

# Research of modular multilevel converter with phase-shifted pulse-width modulation

Ihor Kozakevych<sup>1,\*</sup>, and Roman Siyanko<sup>1</sup>

<sup>1</sup>Kryvyi Rih National University, Automatic Electromechanical Systems in Industry and Vehicles Department, 11 Vitalii Matusevych Str., 50027, Kryvyi Rih, Ukraine

**Abstract.** The work is devoted to the study of performance of a multilevel electric energy converter using phase-shifted pulse-width modulation. Equations describing the state of a dynamic system multilevel converter - load are investigated and a mathematical model of the system in Matlab / Simulink environment has been constructed. Variants of implementation of phase-shifted pulse-width modulation systems from the point of view of influence on harmonics of output voltage and magnitude of circulating current in the converter are investigated.

## 1 Introduction

The introduction of an adjustable frequency electric drive for low-voltage AC motors over the last decade has proven to be an effective method of improving energy efficiency in industry and utilities [1–3]. The uncontrolled rectifier- voltage-source inverter circuit has become a kind of industry standard for low- and medium-power AC drives [4]. However, high-power electric drives using medium-voltage motors also have significant energy saving potential. There is no single approach to the construction of power converters of such systems [5]. Another area of use of high-power converters is distributed generation systems, which provide for the integration of renewable energy sources into power supply systems. Therefore, the development of means of converting electricity in systems with a medium level of rated voltage is an important area.

Cases of using direct converters in systems with a medium level of rated voltage are isolated, specific industrial models that are mass-produced are absent [6], and therefore it is advisable to focus on converters with intermediate DC link, which, in turn, are divided into converters based on voltage-source inverters and converters based on current-source inverter depending on the configuration of passive elements of the DC link. The advantage of converters based on current-source inverters is the ability for the electric drive to work in four quadrants without the use of additional hardware or software. However, their main parts must have a controlled rectifier, which leads to an increase in reactive power consumption levels. In addition, this type of converter is able to switch the inverter switches only when operating on active-capacitive load, and therefore its use without additional capacitive elements is possible only when used as a motor synchronous motor with excitation that is greater than the rated one. Therefore, more

promising now is the use of circuits based on voltage-source inverters [7 – 9]. These circuits, in turn, are divided into two-level converters and multilevel converters. However, due to the fact that the operation of a two-level converter in a system with a medium level of rated voltage will lead to significant values of  $du / dt$ , their use in this case is not possible [10]. The use of multi-level converters allows to reduce the  $du / dt$ , as well as the total harmonic distortion ratio (THD), which reduces the size of the filters on the AC side [11]. Multi-level converters based on a circuit with cascaded H-bridges, circuits with "flying" capacitors, with a diode-clamped converters and modular multi-level converters are currently being mass-produced [12]. In addition, scientists are constantly developing new schemes that are certain combinations of existing options. The main disadvantage of the circuit with cascaded H-bridges [13] is the need to use a phase-shift transformer to obtain several galvanically isolated DC sources. The disadvantages of circuits with "flying" capacitors and clamped diodes are the difficulty of balancing the voltages on the capacitor dividers. The scheme of a modular multilevel converter does not require a complex transformer, and therefore its use is more appropriate for reasons of economy and reliability.

## 2 Analysis of the modular multilevel inverter and mathematical dependences describing its state

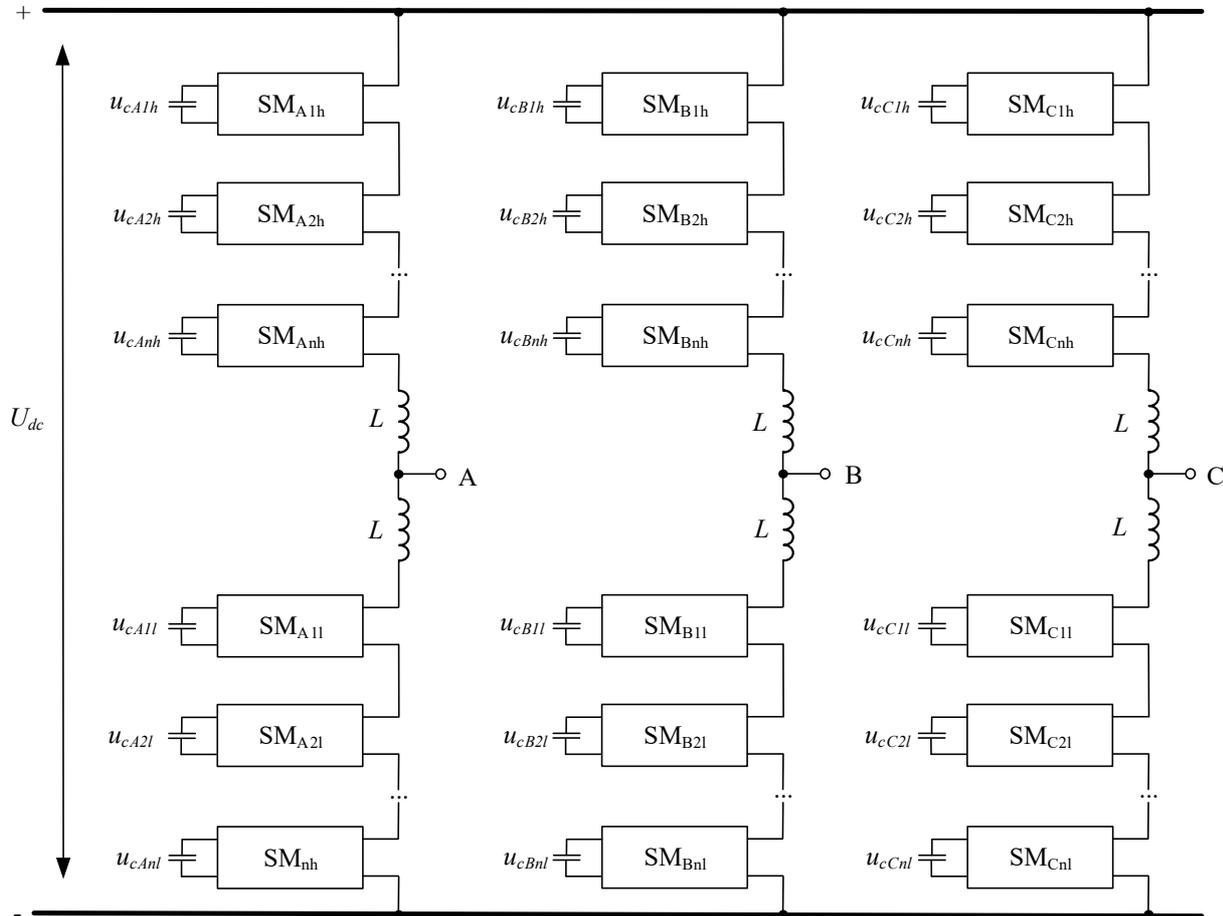
The generalized structure of the modular multilevel inverter is shown in fig. 1. It consists of three legs designed to power the load phases and connected to a common DC link. A three-phase symmetrical load is connected to the midpoints of the inverter legs through an inductor L.

