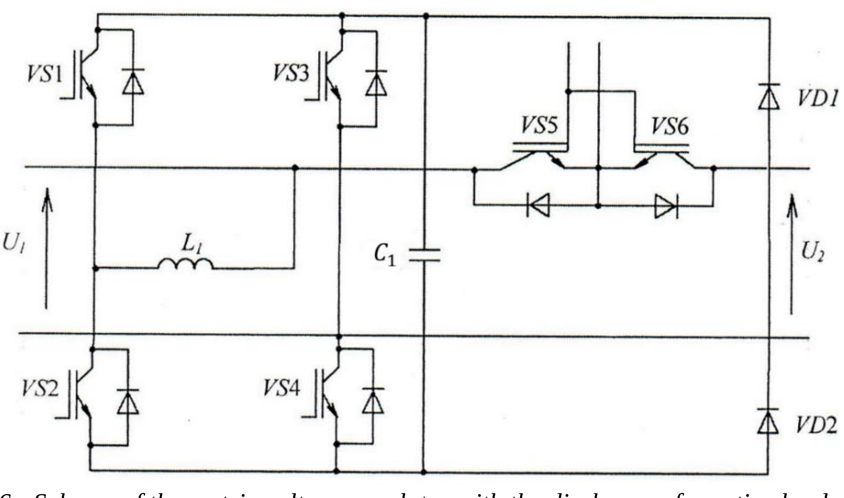


Figure 6 - Scheme of the matrix voltage regulator with the discharge of reactive load energy into the network

The composition of such a regulator includes: reversible rectifier on semi-controlled AC switches *VS1 - VS4*; buffer capacitor C_1; fully controlled power switch *VS5, VS6*; reverse diodes *VD1, VD2* to discharge the load energy into the capacitor and the mains; input choke L_1 to limit the current in the buffer capacitor when the regulator is turned on and possible voltage drops. The rectifier, in contrast to inverter regulators, conducts reactive load current in non-operating intervals (intervals of pauses in the output voltage). Longitudinal switches *VS5, VS6* conduct load current in working time intervals. Counter-series transistors of the longitudinal switches of the regulator have common clamps and the same control algorithm, which simplifies the control system.

Fig. 7 shows a diagram of the simulation model of this regulator; Fig.8 - the results of modelling when working on low-cosine load ($L_2 = 40$ мГн, $R_{\text{Н}} = 10$ Ом): diagrams of voltage on the buffer capacitor u_{C1}, voltage u_2 and current i_2 at the output of the converter. From the diagrams in Fig.8 it is seen that there is a time zone during which the load voltage is not regulated (zone of insensitivity to control). The appearance of the insensitivity zone is due to the fact that at this time the load current is shorted to the network bypassing the power switch through the transistors of the reverse rectifier and reverse diodes. The duration of the insensitivity zone depends on the magnitude of the phase shift angle of the load current relative to the mains voltage. Due to the presence of insensitivity zones, the control characteristic of this converter is non-linear, which does not affect its operational capabilities [7-8].

