МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ
НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ
Факультет аеронавігації, електроніки та телекомунікацій
Кафедра авіаційних комп‘ютерно-інтегрованих комплексів

ДОПУСТИТИ ДО ЗАХИСТУ
Завідувач випускової кафедри
_______ Віктор СИНЄГЛАЗОВ
“___” ____________ 2024

КВАЛІФІКАЦІЙНА РОБОТА
(ПОЯСНЮВАЛЬНА ЗАПИСКА)

ВИПУСКНИКА ОСВІТНЬОГО СТУПЕНЯ — “БАКАЛАВР”
Спеціальність 151 «Автоматизація та комп'ютерно-інтегровані технології»
Освітньо-професійна програма «Комп‘ютерно-інтегровані технологічні процеси і виробництва»

Тема: Система керування перетворенням електричної енергії
Виконавець: студент групи ІК-421Ба Петрина Вадим Андрійович
Керівник: доцент Василенко Микола Павлович

Нормоконтролер: ________ Філяшкін М. К.

Київ – 2024

MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE
NATIONAL AVIATION UNIVERSITY
Faculty of Aeronautics, Electronics and Telecommunications
Department of aviation computer-integrated systems

ADMIT TO DEFENCE
Head of department
_______ Viktor SINEGLAZOV
“___” _____________ 2024

QUALIFICATION WORK

(EXPLANATORY NOTE)

BACHELOR'S DEGREE GRADUATE

Specialty 151 «Automation and Computer-Integrated Technologies»

Educational-Professional Program "Computer-Integrated Technological Processes and Productions"

Topic: Electric energy conversion control system

Done by: student of the group IK-421ba Petryna Vadym Andriyovych
Supervisor: associate professor Vasylenko Mykola Pavlovych

Regulatory inspector: ___________ Fylyashkin M.K.

Київ – 2024

НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ

Факультет аеронавігації, електроніки та телекомунікацій

Кафедра авіаційних комп‘ютерно-інтегрованих комплексів

Освітній ступінь: бакалавр

Спеціальність 151 «Автоматизація та комп'ютерно-інтегровані технології»

Освітньо-професійна програма «Комп’ютерно-інтегровані технологічні процеси і виробництва»

ЗАТВЕРДЖУЮ
Завідувач кафедри
__________ Віктор СИНЄГЛАЗОВ
“____” __________2024 р.

ЗАВДАННЯ

на виконання кваліфікаційної роботи студента

Петрина Вадим Андрійович

1.Тема роботи: Система керування перетворенням електричної енергії

2.Термін виконання роботи: з 13.05.2024 до 3.06.2024

3.Вихідні дані до роботи: $U_{ВХМ}$=500 В, $f_{ВХ}$=60 Гц, $U^*_{ВИХМ}$=220 2 В, $f_{ВИХ}$=50 Гц та ε =0.05 при симетричному RL навантаженні за схемою зірки з нульовим дротом з параметрами R =1 Ом, L = 1.0 Гн.

4.Зміст пояснювальної записки (перелік питань, що підлягають розробці): Вступ. Аналіз методів та засобів керування перетворенням електричної енергії. Комп’ютерне моделювання мікропроцесорної системи керування перетворенням електричної енергії. Засоби підвищення ефективності мікропроцесорних систем керування процесом перетворення електричної енергії Висновки.

5.Перелік обов’язкового графічного матеріалу: 1. Загальна класифікація автономних енергетичних установок. 2. Загальний вигляд вітроенергетичної установки ТГ-1000. 3. Схема електричної частини турбогенераторної вітроенергетичної установки ТГ-1000. 4. Структура автономної енергетичної системи із матричним перетворювачем (СК – система керування)5. Схема моделювання процесу перетворення електричної енергії. 6. Модель для визначення комутаційної функції h_{ij}. 7. Функціональна схема мікропроцесорної системи автоматизованого керування перетворенням електричної енергії в автономних енергетичних системах. 8. Загальна модель для визначення залежності похибки цифрового фільтра δ від відносної частоти $\bar{f}$. 9. Структура підсистеми Fixed для цифрової фільтрації з обробкою чисел в форматі з фіксованою комою.10. Структурна схема слідкуючого електроприводу зі змінним моментом інерції із позитивним зворотним зв'язком за швидкістю.

6.Календарний план-графік

№ п/п	Завдання	Термін виконання	Відмітка про виконання
1	Аналіз методів та засобів керування перетворенням електричної енергії	13.05.24-18.05.24	
2	Показники якості електричної енергії в автономних енергетичних системах	18.05.24-20.05.24	
3	Комп'ютерне моделювання мікропроцесорної системи керування перетворенням електричної енергії	20.05.24-23.05.24	
3	Моделювання регулятора мікропроцесорної системи керування перетворенням електричної енергії	23.05.24-26.05.24	
4	Засоби підвищення ефективності мікропроцесорних систем	26.05.24-29.05.24	

	керування процесом перетворення електричної енергії		
5	Керування виконавчими приводами технологічних машин	29.05.24-31.05.24	
6	Висновки по роботі та підготовка презентації	31.05.24-03.06.24	

7.Дата видачі завдання 13.05.2024.

Керівник: ___________________________ Василенко М.П.

Завдання прийняв до виконання __________________ Петрина В.А.

NATIONAL AVIATION UNIVERSITY
Faculty of Aeronautics, Electronics and Telecommunications
Department of aviation computer-integrated systems

Educational level: Bachelor
Specialty 151 «Automation and Computer-Integrated Technologies»
Educational-Professional Program "Computer-Integrated Technological Processes and Productions"

APPROVED
Head of department
_______ Viktor SINEGLAZOV
“___” ____________ 2024

TASK
to perform the qualification work of the student
Petryna Vadym Andriyovych

1.Topic: Electric energy conversion control system

2.Deadline: from 13.05.2024 to 3.06.2024

3.Initial data for the work: U_{INM}=500 V, f_{IN}=60 Hz, U^*_{OUTM}=220$\sqrt{2}$ V, f_{OUT}=50 Hz and ε=0.05 with symmetrical RL load in a star configuration with a neutral wire, and parameters R = 1 Ohm, L = 1.0 H.

4.Content of the Explanatory Note (list of issues to be developed): Introduction. Analysis of methods and means of electric power conversion control. Computer modeling of a microprocessor-based electric power conversion control system. Means of improving the efficiency of microprocessor-based systems for electric power conversion control. Conclusions.

5.List of mandatory graphic material: 1. General classification of autonomous power plants. 2. General view of the TG-1000 wind turbine. 3. Schematic diagram of the electrical part of the turbine generator wind turbine TG-1000. 4. Structure of an autonomous power system with a matrix converter (CS - control system). 5. Scheme of modeling the process of electric energy conversion. 6. Model for determining the switching function h_{ij}.

7. Functional diagram of a microprocessor-based system for automated control of electric power conversion in autonomous power systems 8. General model for determining the dependence of the error of a digital filter on the relative frequency $\bar{f}$. 9. Structure of the Fixed subsystem for digital filtering with processing of numbers in fixed-point format. 10. Block diagram of a variable moment of inertia tracking electric drive with positive speed feedback.

6.Calendar Schedule

№ p/p	Task	Deadline	Completion Mark
1	Analysis of methods and means of controlling the conversion of electric energy	13.05.24-18.05.24	
2	Electricity quality indicators in autonomous energy systems	18.05.24-20.05.24	
	Computer modeling of the microprocessor control system for electric power conversion	20.05.24-23.05.24	
3	Modeling of the controller of a microprocessor-based control system for electric power conversion	23.05.24-26.05.24	
4	Means of increasing the efficiency of microprocessor-based control systems for the process of electrical energy conversion	26.05.24-29.05.24	
5	Controlling the actuators of technological machines	29.05.24-31.05.24	
6	Conclusions on the work and preparation of presentation	31.05.24-03.06.24	

7.Date of assignment issuance 13.05.2024.

Supervisor: ________________________________ Vasylenko M.P.

The task was accepted for execution ________________________ Petryna V.A.

РЕФЕРАТ

Пояснювальна записка кваліфікаційної роботи «Система керування перетворенням електричної енергії» 63 с., 27 рис., 4 табл, 13 джерел.

Об'єкт дослідження - система керування процесами перетворення електричної енергії в автономних енергетичних систем.

Предмет дослідження - моделі та методи підвищення ефективності процесів керування перетворенням електричної енергії.

Мета кваліфікаційної роботи - підвищення ефективності процесів керування перетворенням електричної енергії в автономних енергетичних ситсем за рахунок розробки удосконаленого методу автоматизованого керування, що забезпечує узгодження параметрів вироблюваної й споживаної електроенергії в автономних енергетичних систем та надійність функціонування систем перетворення, а також проведення оптимізації процесів перетворення електричної енергії.

Метод дослідження - при проведенні досліджень застосовані: методи теорії електричних кіл для аналізу процесів перетворення електричної енергії; принципи автоматизованого керування для визначення стратегії керування силовими ключами перетворювача.

Кваліфікаційна робота присвячена одному з перспективному напряму автоматизації систем енергозабезпечення з комбінованим використанням енергії вітру, дизельних електростанцій та централізованих електричних мереж за допомогою автономних енергетичних систем. Вдосконалення процесів перетворення енергії є одним з напрямків підвищення ефективності генерації електричної енергії в автономних енергетичних системах. Безпосереднє перетворення частоти є одним з найбільш перспективних напрямків розвитку силових перетворювачів автономних енергоустановок. На теперішній час великий інтерес представляє застосування в системах перетворення електричної енергії матричних перетворювачів, що характеризуються високим коефіцієнтом корисної дії через безпосереднє одноступеневе перетворення енергії; відносно простою силовою частиною; можливістю рекуперації енергії до мережі; високим коефіцієнтом потужності через відсутність реактивних елементів.

У результаті проведених досліджень запропонований критерій для узагальненої оцінки якості вхідних струмів багатофазного матричного перетворювача, що враховує всі гармонійні складові та дозволяє аналізувати ступінь спотворень струмів мережі живлення та удосконалений метод оптимального керування за сформульованим критерієм, якій заснований на принципі керування за інтегральною помилкою та забезпечує зменшення рівнів спотворень струму на вході перетворювача і високочастотних складових у перетвореній напрузі.

Ключові слова: *автономна енергоустановка, матричний перетворювач, рекуперація енергії, гармонійні складові.*

ABSTRACT

Explanatory note of the qualification work «Electric energy conversion control system» 63 p., 27 fig., 4 table, 13 source.

The object of research - is a system for controlling the processes of electric energy conversion in autonomous power systems.

The subject of the research - is models and methods for improving the efficiency of electric power conversion management processes.

Purpose of the qualification work - the purpose of the research conducted by the author of the bachelor's thesis is to increase the efficiency of the control processes of electricity conversion in autonomous power systems by developing an improved method of automated control that ensures the coordination of the parameters of generated and consumed electricity in autonomous power systems and the reliability of the conversion systems, as well as optimization of electricity conversion processes.

Research methods - the following methods were used in the research: methods of electrical circuit theory to analyze the processes of electrical energy conversion; principles of automated control to determine the strategy for controlling the converter power keys.

Qualification work is devoted to one of the promising areas of automation of energy supply systems with the combined use of wind energy, diesel power plants and centralized electrical networks using autonomous energy systems. Improving energy conversion processes is one of the ways to increase the efficiency of electricity generation in autonomous energy systems. Direct frequency conversion is one of the most promising areas of development of power converters of autonomous power plants. At present, the use of matrix converters in electric energy conversion systems, which are characterized by a high efficiency due to direct one-stage energy conversion, is of great interest; relatively simple power part; the possibility of energy recovery to the network; high power factor due to the lack of reactive elements.

As a result of the research, a criterion for generalized evaluation of input current quality of a multiphase matrix converter is proposed, which takes into account all harmonic components and allows to analyze the degree of distortions of power supply currents and an improved method of optimal control. distortion of the current at the input of the converter and high-frequency components in the converted voltage.

Keywords: *autonomous power plant, matrix converter, energy recovery, harmonic components.*

CONTENTS

INTRODUCTION

Relevance of the topic of the bachelor's thesis. The problems of development of the energy sector of Ukraine and meeting the needs of the economy in all types of fuel and energy are addressed within the framework of the National Energy Program of Ukraine until 2010, approved by the Verkhovna Rada of Ukraine on May 15, 2006, No. 961. The state policy of Ukraine in the electric power industry is implemented taking into account the significance of the economic effect provided by the reliable and uninterrupted operation of electric power enterprises in order to improve the quality of energy supply to consumers. The further development of the electricity sector of Ukraine involves its modernization based on the use of the latest technologies to ensure energy efficiency and environmental friendliness of electricity production [1].

Meeting the current requirements for energy systems, driven by global trends in rising energy costs and strict restrictions on environmental impact, can be achieved through the development and implementation of energy-saving technologies and an increase in the share of non-conventional energy sources.

Energy supply with the combined use of wind energy, diesel power plants and centralized power grids is carried out by means of autonomous power systems that provide guaranteed uninterrupted power supply to consumers in conditions of energy instability. The peculiarity of autonomous power systems is the need to convert the mechanical energy of the engine into electrical energy of industrial frequency and voltage. In this case, it becomes necessary to solve the following tasks [2-7]: ensuring the efficient use of energy resources and matching the parameters of generated and consumed electricity. Improving energy conversion processes is one of the ways to increase the efficiency of electricity generation in autonomous power systems.

The formation and stabilization of voltage with the required quality characteristics is carried out in such systems using secondary power sources, which can be built on the basis of inverters or direct frequency converters (cycloconverters) [8-10] with natural or artificial switching (matrix converters).

Direct frequency conversion is one of the most promising areas for the development of power converters for autonomous power plants. The advantages of matrix converters (MCs) include [11]: high efficiency due to one-stage energy conversion; relatively simple power part; the possibility of energy recovery to the grid; and, for converters with forced switching (matrix frequency converters), high power factor due to the absence of reactive elements. To perform the tasks of controlling, blocking, organizing the synchronization of the computing process with the supply voltage, inputting and outputting information, it is necessary to develop effective automated control systems for power converters.