Each arm consists of a number of semiconductor (SM) cells connected in series. Inductors L are designed to limit

\* Corresponding author: [aepigor@gmail.com](mailto:aepigor@gmail.com)

the intensity of the current rise in the circuit on the DC and AC side, as well as to compensate for the difference between phase voltage and voltage in the DC link caused by voltage changes on cell capacitors or other reasons. However, the active component of the resistance of these inductors leads to an increase in the overall level of losses in the converter. A significant advantage of such a circuit

is the ability to build it using the same type of circuit modules, which provides the ability to replace them quickly in case of failure of semiconductor elements. In this case, there are a significant number of options for constructing circuits of individual cells, which allows you to modify the general characteristics of the converters and the number of output voltage levels.



**Fig. 1.** The structure of a modular multilevel converter.

The most popular is the scheme of half-bridge modules, which is shown in Fig. 2a. It contains two switches operating in inverse mode and provides two levels of output voltage - zero voltage and a voltage equal to the voltage on the capacitor  $u_c$ . This scheme is able to provide a low level of energy loss and high reliability. The use of more complex schemes of converter modules is explained by the need and expediency to have more levels of output voltage, which reduces the total number of semiconductor elements used and the overall dimensions of the modular multilevel converter. As such modules their full-bridge variant which is shown in fig. 2b. This scheme allows to obtain a bipolar output voltage, which is useful both in terms of increasing the flexibility of voltage balancing on capacitors, and in terms of the possibility of reducing the magnitude of the emergency current. The use of circuits with a fixed zero point (Fig. 2c) and with "flying" capacitors (Fig. 2d) allows to significantly expand the number of switching states, and therefore requires more complex control methods with the ability to maintain voltage balance on capacitors.

Consider the equivalent scheme of one phase of a modular multilevel inverter (Fig. 3). The voltage in the DC link is divided into two sources with voltages of  $\frac{1}{2}U_{dc}$  to obtain an artificial zero point. The output voltage of phase  $j$  is denoted by  $u_{jout}$ , and the output current is denoted by  $i_{jout}$  ( $j \in \{a, b, c\}$ ). In the upper and lower arms, switching of the semiconductor switches of the modules leads to the sequential turning-on of a certain number of capacitors and the emergence of voltages  $u_{jh}$  and  $u_{jl}$ , respectively. The currents  $i_{jh}$  and  $i_{jl}$ , respectively, flow in the upper and lower arms.

Using Kirchhoff's second law for the contour of the upper and lower arms, the following equations can be obtained:

$$\frac{1}{2}U_{dc} - u_{jh} - u_{jout} = i_{jh}R + L \frac{di_{jh}}{dt}; \quad (1)$$

$$\frac{1}{2}U_{dc} - u_{jl} + u_{jout} = i_{jl}R + L \frac{di_{jl}}{dt}. \quad (2)$$

As a rule, in order to reduce the overall dimensions of inductive elements, conditions are created for the occurrence of mutual inductance between them. If we

denote the mutual inductance of inductive elements  $M$ , then equations (1), (2) can be written as:

$$\frac{1}{2}U_{dc} - u_{jh} - u_{jout} = i_{jh}R + L \frac{di_{jh}}{dt} + M \frac{di_{jl}}{dt}; \quad (3)$$

$$\frac{1}{2}U_{dc} - u_{jl} + u_{jout} = i_{jl}R + L \frac{di_{jl}}{dt} + M \frac{di_{jh}}{dt}. \quad (4)$$

The voltage on the inductive elements of the inverter's leg can be determined as follows:

$$u_{jL} = L \frac{di_{jh}}{dt} + M \frac{di_{jl}}{dt} + L \frac{di_{jh}}{dt} + M \frac{di_{jh}}{dt}. \quad (5)$$