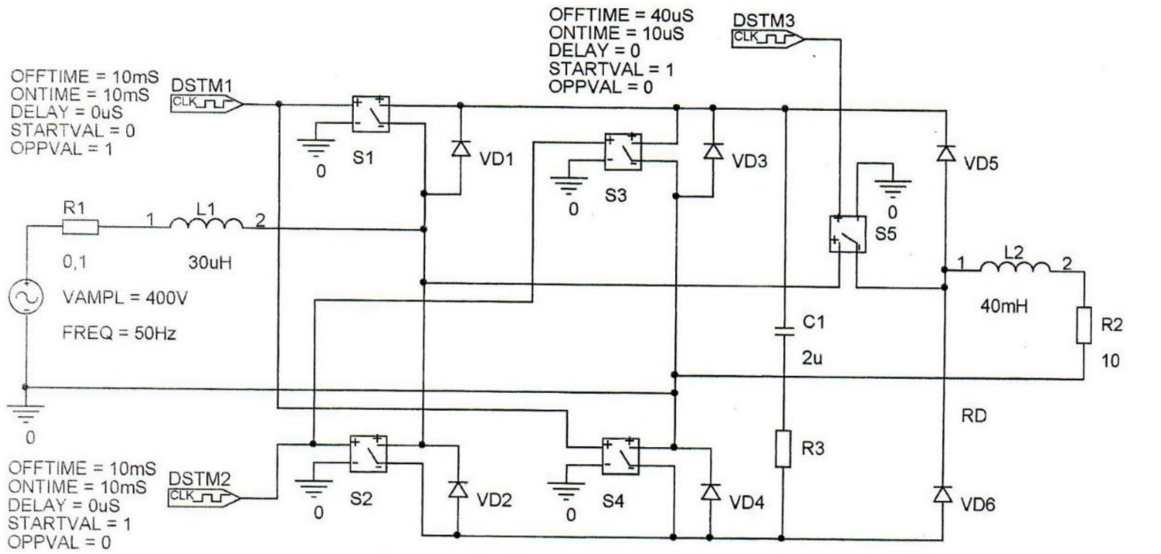


Figure 7 - Simulation model of a matrix controller with a discharge of reactive load energy into the network

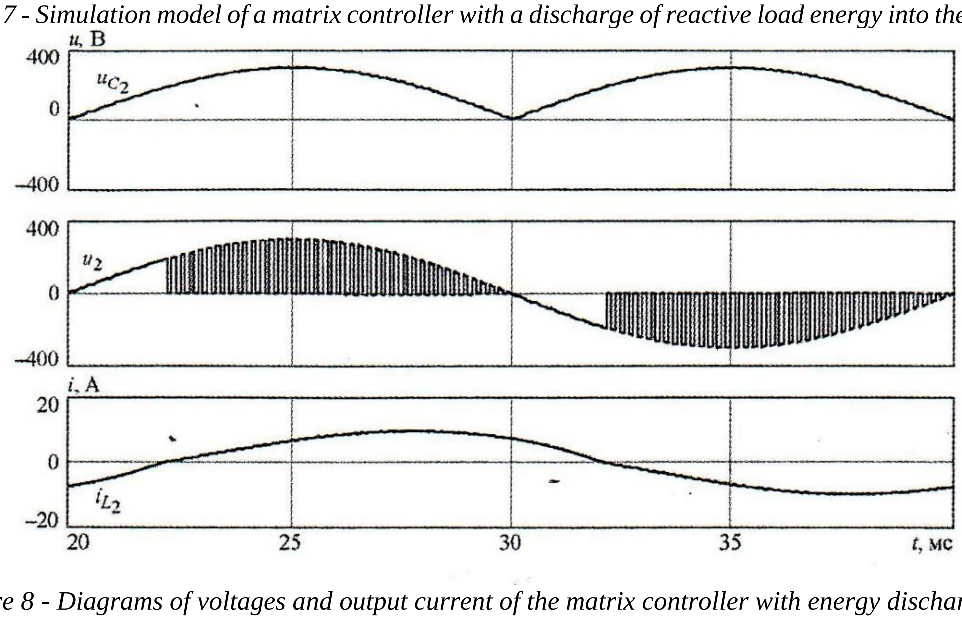


Figure 8 - Diagrams of voltages and output current of the matrix controller with energy discharge into the network

Fig. 9 shows diagrams of current pulsations in the power circuits of the regulator: input current i_1, reverse diode current i_{VD6}, output current i_2.

From the analysis of the regulator model its substitute schemes on switching intervals of invariant structure follow (table 4).