Meeting the current requirements for energy systems (ES), driven by global trends in energy prices and strict restrictions on environmental impact, can be achieved through the development and implementation of energy-saving technologies and an increase in the share of non-conventional energy sources using autonomous energy systems. At the same time, there is a need to solve the problems of ensuring the efficient use of energy resources and harmonizing the parameters of electricity produced and consumed.

One of the most promising areas for improving the efficiency of autonomous energy systems is the improvement of the control processes for converting electricity. At present, the use of matrix converters in power conversion systems is of great interest, as they are characterized by high efficiency due to direct one-stage energy conversion; relatively simple power part; possibility of energy recovery to the grid; high power factor due to the absence of reactive elements. However, the efficiency of conversion using matrix converters largely depends on the chosen control strategy.

The use of fully controlled bidirectional switches and closed-loop converter control systems allows to some extent to increase the efficiency of power conversion processes by reducing the level of non-main harmonics of the converted voltage, expanding the frequency control range, and improving electromagnetic compatibility with consumers. The issue of improving the quality of the converted voltage is well enough developed, but the task of reducing the impact of the converter on the power grid remains unresolved.

In this regard, the development of highly efficient automated control systems for power converters in autonomous power supply systems is an urgent task, which will significantly improve their energy efficiency.

Purpose and objectives of the thesis. The purpose of the research conducted by the author of the bachelor's thesis is to increase the efficiency of the control processes of electricity conversion in autonomous power systems by developing an improved method of automated control that ensures the coordination of the parameters of generated and consumed electricity in autonomous power systems and the reliability of the conversion systems, as well as optimization of electricity conversion processes. To achieve this goal, the following tasks were solved:

- to analyze existing models and methods for managing electricity conversion processes in autonomous power plants, ways to improve the efficiency of conversion systems and coordinate autonomous power plants with consumers;
- to improve the model of the process of converting electrical energy using matrix converters for autonomous power supply systems;
- to propose a method of automated control of the electric power conversion system with a minimum of input current distortion;
- substantiation of the structure of an adaptive microprocessor-based control system for electric power conversion.

The object of research is a system for controlling the processes of electric energy conversion in autonomous power systems.

The subject of the research is models and methods for improving the efficiency of electric power conversion management processes.

Research methods. The following methods were used in the research: methods of electrical circuit theory to analyze the processes of electrical energy conversion; principles of automated control to determine the strategy for controlling the converter power keys.

The MATHCAD package was used for modeling and processing of experimental data.

Scientific novelty of the results.

- a criterion for generalized assessment of the quality of input currents of a multiphase matrix converter is proposed, which takes into account all harmonic components and allows analyzing the degree of distortion of the supply network currents.
- an improved method of optimal control according to the formulated criterion, which is based on the principle of integral error control and ensures a reduction in the levels of

current distortion at the converter input and high-frequency components in the converted voltage.

The practical significance of the results is that:

- application of the proposed method of matrix converter control allows to improve the quality of electric power in autonomous power systems (harmonic amplitudes are significantly reduced, thus reducing the input current distortion factor by 8-30%);

- The developed practical recommendations can be used in the design of automated control systems to ensure a low level of errors associated with quantization processes and to increase the performance of automated control systems.

CHAPTER 1
ANALYSIS OF METHODS AND MEANS OF CONTROLLING THE CONVERSION OF ELECTRIC ENERGY

1.1 Autonomous energy systems

An energy system is defined [13] as a set of power plants, power grids, interconnected and connected by common modes in a continuous process of generation, conversion, transmission and distribution of electricity under coordinated control. Ensuring guaranteed uninterruptible power supply is of particular importance for both mobile consumers (autonomous power supply systems for aircraft, ships, etc.) and stationary consumers, especially those that cannot be connected to a single power supply system. In general, this increases the reliability of energy supply, while forcing the application of measures to ensure system stability. Guaranteed power supply to consumers can be provided by autonomous energy systems [8].

An autonomous energy system can function both as part of a single power grid and separately from it [10]. Such energy systems can provide energy to consumers through the use of autonomous power plants (diesel, gasoline, etc.) or energy from non-traditional renewable sources, such as geothermal, solar and wind power, as well as alternative hydropower (tidal and wave power plants) [4-5].

The main component of an autonomous energy system is an autonomous power plant (APP), which is a complex of interconnected equipment and facilities designed to produce, accumulate, convert, distribute, transmit or consume energy.

The general classification of an autonomous power plant is shown in Fig. 1.1, which, depending on the type of energy, are divided into two groups: mechanical and electrical [9]. Electric autonomous power plants, in turn, are divided into autonomous power plants of direct or alternating current.

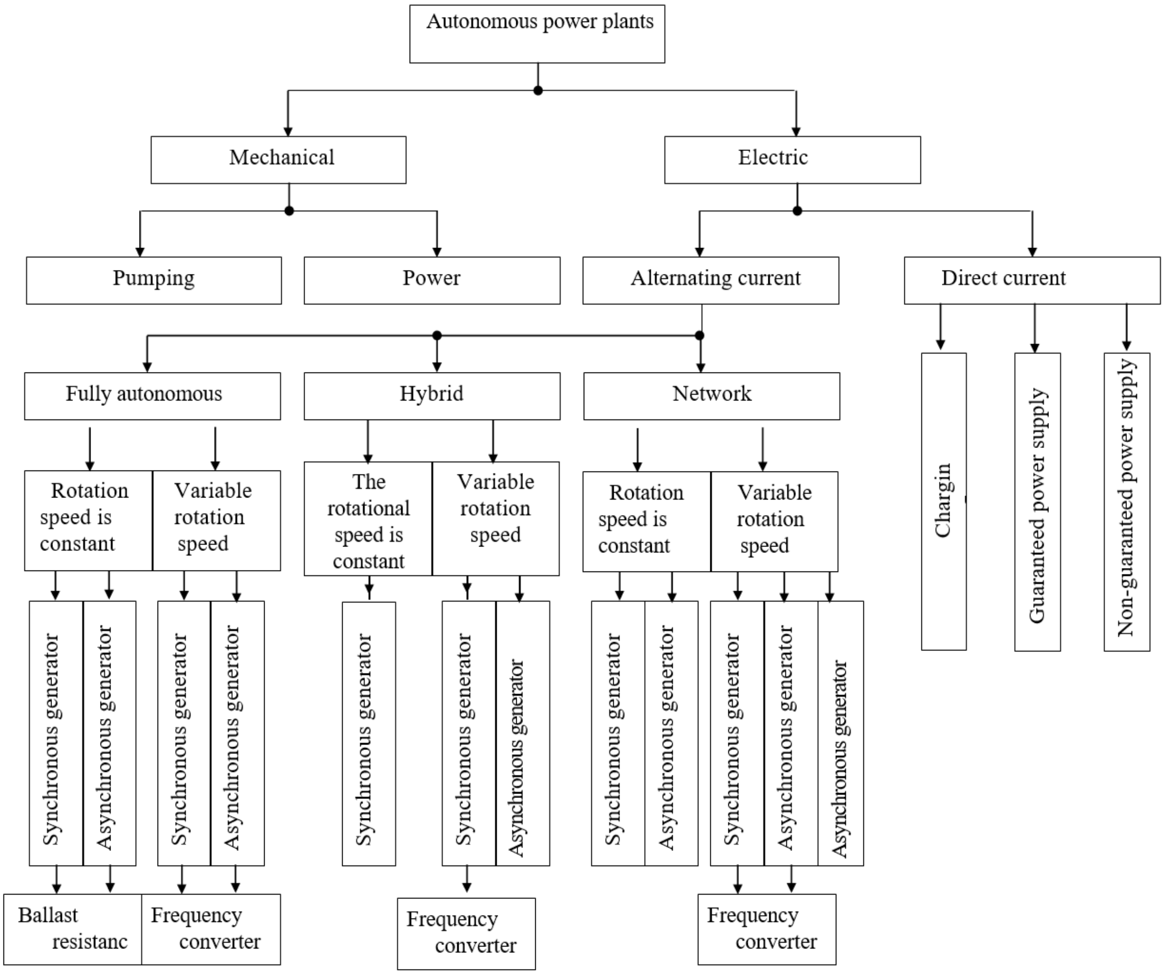


Fig. 1.1. General classification of autonomous power plants

Electric stand-alone power plants of direct current can be: charging, guaranteed power supply and non-guaranteed power supply. Charging autonomous power plants operate only on the charge of the battery, and autonomous power plants of guaranteed power supply operate in parallel with the battery. Installations of these types must have special automatic or automated control systems that ensure high-quality and reliable operation of the autonomous power plant.

For example, in wind power plants (WPPs), it is necessary to stabilize the output voltage parameters, which significantly depend on changes in wind speeds and external load.

Electric autonomous AC power plants are divided into stand-alone, hybrid, and grid-connected [6-8]. In the first case, stand-alone power plants are designed to operate in isolation on their own power grid in order to supply energy to a given consumer; in the second case, to operate in parallel with other power plants of comparable capacity (diesel generators, small hydroelectric power plants, etc.) on a common grid formed by them; in the third case, to operate directly on a power grid of much greater capacity.

The peculiarity of all autonomous power plants of this group, when using the appropriate regulation of the engine and a certain power generation system (PGS), which ensures the conversion of mechanical energy of a rotating engine into electrical energy of industrial frequency and voltage, is that they can be operated in two modes: at a variable engine speed, which allows to obtain the maximum possible energy production, and at a constant engine speed, which allows to simplify the structure of the power generation system. The variable speed mode will be used at motor speeds lower than the design value, and the constant speed mode will be used either over the entire range of operating speeds or only when the design value is exceeded. The constant speed mode is provided by a speed regulator, and the variable speed mode is provided by an electric power generation system using ballast resistance.

Hybrid and grid-connected installations operating at constant engine speeds can develop power in excess of their rated values, but to avoid possible overloads, they must have power limiting systems in addition to the engine speed control system [7].

1.2 Stand-alone wind power plants

Currently, the most promising autonomous energy systems in Ukraine are those using wind energy. The operating conditions of wind power plants are determined by a set of values of physical quantities that characterize external factors affecting the system. The efficiency of the system is determined by a set of parameter values (power, current, voltage, frequency, resistance, etc.) at a given time under given operating conditions, as well as the structure of the wind turbine.

The classical structures of wind power plants include horizontal-propeller and vertical-axis. Currently, the ratio of wind power plants with horizontal and vertical axes of rotation in the world is approximately 90% and 10%, respectively [8].

Vertical-axis plants are characterized by increased requirements for the strength of materials and construction, so a vertical-axis plant is more massive than a horizontal-propeller plant. Vertical-axis plants also require the use of external energy sources to accelerate the rotor.

The use of classical wind power plants for areas with low wind speeds is problematic, requiring the use of unconventional structures. One of such solutions can be a wind power plant made according to the turbine-generator horizontal-propeller scheme with the rotor positioned in front of the wind direction. [3]. A general view of the turbogenerator horizontal-propeller wind turbine TG-1000 is shown in Fig. 1.2.

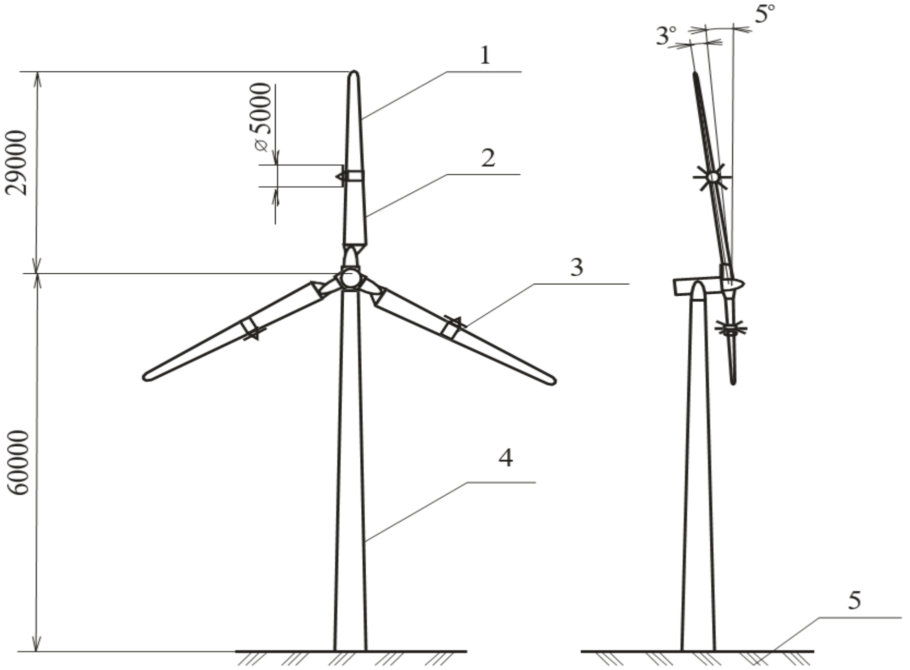


Fig. 1.2. General view of the TG-1000 wind turbine

A turbine generator wind turbine consists of a tower (4) mounted on a base (5), on which a main rotor with three blades is mounted, each of which consists of a fixed (2) and a rotating (1) part. A distinctive feature of the turbogenerator scheme is the presence of additional small turbogenerators (3) on the blades of the main rotor, which are driven by additional blades. The resulting speed of the air hitting these blades is determined by adding the effective wind speed and the circumferential speed of the main rotor blades.

The turbo-generator scheme has the following advantages compared to analogs based on the horizontal propeller scheme:

- no need to use multipliers;

- start, stop, and power control in the process of generating electricity are ensured by turning the end parts of the blades using autonomous electromechanical drives instead of full rotation of all blades by a single central drive;
- the main rotor automatically operates at a variable speed, thereby maximizing the efficiency of the main rotor in almost the entire wind range;
- power fluctuations caused by wind gusts are reduced due to the large moment of inertia of the main rotor, which also reduces the level of requirements for electromechanical systems in terms of performance.