With a unit coefficient of mutual inductance  $L = M$ , then:

$$u_{jL} = 4L \frac{di_{jc}}{dt} = U_{dc} - u_{jh} - u_{jl}, \quad (6)$$

where  $i_{jc}$  – the circulating current of the converter's arm that feeds the load phase  $j$  and flows in the upper and lower converter's arms, which can be defined as:

$$i_{jc} = \frac{1}{2}(i_{jh} + i_{jl}). \quad (7)$$

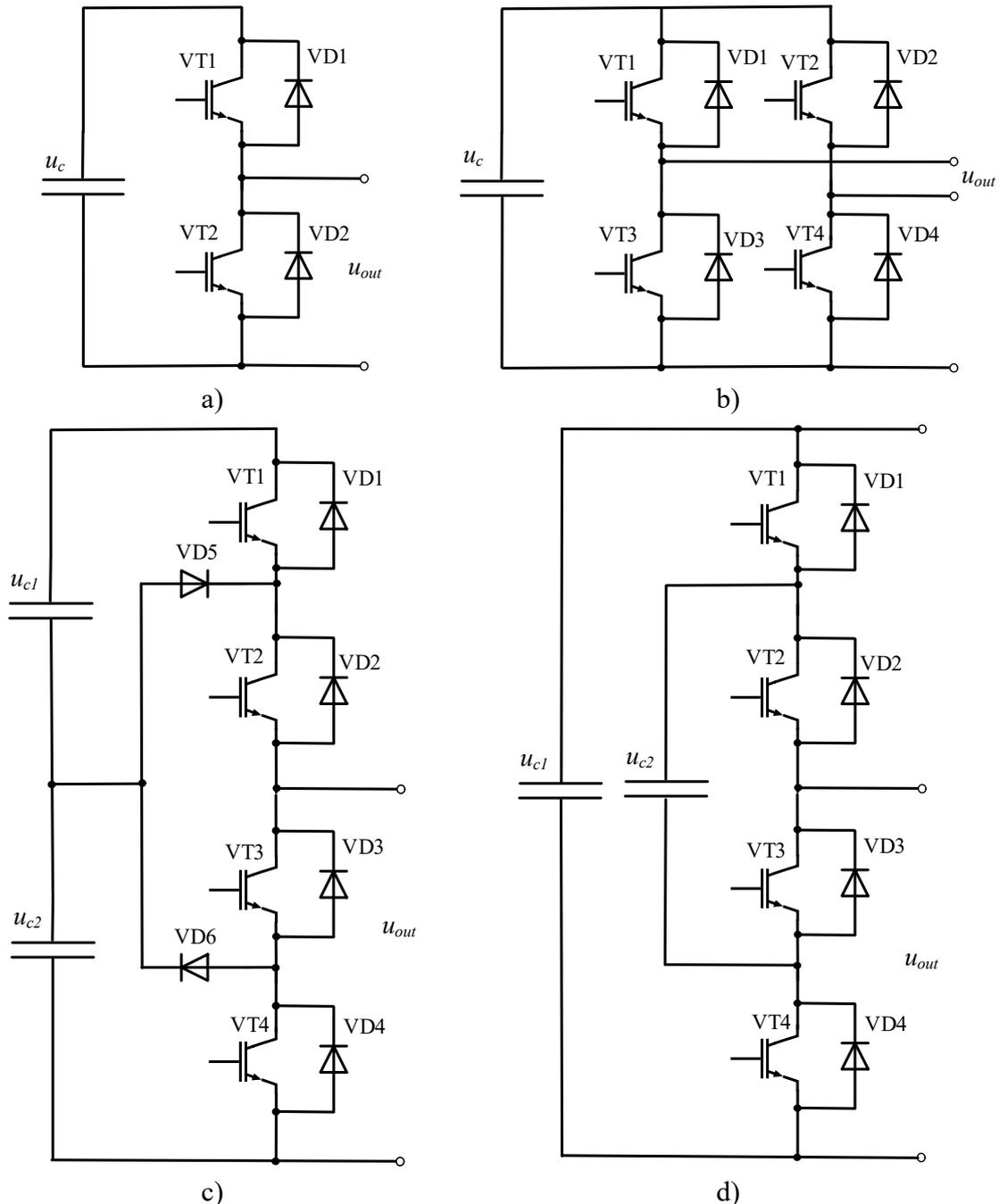
Ideally, the phase load current  $i_{jout}$  is divided equally between the upper and lower arms, then the arm currents can be defined as follows:

$$i_{jh} = \frac{1}{2}i_{jout} + i_{jc}. \quad (8)$$

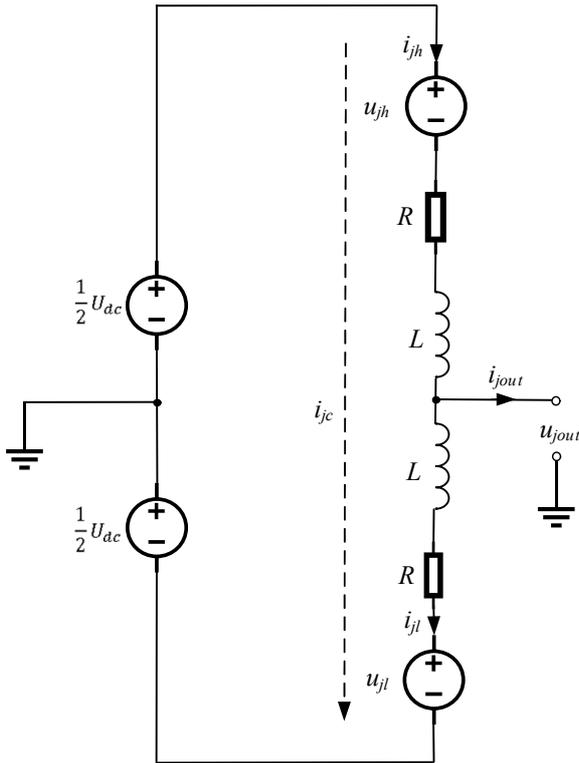
$$i_{jl} = \frac{1}{2}i_{jout} - i_{jc}. \quad (9)$$

The output voltage of the converter through the voltages of the upper and lower arms of the previously obtained dependences can be expressed as:

$$u_{jout} = \frac{1}{2}(u_{jl} - u_{jh}). \quad (10)$$



**Fig. 2.** Some cell diagrams that are suitable for use in a modular multi-level converter circuit.



**Fig. 3.** Equivalent scheme of one leg of the converter.

From equation (6) the circulating current of the converter can be determined as follows:

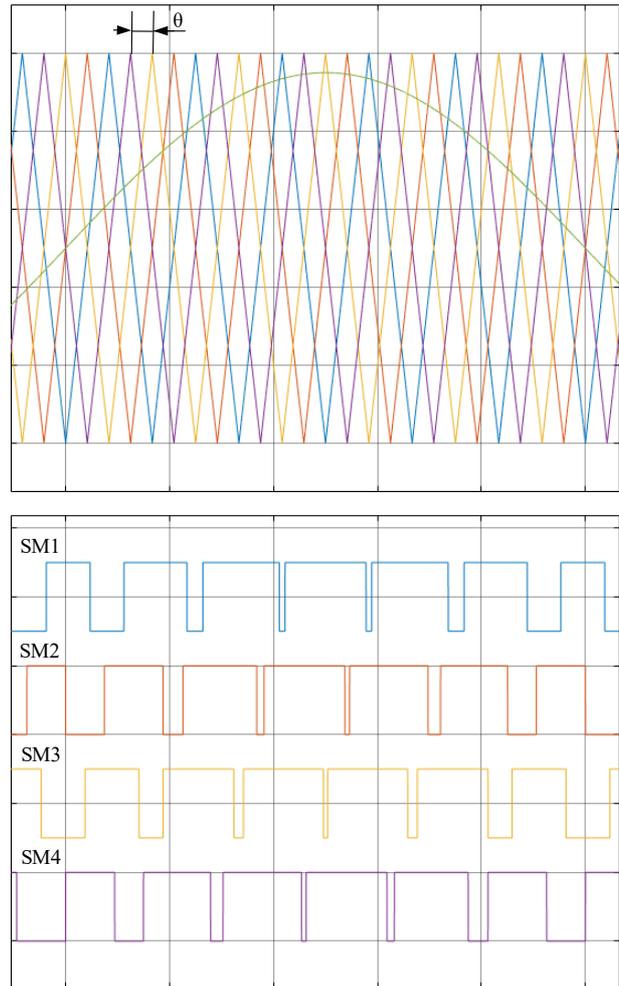
$$i_{jc} = \frac{1}{4L} \int_0^t u_{jl} dt + I_{jcDC}, \quad (11)$$

where  $I_{jcDC}$  is a constant component of the circulating current.

### 3 Phase-shifted pulse-width modulation

The principle of pulse-width modulation with phase shift of the carrier signals is presented in Fig. 4. To obtain the switching signals of the switches of the converter modules containing  $N$  modules in one arm,  $N$  phase-shifted triangular carrier signals are generated to control the upper half of the circuit and  $N$  the same signals to control the switches of the lower half of the circuit. The frequency of the triangular signal carriers is selected depending on the required switching frequency of the semiconductor elements. Subsequently, the sinusoidal reference signal of each phase is compared with a number of triangular carrier signals and the corresponding control signals of the circuit switches are obtained. To improve the coefficient of total harmonic distortion between the triangular carrier signals, a phase shift of  $\theta = 2\pi / N$  is set. Thus, it is expedient to investigate the influence of the magnitude of this shift on the performance of a modular multilevel converter.

A mathematical model in Matlab / Simulink environment has been developed to study the influence of the carrier shift angle on the operation of a modular multilevel converter. The parameters of the simulated converter are given in Table. 1.