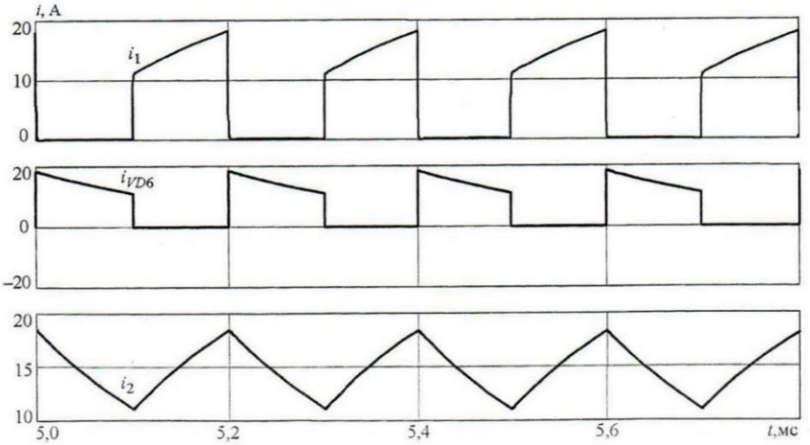
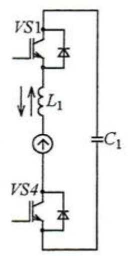
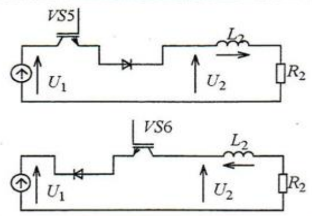
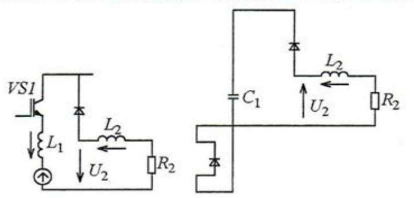
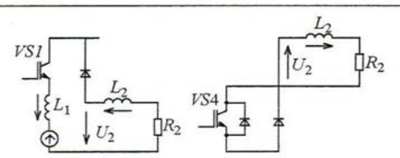


Figure 9 - Diagrams of current pulsation in a matrix controller with a discharge of energy into the network

T4 shows that at all switching intervals there is a charge-discharge circuit of the buffer capacitor C_1. The direction of current in this circuit does not depend on the state of the power switches *VS5, VS6,* and the voltage on the capacitor almost repeats the mains voltage in absolute value and phase. To limit the starting current, the initial charge current of the capacitor when the regulator is connected to the mains, the capacitance of the buffer capacitor C_1 is chosen to be minimal, assuming that the impedance of the circuit must be greater than the load impedance, i.e. $p = \sqrt{L_1/C_1} \geq Z_2$. Due to the small capacitance of the capacitor, the currents in the charge-discharge circuit of the capacitor are small, so this circuit has little effect on the course of electromagnetic processes in the regulator. The right part of table T4 shows other circuits that are formed at intervals of the constant structure of this converter with a positive polarity of the mains voltage. At the first operating interval, the load is connected to the network with power switches *VS5*, *VS6* and according to their state, the load current passes through either the upper or lower circuit. After switching off the power switches, two variants of electromagnetic processes are possible - with or without the second interval.

The second interval occurs only in the time zone where the direction of the load current does not coincide with the direction of the mains current, i.e. in the zone of insensitivity of the controller. Two circuits are formed in this zone: load energy recovery circuit into the network; buffer capacitor recharge circuit. Two options are also possible in the third interval. If the direction of the load current does not coincide with the direction of the mains voltage, the recovery circuit remains; if it coincides, a short-circuit of the load short circuit is formed, which ensures the formation of a zero shelf in the output voltage and control of this voltage.

Table 4. Substitute schemes on switching intervals of invariant structure

Interval	Substitute schemes	
1		
2		
3		

Simplified calculation formulas for the regulator with the discharge of energy into the network are as follows: basic harmonics of output voltage $U_2 = \gamma * U_1$, input $I_1 = \gamma * I_2$ and output $I_2 = \gamma * U_1/Z_2$ currents, maximum amplitude of output current $\Delta I_{2max} = \frac{U_{1max}}{R_2}\left[1 - exp\left(-\frac{R_2*\gamma}{f_K*L_2}\right)\right]$.