The issues that need to be addressed in wind power plants built according to the turbine-generator scheme include:

- synchronization of generators installed on additional rotors with each other and coordination of their parameters with the industrial network;
- the difficulty of using traditional synchronous machines due to the wide range of wind changes.

It is possible to drive a generator from a wind turbine without a multiplier thanks to the use of induction machines.

An inductor generator is an alternating current electric machine in which a change in the magnetic flux permeating the stator windings is caused by the movement of a ferromagnetic toothed rotor [1-2]. The flux coil is created by a winding powered by direct current. The excitation winding and the operating winding are stationary on the stator.

Such generators, in contrast to conventional electric machines, are characterized by a high specific electromagnetic torque (up to 0.9...1.8 Н□м/kg of generator weight). This is possible due to the use of the principle of multiplication of magnetic flux cohesion and ensuring a high load capacity of the electric machine. The principle of magnetic flux multiplication implies, firstly, ensuring the highest rate of change of the magnetic flux component under given conditions and, secondly, ensuring multiple flux coupling with the armature coils. The first is achieved by increasing the frequency of change of the magnetic flux by selecting a large number of rotor teeth, and the second is achieved by creating special distribution schemes for multiphase armature windings.

The main advantages of inductor generators over conventional generators include simplicity of design, high energy and operational performance.

The disadvantage of induction machines is their considerable weight and size, high level of acoustic noise and vibrations due to the presence of electromagnetic force pulses acting on the stator and rotor teeth, as well as the associated pulsations of the motor's total torque, which impair the functioning of the electromechanical system at low speeds. In certain conditions, the number of conductors connecting the motor phase terminals to the power converter and control system is a disadvantage compared to conventional machines. One of the main disadvantages of inductor generators is the low quality of its current, which requires the use of electronic control systems to reduce the impact of high-frequency components. The electrical part of a turbine generator wind power plant is built according to the scheme shown in Fig. 1.3.

The power plant is based on additional turbogenerators DTG1...DTG3 with rotor-mounted inductor synchronous generators SG1...SG3 with a capacity of 350 kW, which are connected to the general grid through power frequency converters FC1...FC3. A 1 MW backup diesel generator RDG is provided to ensure guaranteed power supply to consumers in the absence of wind. Conversion of mechanical energy of the DG into electrical energy is carried out by the standby synchronous generator RSG. The functions of power converters

1...FC3 include: synchronization of generator voltages by amplitude, phase and frequency and ensuring certain indicators of electricity quality.

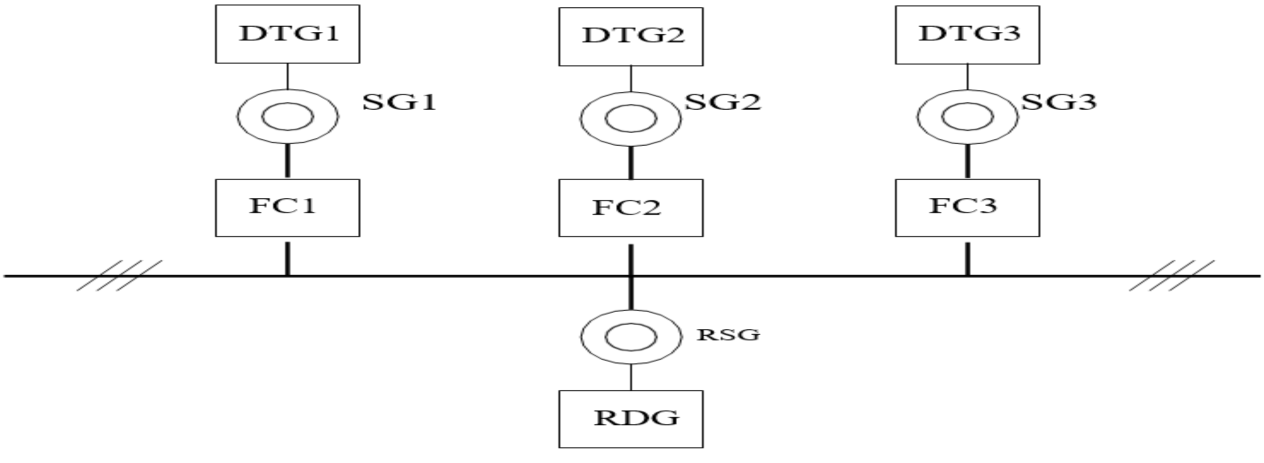


Fig. 1.3. Schematic diagram of the electrical part of the turbine generator wind turbine TG-1000

The use of modern microprocessor-controlled power converter structures based on the latest element base makes it possible to coordinate autonomous power plants with the consumer, increase the efficiency of the process of converting electrical energy, improve its quality indicators, and significantly increase the time between failures of the electromechanical system of a wind power plant [5].

The instability of the output parameters of a wind power plant due to wind variability and fluctuations in the total power of consumers, which leads to changes in the output parameters of electricity and load asymmetry over time, necessitates the coordination of autonomous power plants with consumers. The following tasks should be solved in the process of coordination:

ensuring the most efficient use of energy resources; matching the generated and consumed electricity, which, in most cases, requires the inclusion of energy storage in the power system; controlling the operating modes of energy converters to stabilize the parameters of the generated electricity (power, frequency, amplitude values of voltage and current).

Systems using static converters make efficient use of the primary energy resource, are characterized by high efficiency and reliability. The structure of a generalized autonomous AC power plant with a frequency converter is shown in Fig. 1.4.

Such a static converter system can generally include a DC source (e.g., solar panels), an AC source (generator), a battery, and a converter. The directions of energy flows are controlled by a control unit.

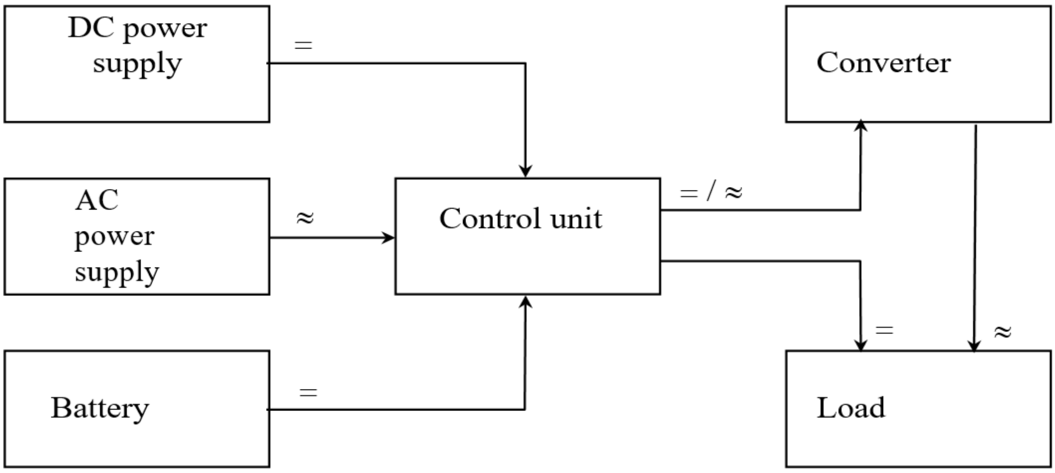


Fig. 1.4. Block diagram of an autonomous power plant with a static converter

Static frequency converters can be classified according to the method of converting electrical energy, composition, and purpose. According to the method of conversion, they can be divided into: converters with a direct current link (DCL), matrix and hybrid frequency converters (Fig. 1.5).

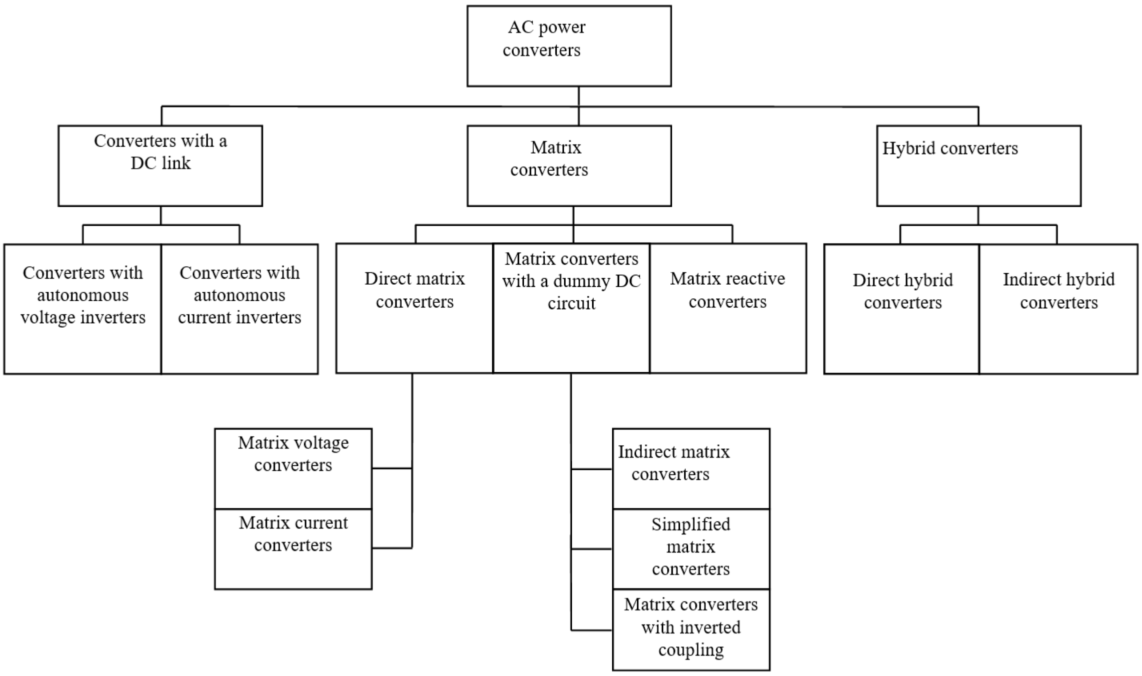


Fig. 1.5. Classification of AC converters by the method of converting electrical energy

Table 1.1 shows the classification of modern AC converters by their composition and purpose. The following abbreviations are used in the table: AFG - active harmonic filter; DFI - direct frequency converter; BSRU - energy reset or recovery unit; UPS - uninterruptible power supply; CV - controlled rectifier; MC - matrix switcher; Rectifier - uncontrolled rectifier; LVC - low-frequency switcher; VFD - voltage regulator; PWM-R - PWM rectifier; PWM-I - PWM inverter; PWM-S - single-pole PWM converter; EP - electric drive. The most common AC conversion technology at present is systems with a DC link that provides energy storage from the primary AC power source. Such a link, in addition to reactive elements (capacitance, inductance), may contain a DC voltage regulator. One of the modern structures of converters with a DC link is shown in Fig. 1.6.

Table 1.1

Classification of AC converters by composition and purpose

Converter	Composition of the converter				Field of application
	Rectifier	Switch (inverter)	Additional tools	Output transformer	
3 DCL	R	LVC	VFD	+	EP
		PWM-I	-	+	APP
			VFD	-	APP, EP
		PWM-S +	-	-/+	APP
	CV	LVC	-	+	EP
		PWM-I	-	+	APP, EP
	PWM-R	PWM-I	-	-	APP, EP
Hybrid converter	R	LVC	VFD +	-/+	EP
		PWM-I	VFD +	-	APP
Matrix converter	-	DFI	-	-/+	EP
		MC	BSRU	-/+	APP, EP

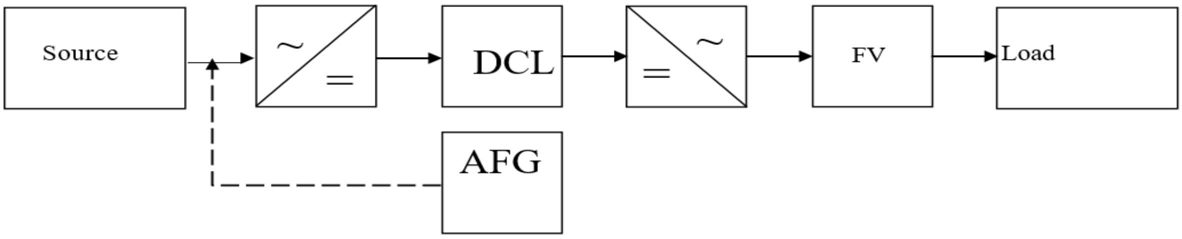


Fig. 1.6. Generalized converter circuit with a DC link

A DC link system is characterized by two power factors that determine the impact of reactive power and distortion power on the energy efficiency of the system: input power factor with respect to the grid and output power factor with respect to the load. The structure of the converter with a PWM rectifier, which has appeared in recent years, allows to increase the value of the input power factor in a wide range of load changes. The main disadvantages of systems with a DC link with input rectifiers include the following:

- increase in the value of the input power factor of the system due to the distortion of the sinusoidality of the input current requires the introduction of passive high-pass filters in the input circuits of the system and leads to an increase in weight and size and the possibility of resonance phenomena;

- limitation of the operating temperature range due to the presence of large-capacity electrolytic capacitors with high operating voltage;

- the occurrence of undesirable electromagnetic conditions in the system when switching power keys.

In recent years, due to significant progress in the development of high-performance power semiconductor devices, there has been a trend toward more advanced AC converter topologies. These topologies primarily include matrix and hybrid structures. This is due to the desire to solve the following main tasks: improving the energy performance of the system (power factor and efficiency); minimizing the higher harmonics of input and output currents to meet the requirements of electromechanical systems at the input and output of the converter; improving the weight and dimensions of converters by reducing the size of the reactive elements used and expanding the power range of converters.

Matrix structures ensure the conversion of AC source parameters (amplitude and frequency) into the voltage required to power the load without accumulating energy in the intermediate link [8]. Such converters are referred to as direct power transmission systems. A matrix frequency converter contains static keys that connect the input and output terminals. The keys are controlled in such a way as to ensure the formation of an output voltage curve with a given fundamental harmonic from segments of the input voltage curve. Frequency converters without LPCs have a number of positive properties that determine the feasibility of their widespread use [6]:

- Due to the absence of large DC link capacitors, which take up 30 to 50% of the inverter's volume, it is possible to create small-sized and highly reliable converters;

- The converter allows for a two-way power exchange between the supply network and the load circuit;

- the converter is powered directly from the mains without intermediate rectification, which in some cases allows you to build circuits with a smaller number of valves compared to converters with DC links.