**Fig. 4.** The principle of phase-shifted pulse-width modulation.

**Table 1.** The parameters of the simulated converter

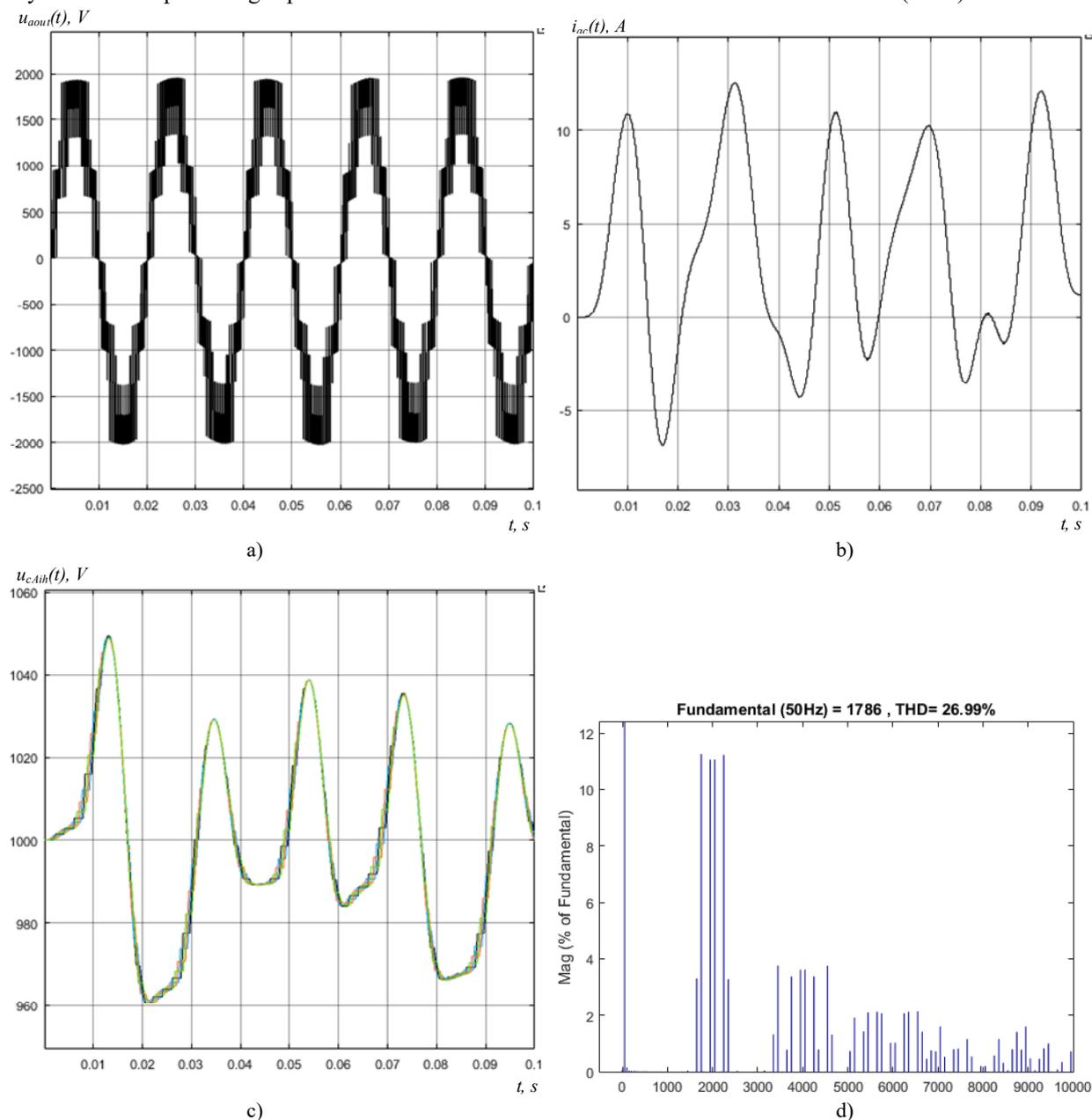
Parameter name	Parameter value
Number of converter modules per arm	4
The scheme of the module of the converter	half-bridge
Voltage in the DC link $U_{dc}$	4000 V
The capacitor capacity of each converter module	750 $\mu$ F
The inductance of the arm of the converter	0.02 H
Modulation factor	0.9
Frequency of carrier signals	500 Hz
The frequency of the reference signal	50 Hz
Active load resistance	85 Ohm
Load inductance	0.167 H

Fig. 5 represents the simulation results of a modular multilevel inverter with a shift of carrier signals by  $\theta = 2\pi / N$ . The shape of the output voltage (Fig. 5a) has a clearly visible number of levels, which corresponds to the number of modules in each arm of the converter, circulating current (Fig. 5b) has a frequency, which corresponds to the frequency of the output voltage of the converter, and its root mean square value for this case is 6.157 A. A positive property of this method of modulation is the ability to balance voltages on capacitors (Fig. 5c) without the use of additional hardware or software. The

\* Corresponding author: aepigor@gmail.com

amplitude of voltage ripple on the capacitors in steady state does not exceed  $\pm 40$  V, which is quite satisfactory. Analysis of the output voltage spectrum of the converter