These formulas can be used in the presence of a filter capacitor at the output of the regulator, because the optimally selected filter capacitor has almost no effect on the value and shape of the output current of the regulator. The output voltage, on the contrary, significantly depends on the capacitance of the filter capacitor. The harmonic coefficient of the output voltage is the starting point when choosing all the parameters of the regulator [9, 10].

In three-phase AC voltage regulators instead of power switches built on counter-series transistors with reverse diodes, it is advisable to use bridge diode-transistor switches, both longitudinal and transverse.

Fig. 10 shows a diagram of a three-phase matrix converter with reset and energy recovery, built on the power bridge longitudinal key VS7. When the key VS7 is closed, the load L2, R2 is connected to the network and there is an accumulation of energy in it; when VS7 is switched off, the load is switched on the clamp of the buffer capacitor C2 and the reversing rectifier VS1-VS6. The energy accumulated in the load through the diodes of the bridge key VS7 and cut-off diodes reset VD1, VD2 enters the buffer capacitor C2, and from there to the network through the transistors VS1-VS6 reversing rectifier. Buffer capacitor C2 performs protective functions of the "snubber"; cut-off diodes VD1, VD2 prevent short circuit of capacitor C2.

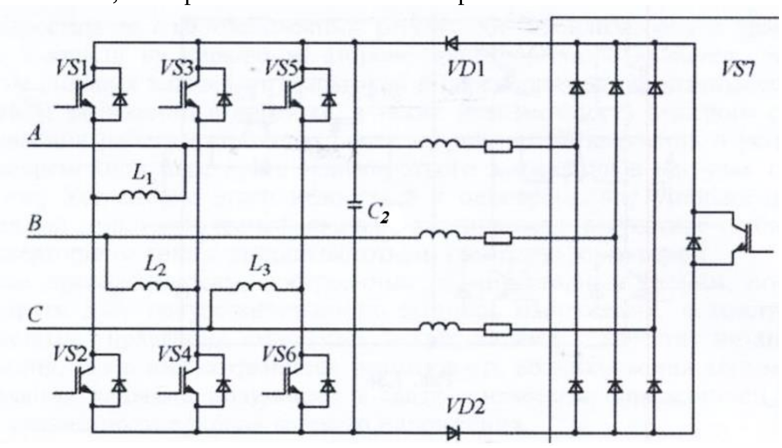


Figure 10 - Scheme of a three-phase voltage regulator with energy discharge into the network

Fig. 11 shows a simulation model of the logic unit of the control system, which forms the algorithms for cyclic switching of transistors VS1-VS7, necessary to create a direct connection of the buffer capacitor C2 with the network without the risk of short circuit.

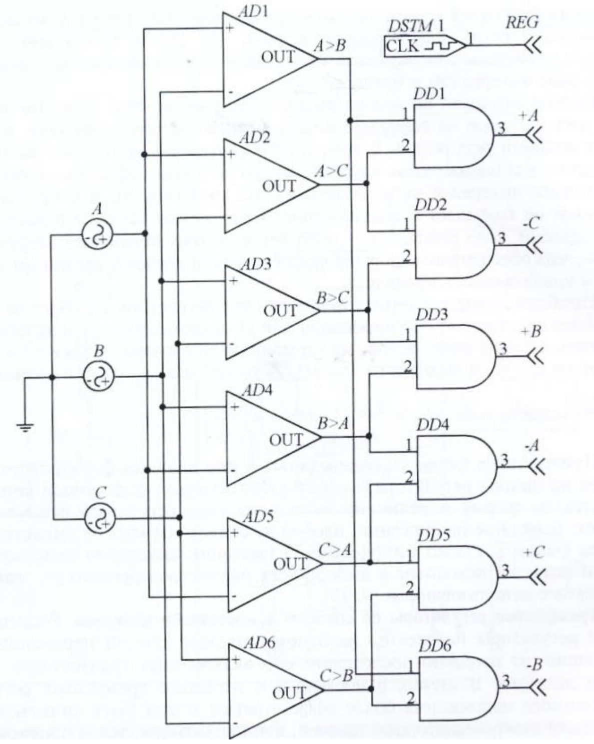


Figure 11 - Simulation model of the logic unit of the converter control system in Fig.10

Fig. 12 shows a simulation model of the power part of this converter, Fig. 13 - the results of modelling his work: diagrams of the algorithm of the control system, pulsating voltage on the buffer capacitor with the designation of individual sections; phase voltage Ua on the load.