The prototype of the matrix structure of the converter is direct frequency converters (direct-coupled converters, or cycloconverters) [3]. Fig. 1.7 shows a diagram of a matrix converter. Bidirectional keys are conventionally shown as mechanical switches.

The matrix converters are based on 9 bidirectional switches that are capable of connecting each of the three input voltage phases to each of the three load phases. The key switching algorithm is based on the strategy of forming the desired output voltage from parts of the periodic functions of the three-phase input voltage.

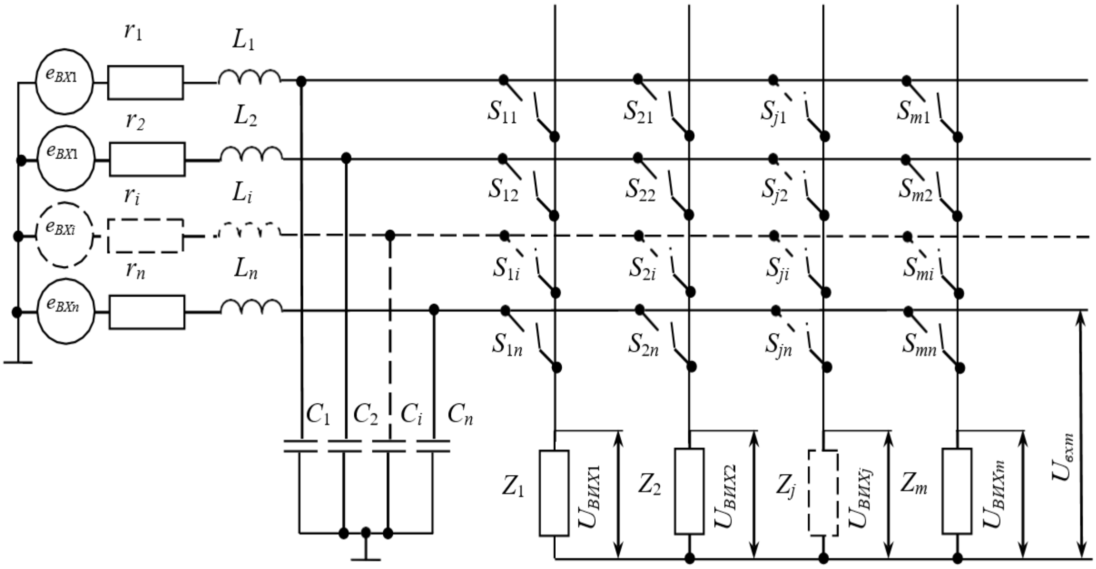


Fig. 1.7. Diagram of the matrix frequency converter

The matrix structure of the converter allows for both increasing and decreasing the frequency of the output voltage relative to the frequency of the primary source. In addition, the use of a matrix structure increases system reliability. If one of the phases of the primary source fails, the bidirectional key control algorithm can be adapted to work with the remaining input voltage phases, providing an output voltage of lower quality, but suitable for powering consumers.

1.3. Electricity quality indicators in autonomous energy systems

Requirements for the quality of energy in general-purpose power grids are regulated by the current standard. The main indicators of electricity quality include [1]:

1.Steady-state voltage deviation as a percentage of the nominal voltage

$$\delta U_{ss} = \frac{U_{ss} - U_{NOM}}{U_{NOM}} \cdot 100\% \qquad (1.1)$$

where U_{ss} - is the steady-state operating voltage, V; U_{NOM} - is the nominal value voltage, V.

2.Voltage change range as a percentage of the nominal voltage

$$\delta U_{l} = \frac{U_{MAXl} - U_{MAX(l-1)}}{\sqrt{2} \cdot U_{NOM}} \cdot 100\% \qquad (1.2)$$

Where U_{MAXl} , $U_{MAX(l-1)}$- values of neighboring extremes, or extremes and horizontal section of the envelope of the voltage amplitude values, V. The voltage swing includes changes (fluctuations) of the effective voltage value of any form with a speed of at least 1 - 2% per second.

3.Voltage unbalance factor in percent:

$$K_{2U} = \frac{U_{2(1)}}{U_{NOM}} \cdot 100\% \qquad (1.3)$$

where $U_{2(1)}$ is the effective value of the reverse sequence voltage of the fundamental frequency of the three-phase system, V.

4.Voltage sinusoidal distortion factor in percent:

$$K_{U} = \frac{\sqrt{\sum_{n=2}^{40} U_{(n)}^{2}}}{U_{NOM}} \cdot 100\% \qquad (1.4)$$

where $U^2_{(n)}$- is the current value of the n-th harmonic component of the voltage, V; n - is the number of the harmonic component of the voltage.

5.The coefficient of the nth harmonic component of the voltage in percent:

$$K_{U(n)} = \frac{U_{(n)}}{U_{NOM}} \cdot 100\% \qquad (1.5)$$

6.Frequency deviation in hertz:

$$\Delta f = f_{y} - f_{NOM} \qquad (1.6)$$

where f_y is the frequency value averaged over 20 seconds, Hz; f_{NOM} - is the nominal frequency value, Hz.

The values of quality indicators in the normal operation of the power grid shall not exceed the maximum permissible values specified in Table 1.2, and for 95% of the time of each day they shall not exceed the normal permissible values.

Table 1.2.

Electricity quality indicators in general-purpose networks

Indicator	Permissible value of the indicator	
	normal	marginal
Steady-state voltage deviation at the terminals of of electrical receivers	±5	±10
Voltage sinusoidal distortion factor K_U(%) in the electrical network voltage (kV):		
to 1	8	12
6– 20	5	8
35	4	6
110– 330	2	3
Inverse voltage unbalance factor K_{2U} and zero K_{0U} sequences (%)	2	4
Frequency deviation, Hz	±0,2	±0,4

Ensuring high quality of electricity in autonomous power systems containing semiconductor converter devices is possible through the introduction of new converter topologies, more advanced switches, high quality filters, as well as through the use of effective strategies for controlling the process of converting electricity. The frequency converter control strategy is understood as a priority course of action to achieve the goals of generating the currents and voltages required for the load and ensuring the electromagnetic compatibility of the converter with the load and the power supply network. The control strategy is developed taking into account the requirements for both the quality of the load voltage and the degree of influence of the frequency converter on the power supply.

As shown by the analysis [11], the optimal way to build systems for automatic stabilization of autonomous power systems is to use a matrix converter with a closed structure and a scalar control strategy.

On the basis of our research, we formulate the problem of optimal control of a matrix converter operating as part of an autonomous power plant to minimize input current distortion under output voltage constraints. The objective function for finding the optimal control of the matrix switch structure is the total integral quadratic estimate of the input current distortion.

An algorithm for optimal control of a matrix converter has been developed, based on the assumption that the output current does not change significantly during the switching period. This makes it possible to predict in real time the change in input currents at the next switching interval under certain configuration options of the matrix switch based on the current values of load currents and the state of the converter keys.

1.4 Conclusions to Chapter 1

1.Ensuring guaranteed power supply to consumers in conditions of energy instability is possible through the use of autonomous energy systems, the most promising of which in Ukraine are wind power systems. The use of turbine-generator horizontal-propeller schemes with inductor generators can significantly increase the wind utilization rate and expand the operating speed range.

2.Along with high energy and operational performance, inductor machines are characterized by low output current quality, which requires the use of efficient control systems for the process of converting electrical energy.

3.Matrix converters are promising for building highly reliable autonomous power supply systems. Due to the use of fully controlled bidirectional gates and the introduction of adaptive control systems for matrix converters, it is possible to improve the harmonic composition of the converted voltage and reduce input current distortion.

4.The implementation of an automated control system for matrix converters based on microprocessors and programmable logic integrated circuits requires the development of structural and functional diagrams, efficient algorithms, and practical recommendations to ensure the stability, performance, and required accuracy of such an automated system.

CHAPTER 2

COMPUTER MODELING OF MICROPROCESSOR CONTROL SYSTEM BY ELECTRICAL ENERGY CONVERSION

The analysis of the conversion of electrical energy using a matrix converter was carried out using the software package "MVTU 3.5" software package, which allows studying the dynamics of various systems and devices and can be used to design automatic control systems [12].

2.1. Computer modeling of electric power conversion processes based on matrix converters in autonomous power systems

The basis for constructing a scheme for modeling the conversion of electric energy in an autonomous power system is the block diagram shown in Fig. 2.1, which ensures minimum distortion of input currents and fulfills the conditions for stabilizing the output voltage.

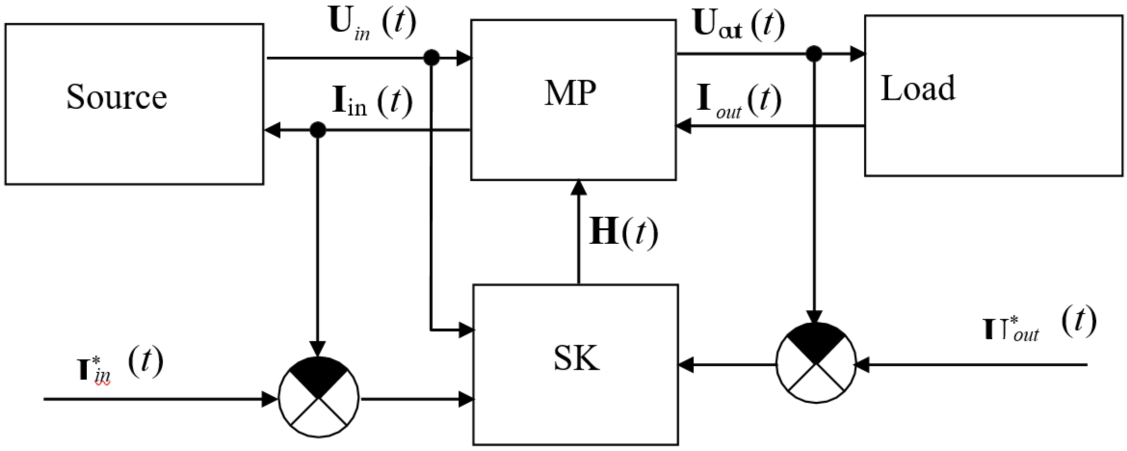


Fig. 2.1. Structure of an autonomous power system with a matrix converter (CS - control system)

The general scheme of modeling the process of electric power conversion in the editor of structural diagrams of the software complex "MVTU 3.5" is shown in Fig. 2.2.

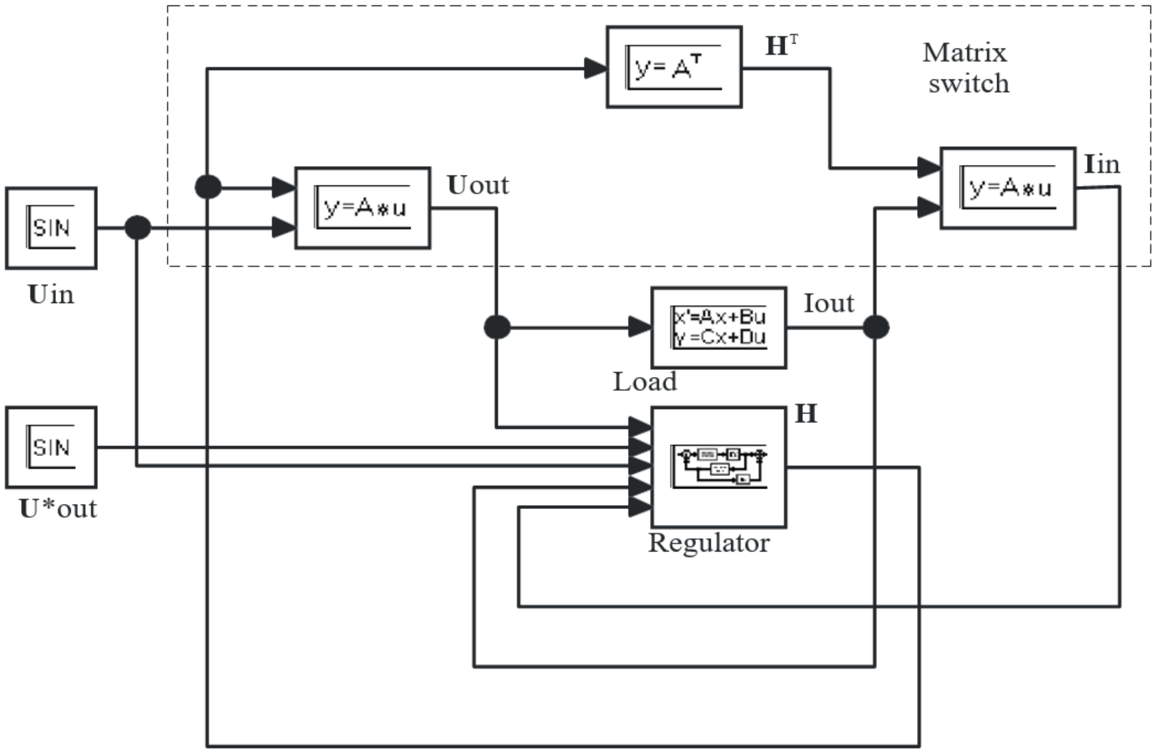


Fig. 2.2. Scheme of modeling the process of electric energy conversion

The general model of the electric power conversion system in autonomous power systems includes:

- a model of a three-phase electrical power source (U_{IN}) connected to the converter input. The source voltages are formed in the form of a vector, the components of which are sinusoids shifted relative to each other by a phase angle 2π/ 3, with amplitudes $U_{\mathrm{IN\,M}}$ and frequencies f_{IN}.
- model of a three-phase reference voltage source (U^*_{OUT}) with parameters $U^*_{OUT\,M}$ and f_{OUT}.
- A matrix switch model represented by matrix multiplication and transposition blocks that allows you to generate output voltage vectors $\mathbf{U}_{OUT}$ and input currents $\mathbf{I}_{IN}$;
- load model represented by equations in the state space, whose response to the converted output voltage determines the vector of output currents $\mathbf{I}_{OUT}$;
- - the model of the controller, shown in the figure as a submodel, which, based on the analysis of the exemplary task voltage ($\mathbf{U}^*_{IN}$), input and

output voltages (**U**$_{IN}$, **U**$_{OUT}$) and currents (**I**$_{IN}$, **I**$_{OUT}$) forms the switching matrix **H**, which is fed to the converter matrix switcher. The regulator implements one of the following control methods: switching the input phases with the maximum instantaneous voltage values ("most positive" and "most negative").