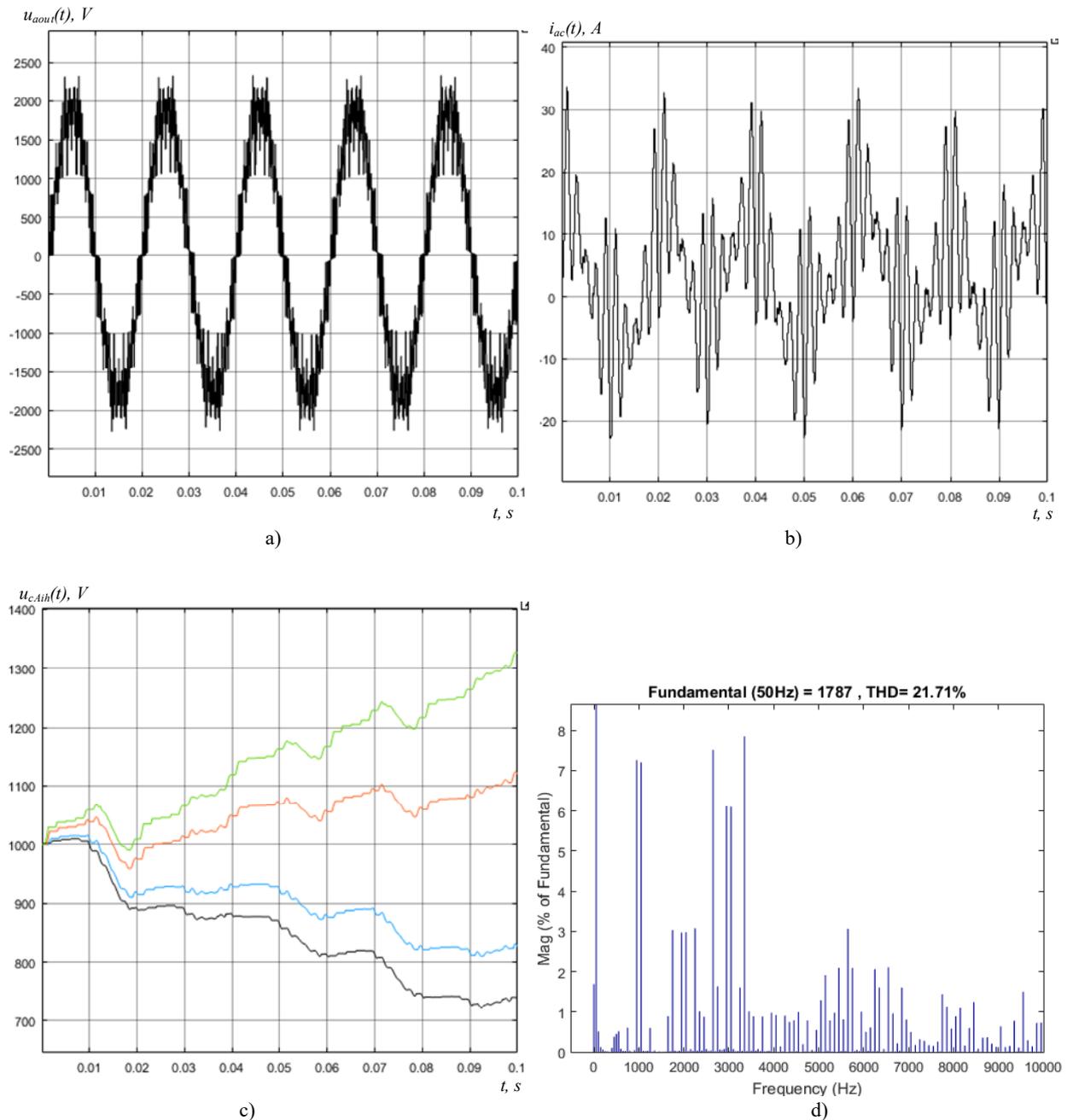
(Fig. 5d) shows the presence of significant harmonic components in the vicinity of 2000 Hz, and the total coefficient of nonlinear distortion (THD) was 26.99%.



**Fig. 5.** The results of modeling the operation of a modular multilevel converter when the carrier signals are shifted by  $2\pi / N$ : a – change in the output voltage of the converter; b – change in the magnitude of the circulating current; c – voltage change on the capacitors of the upper arm of the circuit; d – the spectrum of the output voltage of the converter.

Fig. 6 represents the results of modeling a modular multilevel inverter when reducing the values of the shift of the carrier signals to the level of 2/3 of the previous case. The graph of the output voltage (Fig. 6a) shows a visually greater sinusoidality than in the previous case. The frequency of pulsations of the circulating current (Fig. 6b) has become much higher than the frequency of the output voltage of the converter, although the fundamental harmonic, which corresponds to the frequency of the output voltage, is visually noticeable. However, the rms value of the circulating current increases almost twice to 11.8 A, which leads to an increase in losses in the converter. Another significant disadvantage of this method of modulation is the loss of

the ability to balance the voltages on the capacitors of the modules (Fig. 6c), which during observation (0.1 s) are significantly unbalanced, which allows us to conclude that such a system is unsuitable for practical implementation without developing additional measures to reduce imbalance voltage. The positive effect of using such a system is the reduction of the total harmonic distortion to 21.71%, which confirms the previously described conclusions about the greater sinusoidality of output voltage of the converter. Therefore, in the future it is advisable to perform a search for the shift angle, which minimizes the coefficient of total harmonic distortion without losing the ability to self-balance the voltages on the capacitors of the modules.



**Fig. 6.** The results of modeling the operation of a modular multilevel converter when the carrier signals are shifted by  $4\pi / 3N$ : a – change in the output voltage of the converter; b – change in the magnitude of the circulating current; c – voltage change on the capacitors of the upper arm of the circuit; d – the spectrum of the output voltage of the converter.