From the diagrams in Fig. 13 it follows that the output voltage pulses Ua during the period are evenly distributed within the bypass, which repeats the voltage of phase A of the network, currents and voltages are symmetrical about the time axis. Consequently, the above regulator has a linear regulation characteristic, has a simple power section and provides the required output voltage quality and performance characteristics.

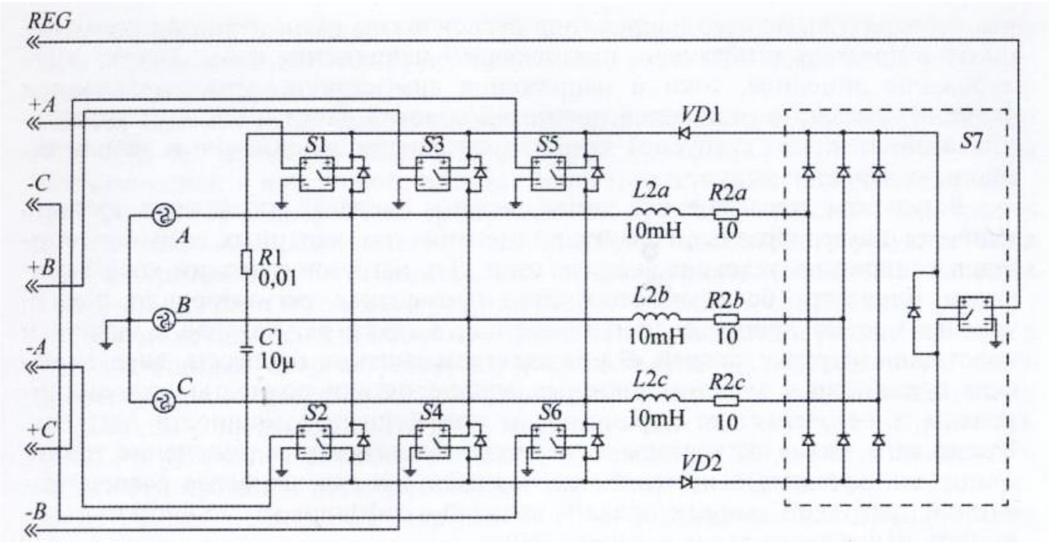


Figure 12 - Simulation model of the power part of the voltage regulator in Fig.10