2.2. Modeling of the controller of a microprocessor-based control system for electric power conversion

The adaptive controller of a three-phase matrix converter contains 9 identical components, each of which is responsible for the formation of the switching function h_{ij} of a certain matrix switch key. The general view of the model for each converter key is shown in Fig. 2.3.

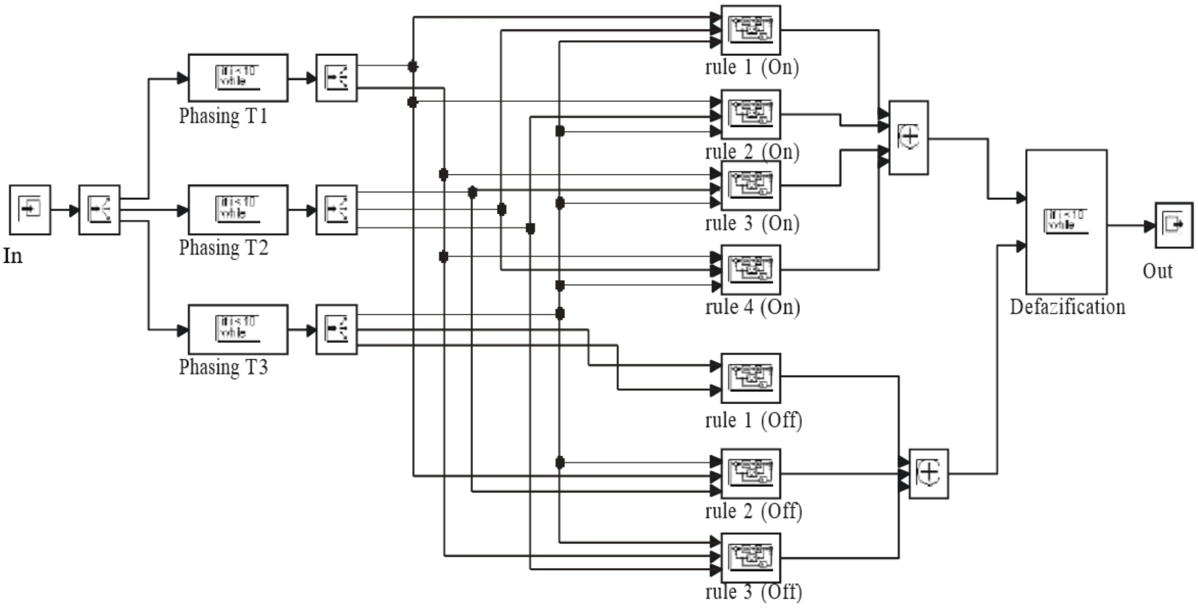


Fig. 2.3. Model for determining the switching function h_{ij}

The study of the operation of the electric power conversion system at constant voltage, frequency, and unchanged load characteristics under different control laws was carried out in the MVTU 3.5 package according to the scheme shown in Fig. 2.2 for the case of U^*_{INM}=500 V, f_{IN}=60 Hz, U^*_{OUTM}=220 $\sqrt{2}$ V, f_{OUT}=50 Hz, and

ε =0.05 under a symmetrical RL load according to the star star scheme with a neutral wire with parameters $R = 1$ Ohm, $L = 0.1$ Gn.

The oscillograms of the output voltages, output and input currents of the electric power conversion system obtained by modeling different methods of controlling the matrix switch are shown in Figs. 2.4 - 2.6.

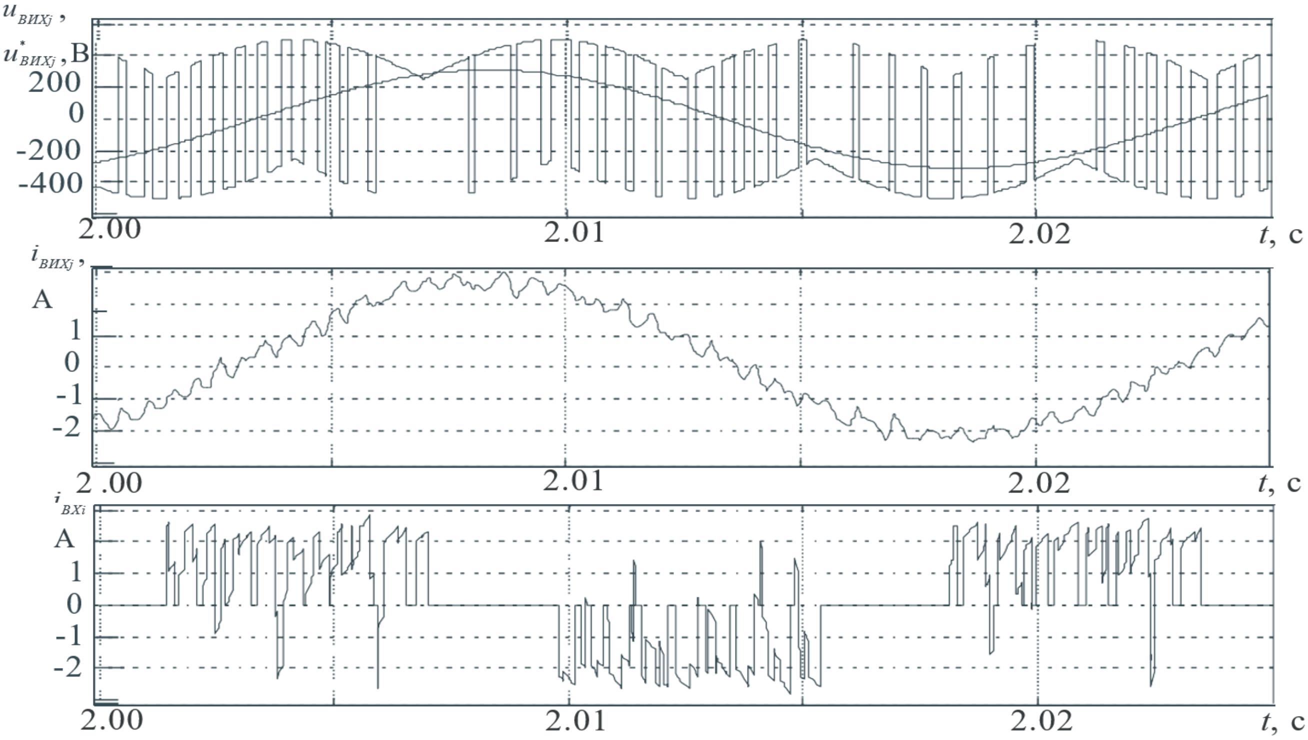


Fig. 2.4 Simulation results for switching limit values

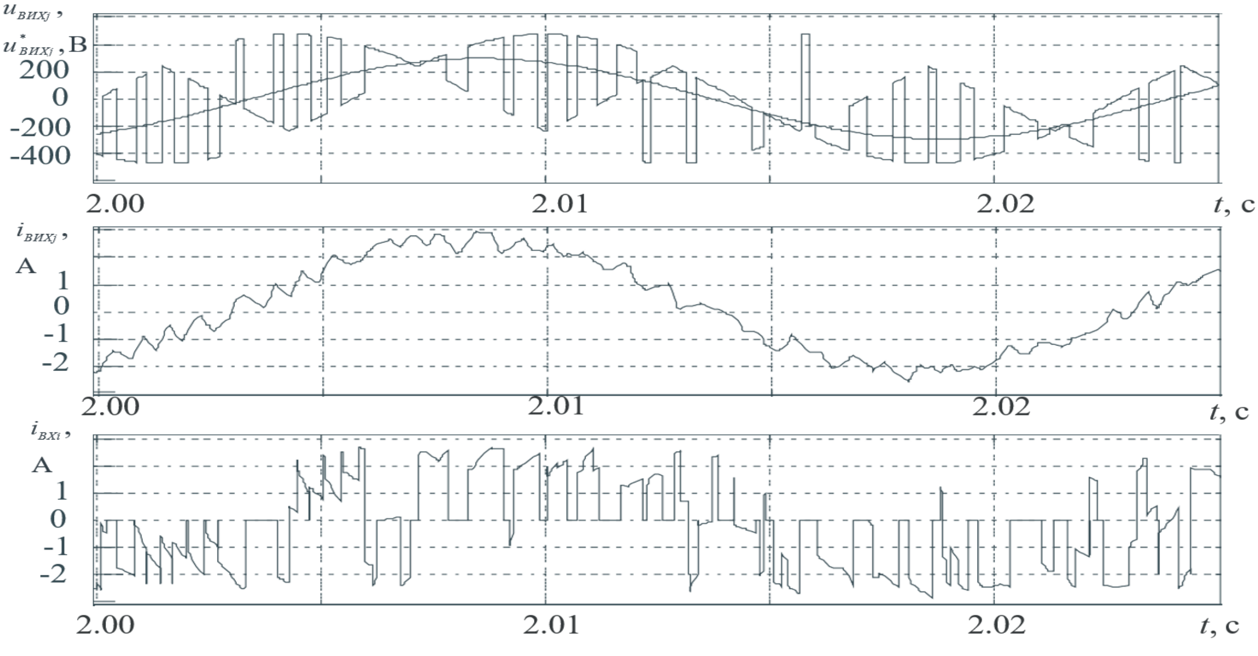


Fig. 2.5. Simulation results for switching the nearest values

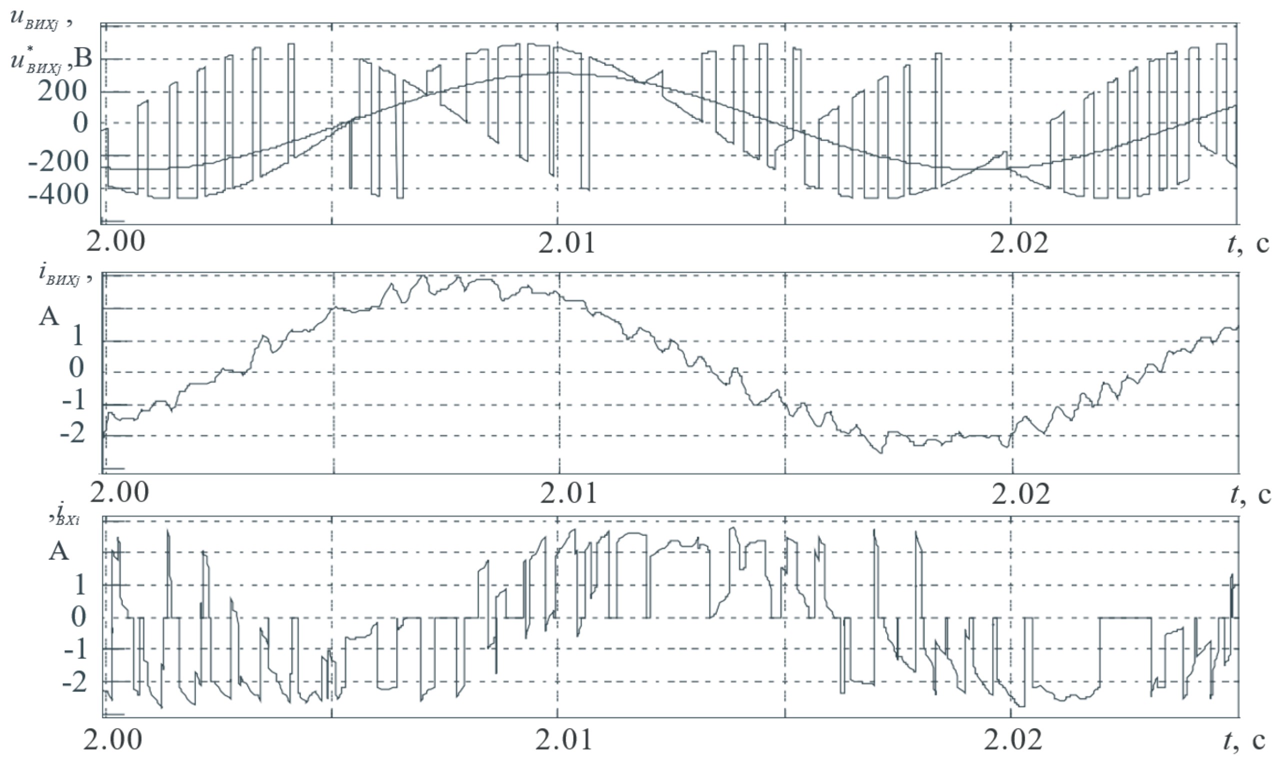
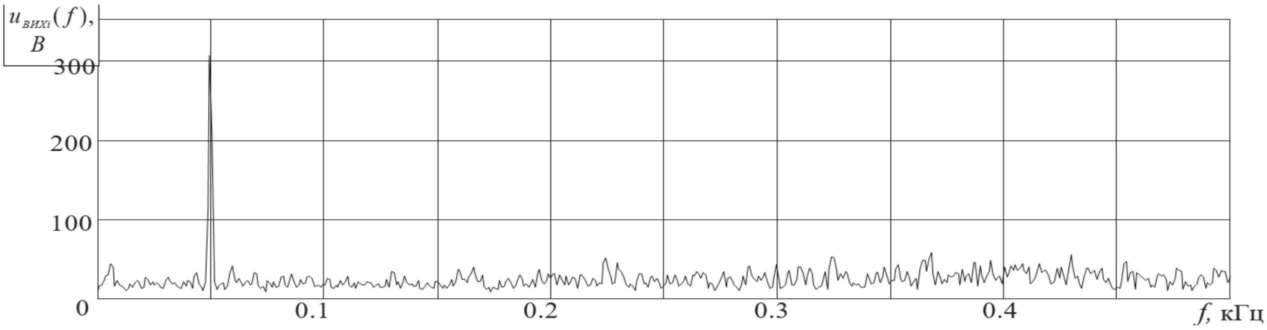