Fig. 7 represents the results of modeling a modular multilevel inverter when reducing the values of the shift of the carrier signals to the level of  $1/2$  from the previous case. The graph of the output voltage (Fig. 7a) visually shows even greater sinusoidality than in the previous case, the presence of individual discrete voltage levels is almost invisible. The nature of the pulsations of the circulating current (Fig. 7b) corresponds to the previous case, but the current value increases significantly to the level of 19.52 A. The ability to balance voltages on capacitor modules is lost (Fig. 7c), as in the previous case, showing a significant difference with time. The coefficient of total harmonic distortions of the output voltage (Fig. 7d) remains lower than when using modulation with a shift of  $\theta = 2\pi / N$ , and is equal to 21.81%. In the demonstrated

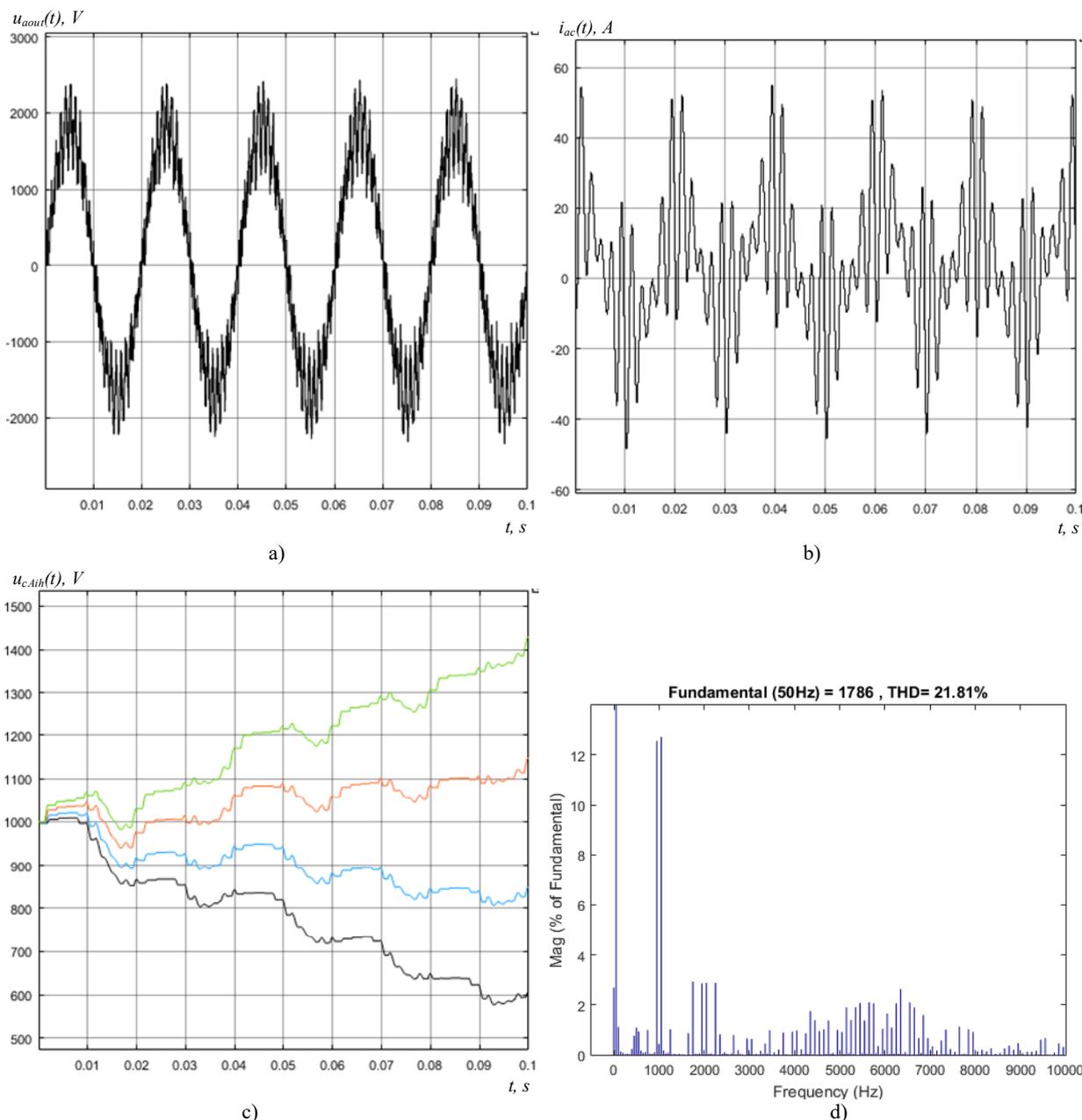
spectrum, harmonic components with a frequency equal to twice the switching frequency of the converter's switches are clearly distinguished, which are lower frequency compared to the dominant harmonic components of the previous cases, and therefore easily eliminated from the output current due to load inductance.

Let's analyze the operation of a modular multilevel inverter using pulse-width modulation with in-phase carrier signals, i.e. in the absence of phase shifts between them. The results of modeling such a system are presented in Fig. 8. The output voltage graph (Fig. 8a) shows a significant decrease in output voltage levels, which is a negative phenomenon, because in this case it is necessary to use more cumbersome passive output filters to bring the output voltage in line with current standards. The current

\* Corresponding author: [aepigor@gmail.com](mailto:aepigor@gmail.com)

value of the circulating current (Fig. 8b) almost corresponds to the previous case and is 19.36 A, which leads to the need to increase the value of the inductance in the arms of the converter to reduce the level of losses due to the influence of this current. A positive characteristic of such modulation is the ability to balance the voltages on the capacitors of the converter modules (Fig. 8c), the

average deviation of these voltages does not exceed  $\pm 30$  V, which is the best result among the analyzed options. The decrease in the output voltage levels leads to a significant increase in the coefficient of total harmonic distortion to the level of 50.49%, which is the worst result among the options analyzed.