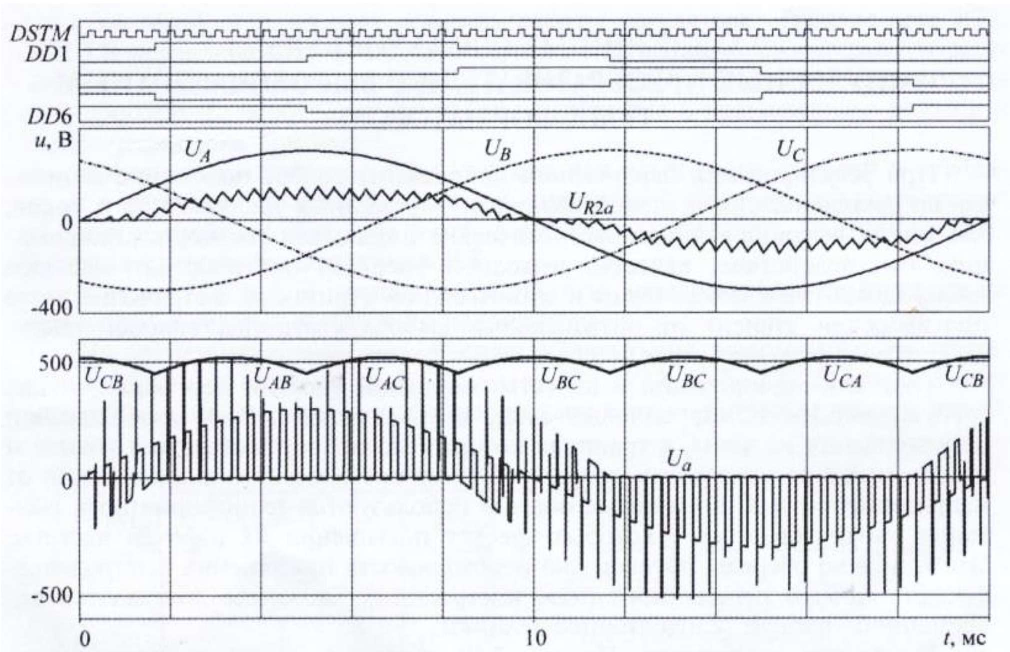


Figure 13 - The results of modelling the voltage regulator in Fig. 13

Conclusions. The results of research of simulation models allow identify the most appropriate areas of use of certain schemes of regulators in specific operating conditions. Thus, the inverter-type AC voltage regulator-stabilizer circuit with intermediate pulsating voltage link (Fig. 1) is the most optimal for the construction of high-efficiency wide-range dual-band voltage converters, uninterruptible units and universal general purpose sources. However, the construction of three-phase converters of this type directly from single-phase is unjustified due to the complexity of the circuit and the presence of high-frequency switches, the simultaneous inclusion of which can cause an internal short circuit in the device.

The scheme of the matrix controller with the discharge of reactive power load into the network (Fig. 6) is simple and reliable due to the lack of high-frequency switches, so it is optimal for building both single-phase and multiphase wide-range regulators and limiters of AC and voltage in the middle and especially low power. In converters of this type, electromagnetic processes, energy performance and operational characteristics are completely determined and do not depend on the parameters and power factor of the load. In addition, such regulators provide intensive braking of induction motors (the most common load for them).

Converters of both types have reversible rectifiers, which allows you to adjust the input power factor [3].

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ОПТИМІЗАЦІЯ ПЕРЕТВОРЮВАЧІВ НАПРУГИ МАТРИЧНОГО ТА ІНВЕРТОРНОГО ТИПУ ШЛЯХОМ ІМІТАЦІЙНОГО МОДЕЛЮВАННЯ

Викладено результати імітаційного моделювання функціональних можливостей імпульсних перетворювачів змінної напруги з вільною циркуляцією енергії двох типів: інверторного типу з проміжною ланкою пульсуючої напруги і матричного типу зі скидом реактивної потужності у мережу. За допомогою пакету програм OrCAD досліджені основні режими роботи вказаних перетворювачів: пониження і підвищення вихідної напруги відносно вхідної. Результати моделювання кожного режиму подано у вигляді епюр алгоритму управління ключами перетворювача і епюр його електричних характеристик: вхідного та вихідного струмів, напруги на проміжній ланці (буферному конденсаторі) і на виході. На основі візуальних моделей для понижувального і підвищувального режимів роботи створено математичні моделі та заступні електричні схеми досліджуваних перетворювачів на інтервалах їх незмінної структури. Для обох режимів запропоновано спрощені формули наближеного розрахунку електричних параметрів з достатньою для практики точністю. Для трифазного матричного перетворювача зі скидом і рекуперацією енергії окремо представлено імітаційні моделі логічного блоку системи управління і схеми силової частини. На основі візуальних моделей, отриманих за допомогою пакету програм OrCAD, створено математичні моделі та заступні електричні схеми вказаних перетворювачів на інтервалах їх незмінної структури. Проведене імітайне моделювання дозволяє визначити найбільш доцільні області використання таких перетворювачів і виконати оптимізацію їх силових схем і систем управління.

Ключові слова: *реверсивний випрямляч, буферний конденсатор, матричний регулятор, інверторний регулятор, імітаційна модель, силовий ключ, реактивна енергія.*

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