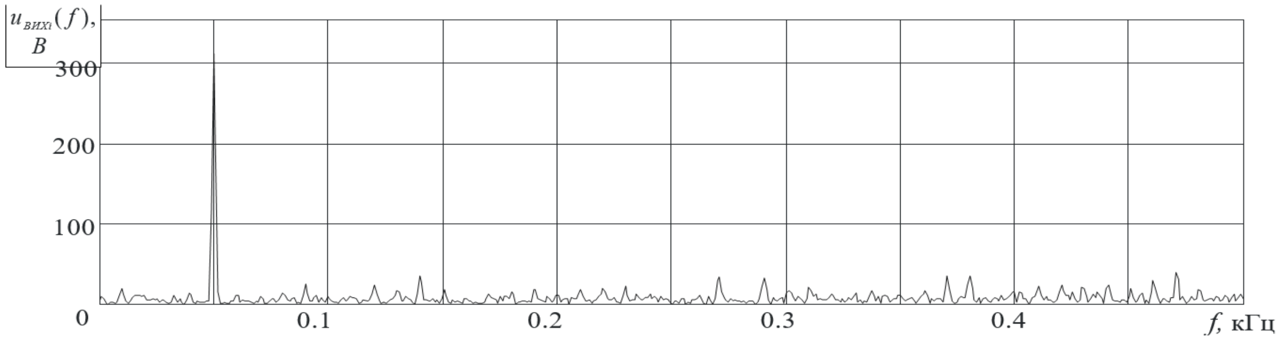
Fig. 2.6. Simulation results for the proposed automated control method

The oscillograms show that the method with limit value switching provides a larger amplitude of the converted voltage ripple compared to other methods, however, under the condition of load inertia, the output currents for any of the control methods under study have an almost sinusoidal shape due to the suppression of high-frequency components by the load. In Fig. 2.7 shows the output voltage spectra of power recycling systems with different control laws.

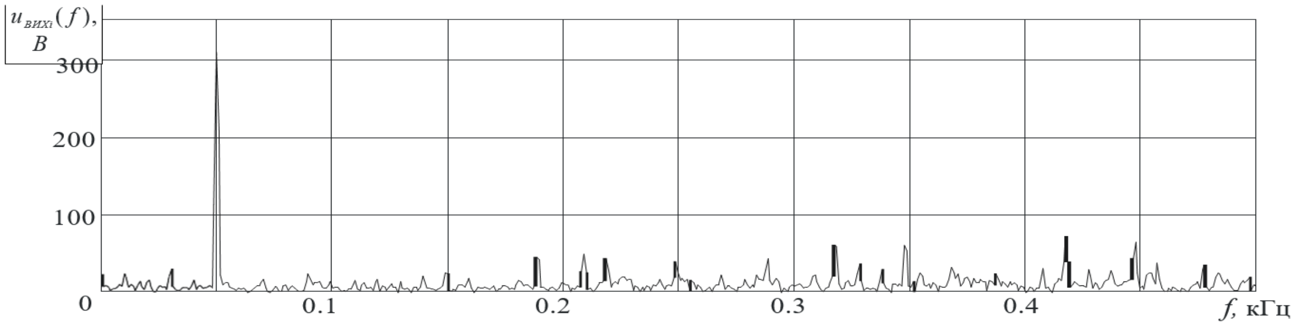
The obtained spectra contain maxima at the frequency f_{OUT}, the power of the spectrum of the distorting components is shifted to the higher frequency region. As expected, the worst quality of conversion is characterized by the method with switching of threshold values. Smaller values of the amplitudes of the distorting components are provided by the control method with phase switching, the instantaneous voltage values of which are closest to the desired output voltage.



a) with switching of limit values ($\mu_{IN} = 2.323$)



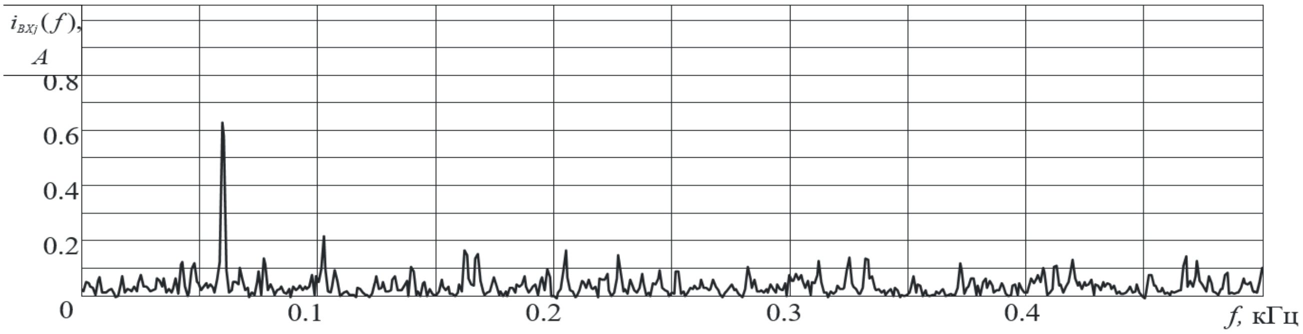
b) with switching of the nearest values ($\mu_{IN} = 1.762$)



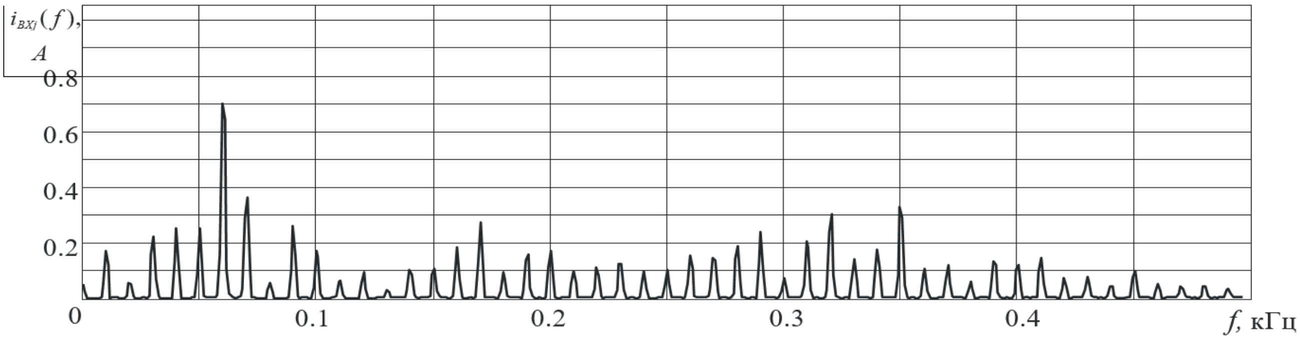
c) the proposed management method ($\mu_{IN} = 2.030$)

Fig. 2.7. Output voltage spectra of a matrix converter with different control methods

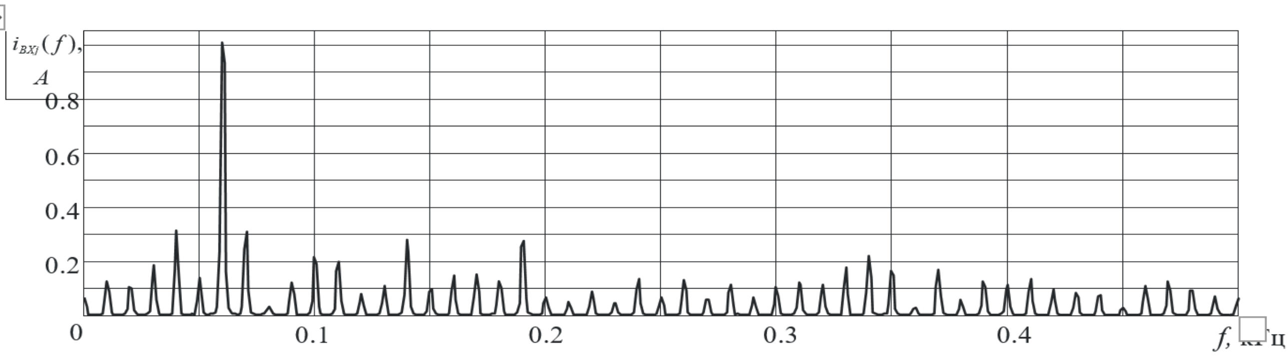
The increase in the amplitudes of the components when using the proposed automated control method is characteristic of the higher frequency region, which can be suppressed by the output filter and due to the inertia of the load. The corresponding spectra of the input current at different methods of controlling the matrix converter are shown in Fig. 2.8.



a) with switching of the largest values (μ_{IN} =1.328)



b) with switching of the nearest values (μ_{IN} =1.401)



c) the proposed management method (μ_{IN} =0.832)

Fig. 2.8. Input current spectra of a matrix converter with different control methods

The modeling results confirm that the spectral compositions of the converted voltage and input current contain frequency components that are multiple of the repetition rate of the switching functions f_s, which, in turn, depends on the input and output voltage frequencies. To enable a comparative analysis of the quality of the converted voltage, the values of the distortion coefficients $\mu(U_{OUT})$ at switching the input voltage limit values (I), the nearest values (II), and at optimal control (III) are summarized in Table 2.1. Table 2.1 shows that in all cases, the output voltage distortion is determined by the ratios of the input and desired output frequencies and voltage amplitudes. Comparative analysis of input current distortion coefficients $\mu(I_{IN})$ is shown in Table 2.2. From the spectral analysis of the results of modeling the electric power conversion system, it is clear that the proposed automated control method provides the largest share of the fundamental harmonic of the input current (with frequency f_{IN}) in the spectrum and the lowest distortion factor compared to other methods. Input current distortion factor $\mu(I_{IN})$ is reduced by 7-38 %, depending on the ratio of input and output amplitudes and frequencies. Thus, the proposed method of automated control of the converter power switches minimizes its impact on the power supply network while ensuring the required output voltage.

Table 2.1

Values of output voltage distortion factors $\mu(U_{out})$

$\frac{f_{OUT}}{f_{IN}}$	$\frac{U_{OUT\ M}}{U_{IN\ M}}$	$\mu(U_{OUT})$		
		I	II	III
0,5	0,2	3,456	1,4502	1,860
	0,4	4,007	1,5976	1,920
	0,6	3,0279	1,6790	1,768
	0,8	1,9438	1,6544	2,121
0,75	0,2	5,0522	1,2074	1,548
	0,4	4,7067	1,4386	1,902
	0,6	2,5383	1,8549	2,430
	0,8	1,2698	2,1450	2,75
1	0,2	1,6471	2,2979	2,946
	0,4	2,7234	2,5124	3,221
	0,6	4,0713	3,0163	3,867
	0,8	2,8826	3,1250	3.991
1,25	0,2	4,3453	3,3893	4,3453
	0,4	4,1567	3,4788	4,1567
	0,6	2,5398	2,5857	2,5398
	0,8	1,5144	1,6544	1,5144
1,5	0,2	1,7159	0,1201	1.416
	0,4	2,1438	1,4510	1.337
	0,6	2,7021	0,9875	1,266
	0,8	4,8078	0,9968	1,278

2.3. Modeling the dynamics of the electric power conversion system based on a matrix converter

The operation of autonomous power plants in real conditions is characterized by unstable operating modes, which can account for 80-95% of the total operating time of an autonomous power plant [13], so modern electrical installations of this type are subject to increased requirements to ensure a stable rated speed, a minimum value of speed "dips" when the load is applied and a minimum duration of the transient process.

Input current distortion coefficients $\mu(I_{IN})$ *Table 2.2*

$\frac{f_{OUT}}{f_{IN}}$	$\frac{U_{OUT\,M}}{U_{IN\,M}}$	$\mu(I_{IN})$		
		I	II	III
0,5	0,2	1,9314	2,0231	2,0824
	0,4	1,7853	1,8151	1,4704
	0,6	3,0096	3,1135	1,2987
	0,8	3,4267	4,1186	1,2518
0,75	0,2	2,2776	2,0231	1,6426
	0,4	2,3284	1,8151	0,733
	0,6	2,4451	3,1135	0,557
	0,8	5,9292	4,1186	0,5176
1	0,2	1,8279	2,3945	1,6079
	0,4	1,8548	1,6043	0,4988
	0,6	1,3045	1,3633	0,2928
	0,8	3,2023	4,0555	0,206
1,25	0,2	1,5457	1,5457	1,5457
	0,4	1,8029	1,8029	1,8029
	0,6	2,9868	2,9868	2,9868
	0,8	3,1017	3,1017	3,1017
1,5	0,2	1,575	4,8843	3,3892
	0,4	1,5163	3,409	1,52
	0,6	1,2257	3,6811	1,2945
	0,8	0,8162	4,128	1,2655

The study of the properties of the electric power conversion system when changing the parameters of the power supply was carried out with an instantaneous increase in the frequency and amplitude of the supply voltage. In Fig. 2.9 shows the oscillograms of the converter currents and voltages normalized to their initial amplitude values when the frequency and voltage increase by 1.5 times at time t = 0.5 s.