**Fig. 7.** The results of modeling the operation of a modular multilevel converter when the carrier signals are shifted by  $2\pi / 3N$ : a – change in the output voltage of the converter; b – change in the magnitude of the circulating current; c – voltage change on the capacitors of the upper arm of the circuit; d – the spectrum of the output voltage of the converter.

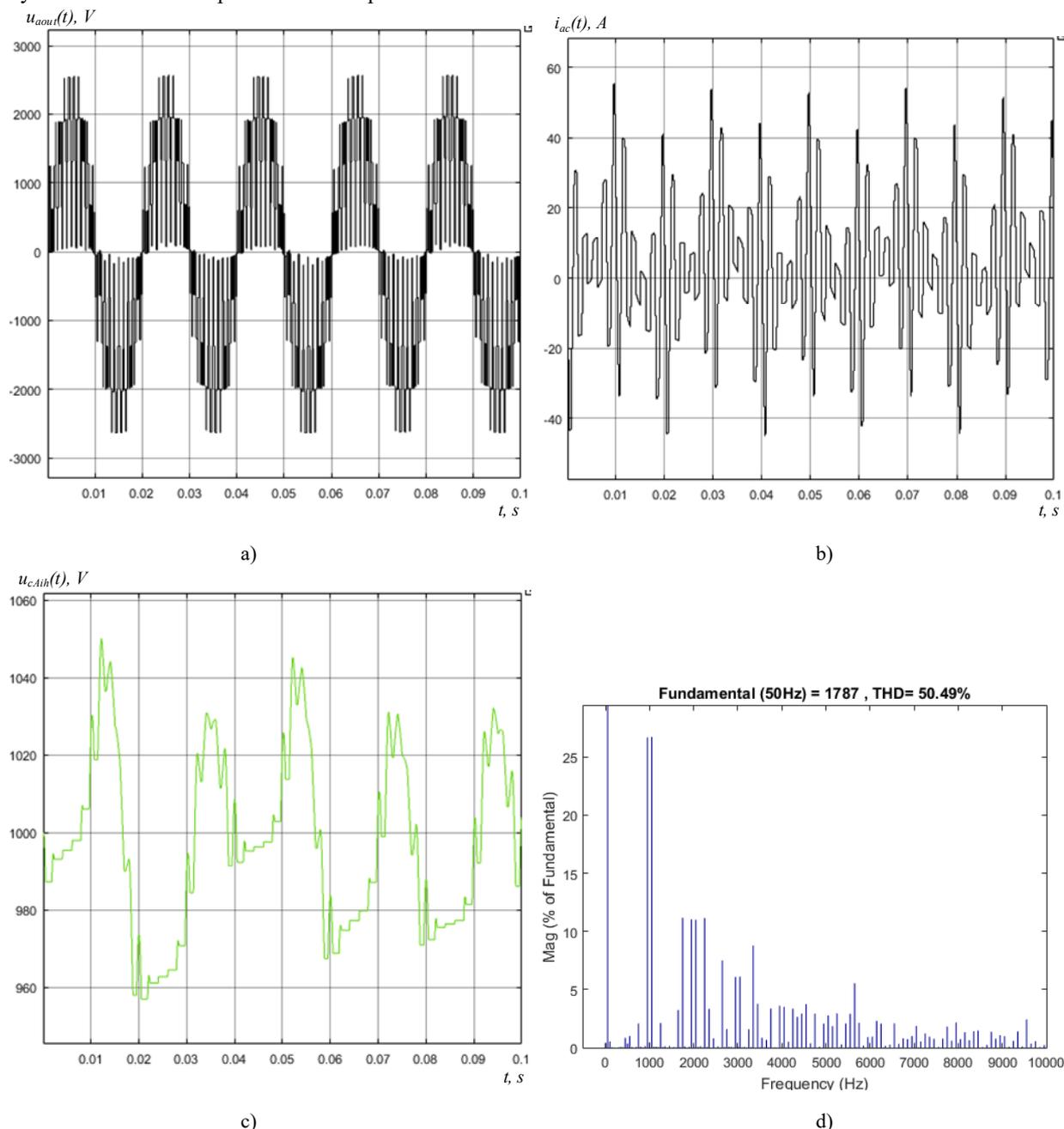
## Conclusions

The aspects of functioning of the modular multilevel converter at use of pulse-width modulation with shift of carrier signals on a phase are analyzed in the work. The general structure of such converter is considered, and also the most widespread circuit decisions concerning

construction of modules. The general analytical dependences describing the relationship between the main variables of the state of the converter are analyzed. A mathematical model in the Matlab / Simulink environment is compiled and the behavior of a modular multilevel converter at different values of the phase shift between the carrier signals of pulse-width modulation is analyzed. It is proved that the absence of this shift shows

the worst indicators in terms of the coefficient of total harmonic distortion of the output voltage of the converter, but the best in terms of accuracy of voltage balancing on the capacitors of the circuit modules. The presented analysis of shift values proves the compromise of the

choice of the shift angle in terms of the total harmonic distortions of the output voltage, the magnitude of the circulating current in the converter arm and the ability to balance voltages on the capacitors of the circuit.



**Fig. 8.** The results of modeling the operation of a modular multilevel converter when the carrier signals are not shifted: a - change in the output voltage of the converter; b - change in the magnitude of the circulating current; c - voltage change on the capacitors of the upper arm of the circuit; d – the spectrum of the output voltage of the converter.

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