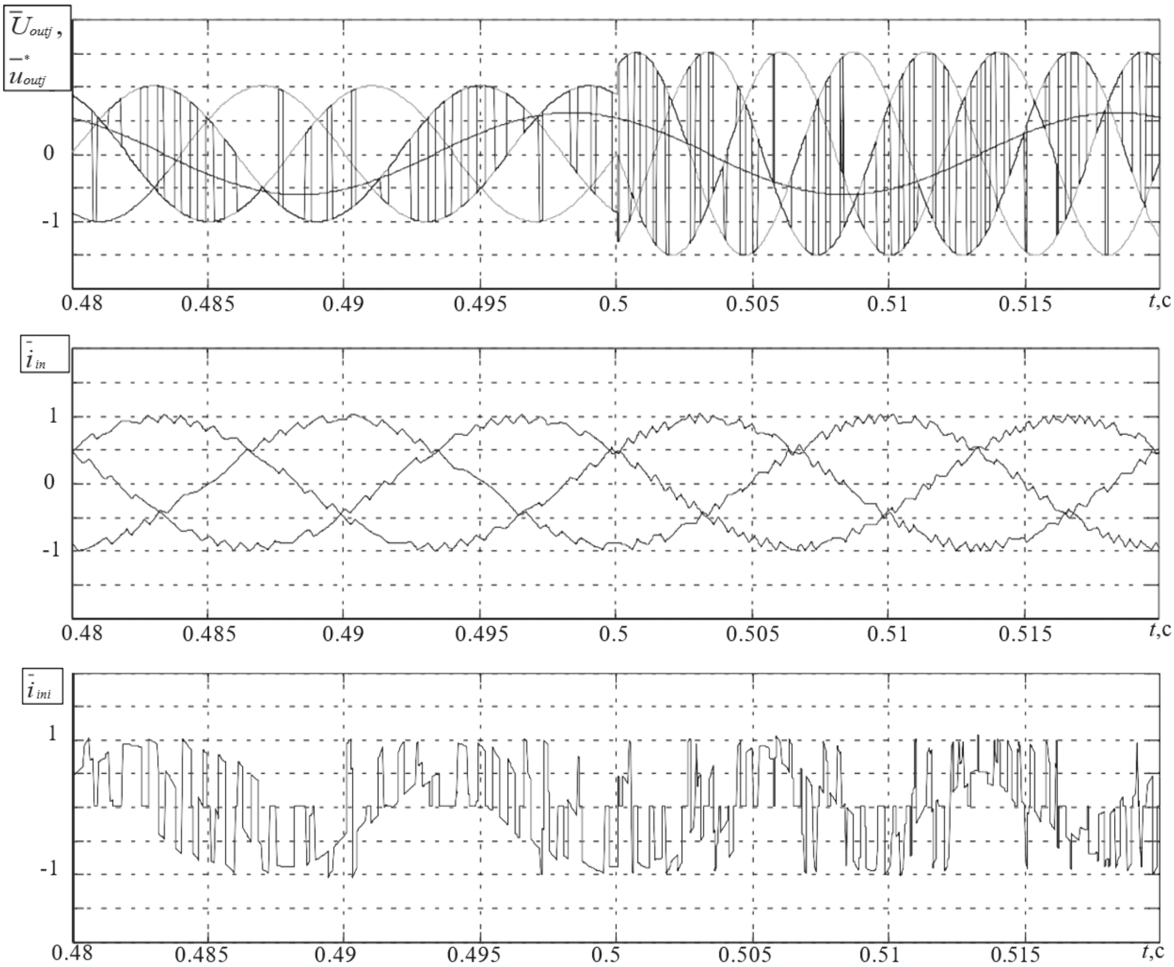


Fig. 2.8. Results of modeling the change in power supply parameters

As can be seen from Fig. 2.8, changes in the frequency and amplitude of the supply voltage have almost no effect on the parameters and shape of the load current. The amplitude of the input current remains unchanged (because it depends on the load current), the frequency of its envelope over the entire time interval corresponds to the frequency of the supply voltage f_{IN} .

The load shedding was modeled by increasing the active and reactive impedances of consumers by a factor of 2 simultaneously in all phases at a given time. Oscillograms of normalized input and output currents are shown in Fig. 2.9.

The load shedding was modeled by increasing the active and reactive impedances of consumers by a factor of 2 simultaneously in all phases at time *t* = 0.5 s. Oscillograms of normalized input and output currents are shown in Fig. 2.9.

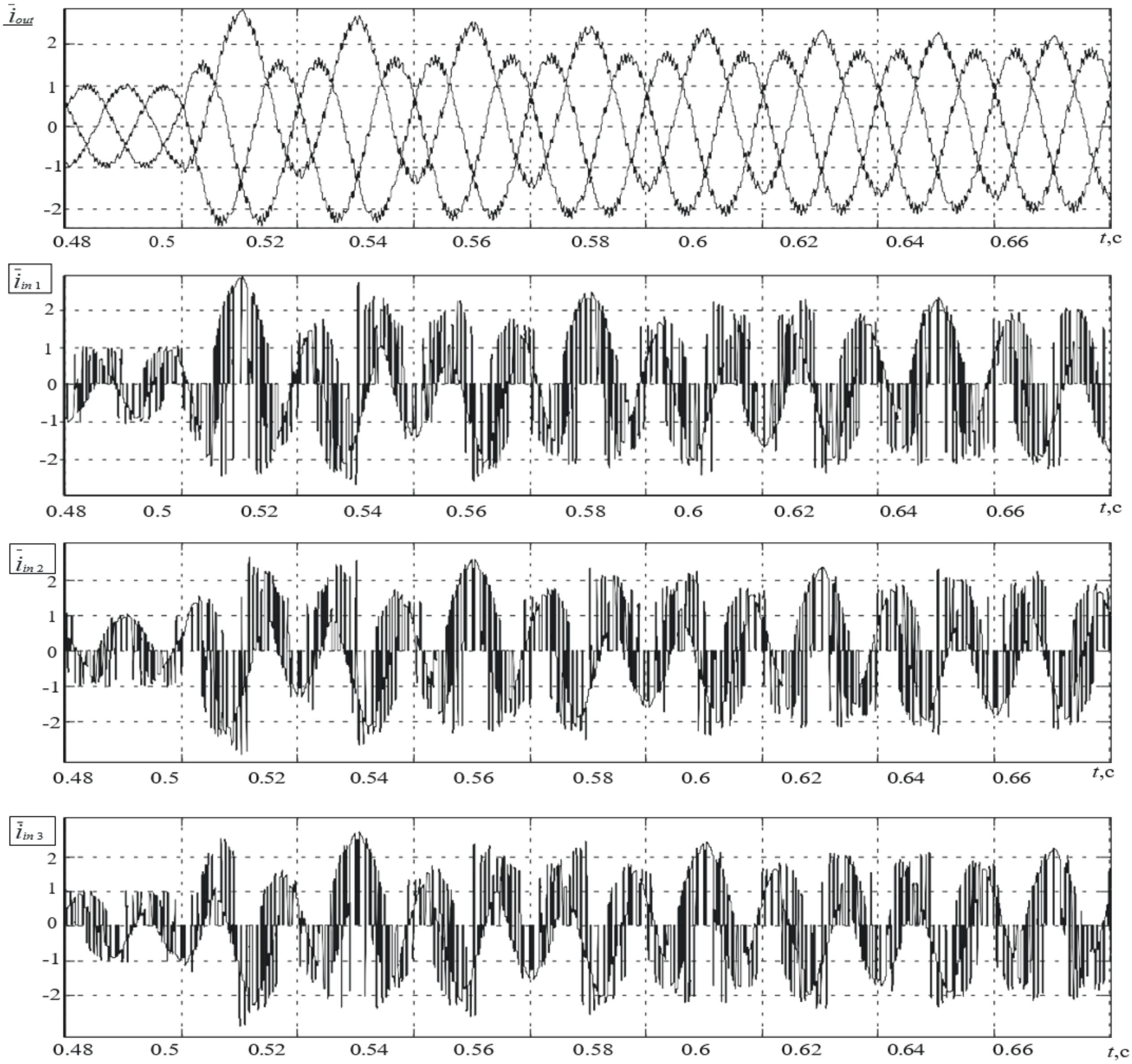


Fig. 2.9. Results of load shedding modeling

From Fig. 2.9 shows that the load shedding is accompanied by transient processes, during which additional distortions of the input current curve shape occur, which can lead to ionization processes in the insulation of the source (synchronous generator) windings, and, as a result, to a decrease in its service life. However, the symmetry of the currents is maintained over the entire simulation interval, which eliminates the flow of equalization current.

2.4. Modeling the operation of an autonomous power system in asymmetric modes

One of the problems that arise in the operation of autonomous power systems is the distortion of voltage and current waveforms due to load asymmetry. In the presence of single-phase consumers, it is assumed that the load distribution by phase is uneven within 15% [5]. However, such an asymmetry can lead to voltage deviations, which can cause equipment malfunctions, damage to equipment, and other undesirable effects. The effects of instantaneous impact in three-phase networks include: distortion of the supply voltage waveform; voltage drop in the distribution network; the effect of harmonics in multiples of three; resonant phenomena at higher harmonic frequencies; interference in equipment of other systems and control networks; increased acoustic noise in electromagnetic equipment; vibration in electrical machine systems. The problems of long-term exposure include heating and additional losses in transformers and electrical machines; heating of capacitors and distribution network cables [6].

To study the effect of an asymmetric dynamic load on the operation of an autonomous power system with a matrix converter, we consider a 100% load on one of the phases at a time $t = 0.5$ s. The waveforms of the normalized output and input currents of the electric power conversion system obtained as a result of modeling are shown in Fig. 2.10.

Just as in the case of a symmetrical load, when the characteristics of consumers change in one of the phases, a transient process occurs, but the symmetry of the input currents is preserved. In contrast to the previous results (Fig. 2.9), the distortions caused by the load asymmetry remain in the steady-state mode.

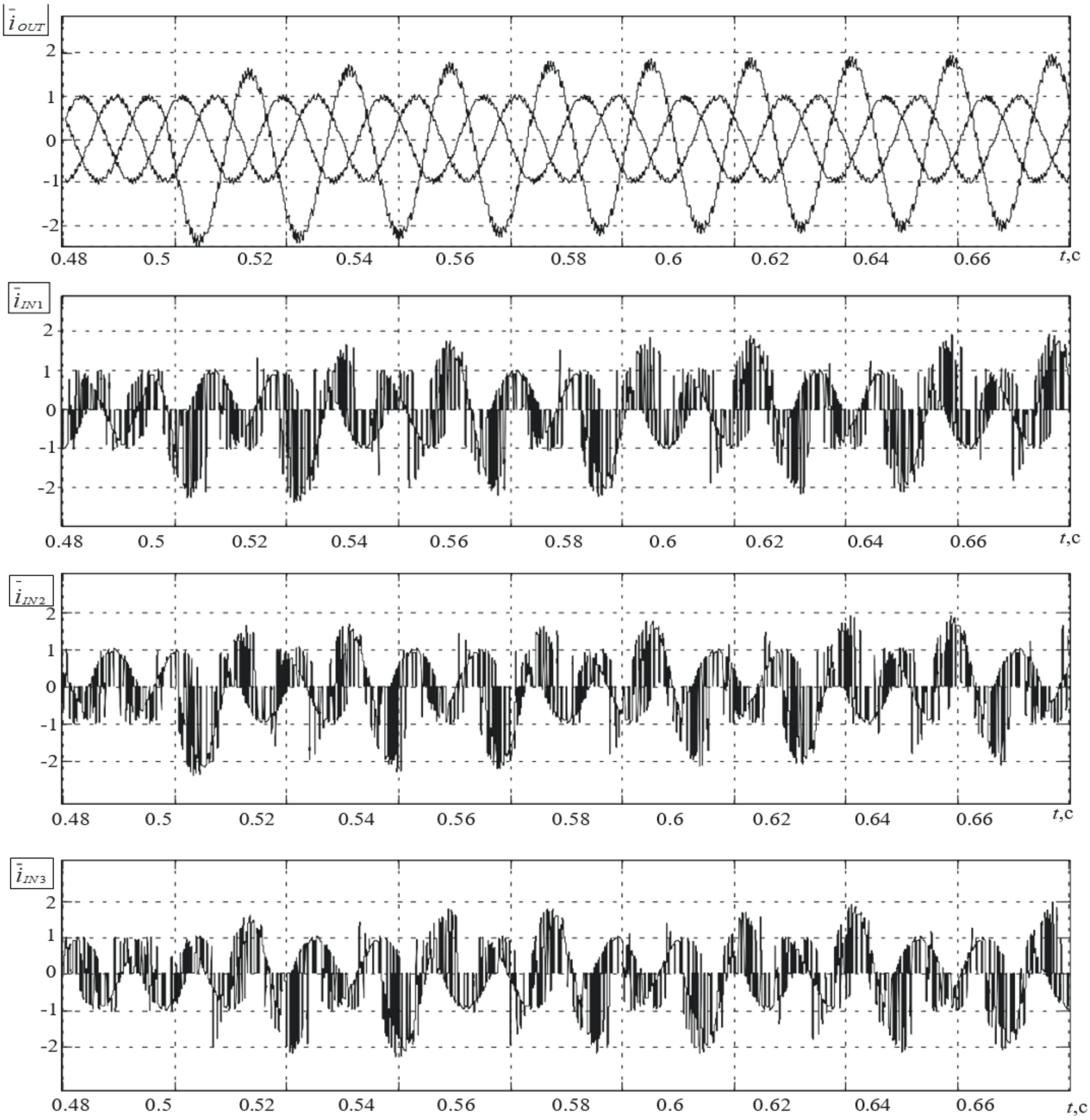
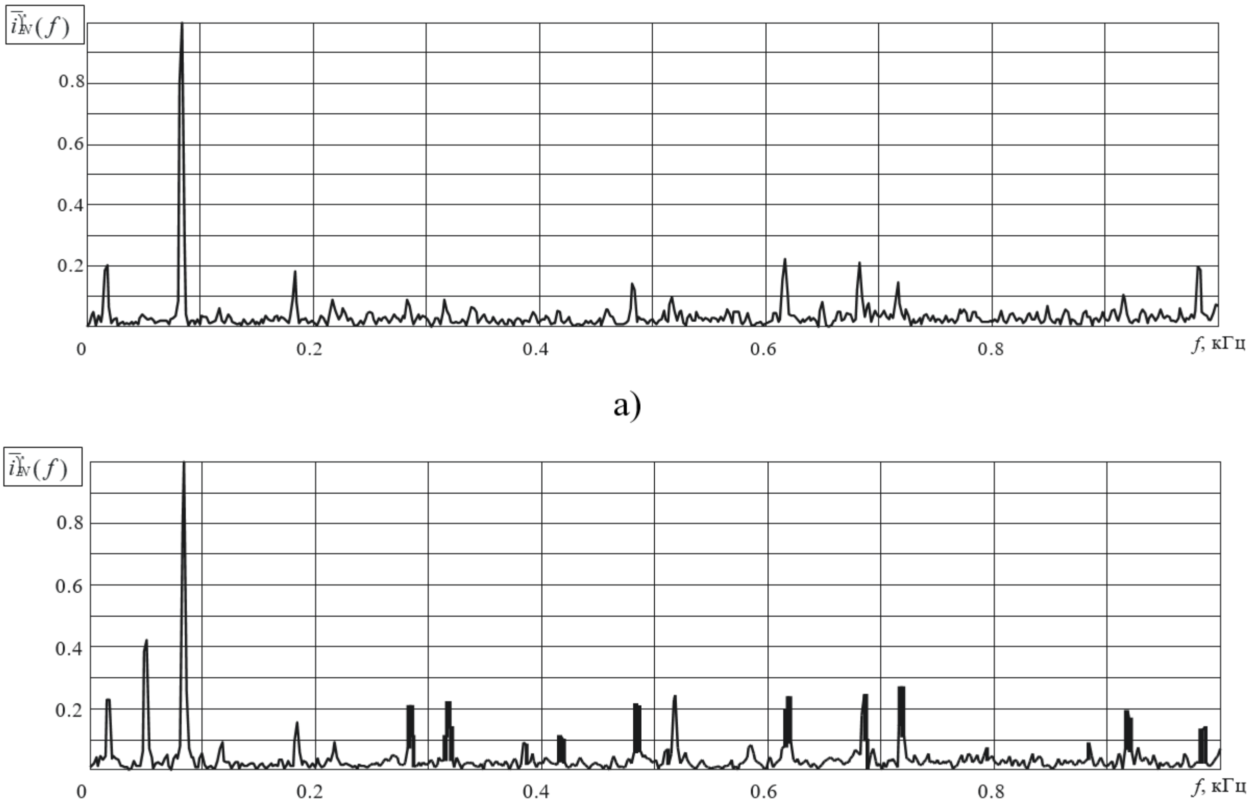


Fig. 2.10. Results of load shedding modeling for one phase

To analyze the effect of load shedding on one of the phases, Fig. 2.11 shows the input current spectra in steady-state modes under symmetrical (before *t* = 0.5 s) and asymmetrical (after *t* = 0.5 s) modes of operation of the conversion system.



а)

б)

Fig. 2.11. Spectra of input current before (a) and after (b) load shedding in one phase

The deterioration in the quality of the input current is due to an increase in the amplitudes of the high-frequency components and the second harmonic of the switching function with a frequency of $2f_s^-$.

2.5 Modeling of emergency modes

Emergencies in the power system are the result of equipment damage, insulation overlap and breakdown, false alarms of various devices and apparatus, and erroneous actions of personnel, which usually result in the shutdown of power plant equipment, the power grid, or consumers. In emergency modes, the configuration of the power system changes, and its parameters go beyond the requirements of technical regulations, which can pose a threat to human life and lead to a restriction of electricity supply and damage to equipment. The analysis of emergency modes allows us to identify the following types of accidents that are often encountered in practice: technological overloads that occur when the load is applied during the operation of the power system, short circuits to ground or between phases, phase or neutral wire breaks.

The voltage and current oscillograms of the electric power conversion system at the breakdown of one of the supply phases at time *t* = 0.5 are shown in Figure 2.12

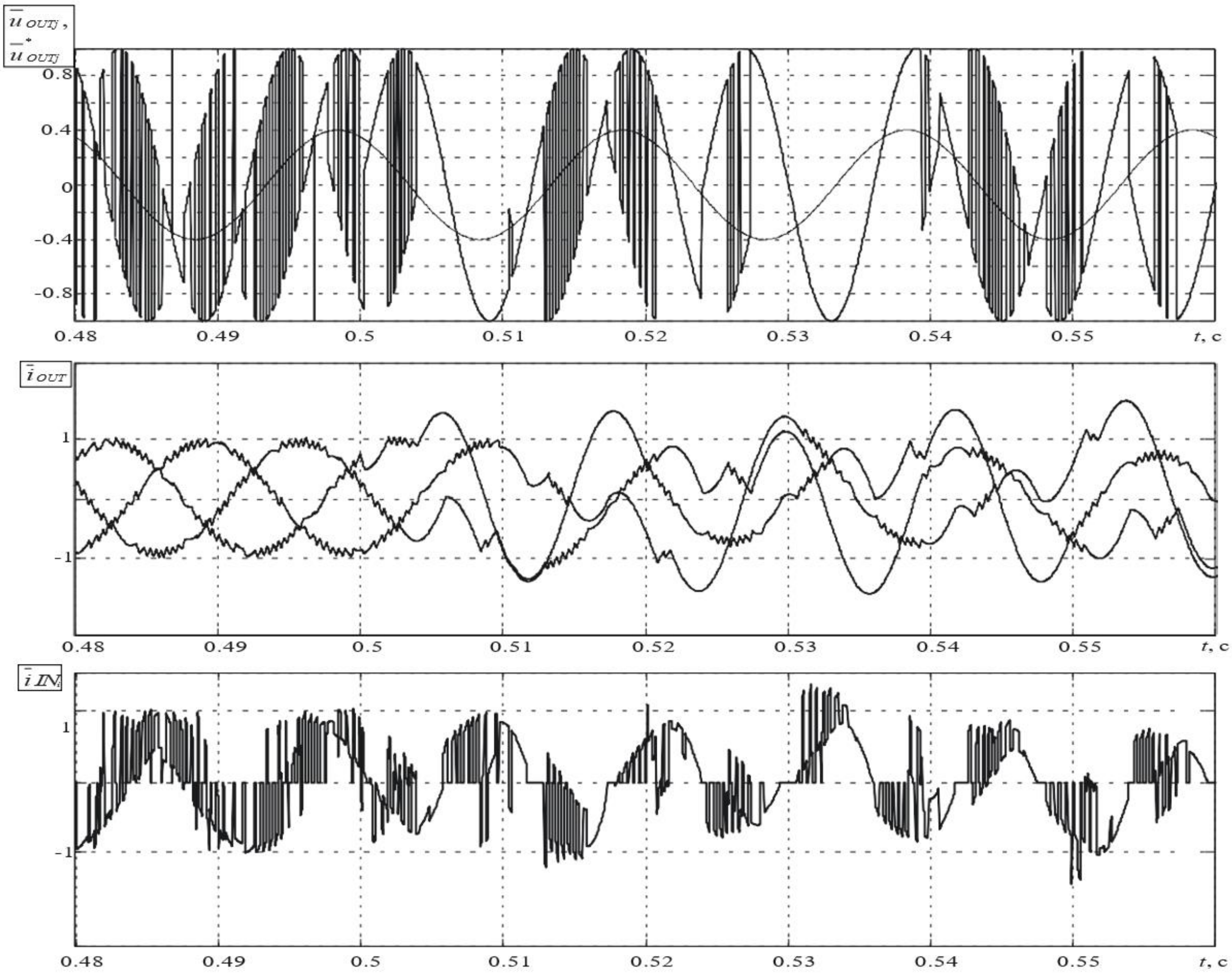


Fig. 2.12. Results of modeling the power supply network phase failure

Based on the algorithm of the control system, in the event of a breakdown of one of the supply phases, the matrix switch generates output voltages based only on the voltages of the two intact phases. Due to the lack of resource, the shape of the output voltages is significantly distorted, which is confirmed by their spectral analysis (Fig. 2.13).

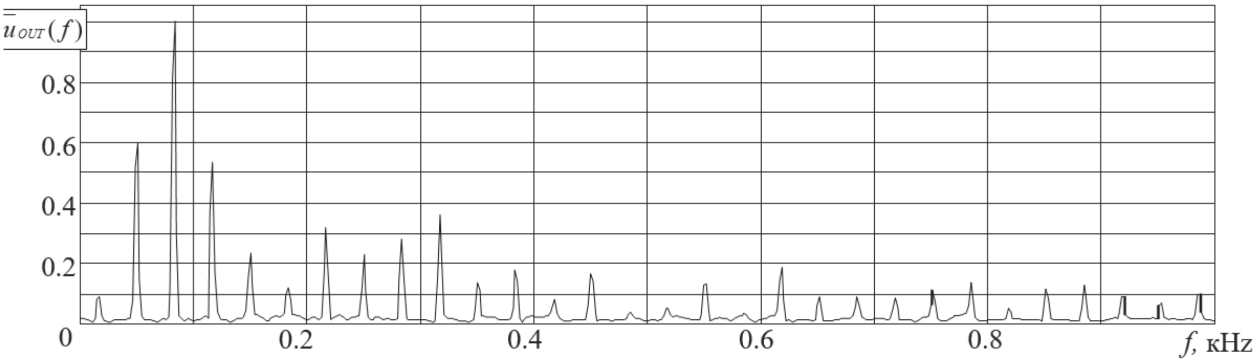


Fig. 2.13. Spectrum of output voltage when modeling a power supply phase failure

In the absence of voltage of one of the phases, periodically, at certain time intervals, the conversion system becomes unable to generate the required output voltage, which causes an increase in the share of low-frequency components in the spectrum. The presence of subharmonics in the output voltage also causes significant distortions in the currents of the intact input phases (Fig. 2.14).

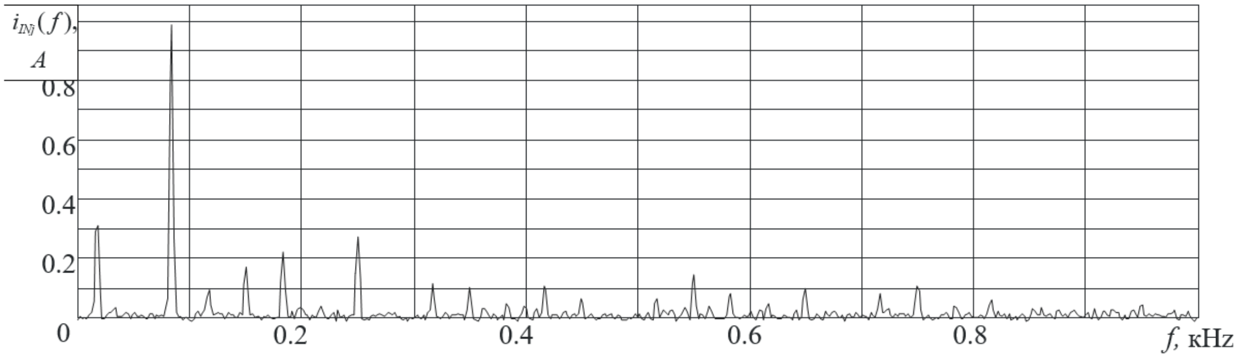


Fig. 2.14. Spectrum of input current when modeling a power supply phase failure

Despite significant distortions in currents and voltages, the adaptive regulator ensures the conversion system operability in the event of a breakdown of one of the supply phases, and its ability to ensure symmetry of input currents provides stability against a neutral wire breakdown.

2.6 Conclusions to Chapter 2

1.The study of the operation of automated control systems for the process of converting electrical energy in autonomous power systems was carried out using a computer model of a closed-loop control system with voltage feedback.

2.As a result of the modeling, it was confirmed that the spectral compositions of the converted voltage and input current contain frequency components determined by the repetition rates of the switching functions, i.e., the voltage formation under closed-loop control is carried out by a combination of modulation functions.

3.The results of static mode modeling have shown that the proposed method of automated control of the power switches of a matrix converter minimizes its impact on the power supply network while ensuring the required output voltage. The input current distortion factor is reduced by 7-38 %, depending on the ratio of input and output amplitudes and frequencies.

4.When modeling dynamic modes, high control efficiency was proved: when the frequency and amplitude of the supply network voltage change, the parameters and shape of the load current almost do not change, the frequency of the input current envelope over the entire time interval corresponds to the frequency of the supply voltage f_{In} ; when the load is switched on, additional distortions occur that are characteristic of a symmetrical load during transients, and in the case of asymmetry - even in steady-state mode, however, the symmetry of the input currents is preserved.

5.To analyze the functioning of the electric power conversion system in emergency modes, we modeled the breakdown of one of the supply phases. It is shown that the adaptive control system allows to ensure the efficiency of the conversion system.

CHAPTER 3

MEANS OF INCREASING THE EFFICIENCY OF MICROPROCESSOR-BASED CONTROL SYSTEMS FOR THE PROCESS OF ELECTRICAL ENERGY CONVERSION

The practical implementation of the proposed method for improving the energy efficiency of autonomous power systems through the use of optimal control of matrix converters requires consideration of a number of issues:

- Building microprocessor-based control systems for matrix converters based on modern microprocessor technology and programmable logic circuits requires analyzing the accuracy and efficiency of computing algorithms and structures and developing practical recommendations for choosing bit depths and quantization frequencies of digital devices;
- It is necessary to consider the possibilities of improving the control systems of electric power conversion processes based on matrix converters to identify ways to further improve their efficiency.

3.1. General structure of the microprocessor-based system for automated control of electric power conversion

The algorithm of functioning of an adaptive microprocessor-based control system for converting electrical energy requires constant real-time monitoring of processes in input and output circuits and generation of control signals for matrix switch keys, which necessitates the presence of interconnected subsystems for measuring parameters and calculating. The increasing degree of integration in microprocessor technology, the use of microcontrollers with a built-in set of specialized peripherals, makes it possible to significantly simplify circuit implementation by reducing the number of interface devices. Direct digital control implies not only the formation of control influences, but also the possibility of direct input of various feedback signals into the controller with subsequent software and hardware processing inside the controller. The functional diagram of the microprocessor-based system for automated control of the process of converting electrical energy in autonomous power systems is shown in Fig. 3.1.

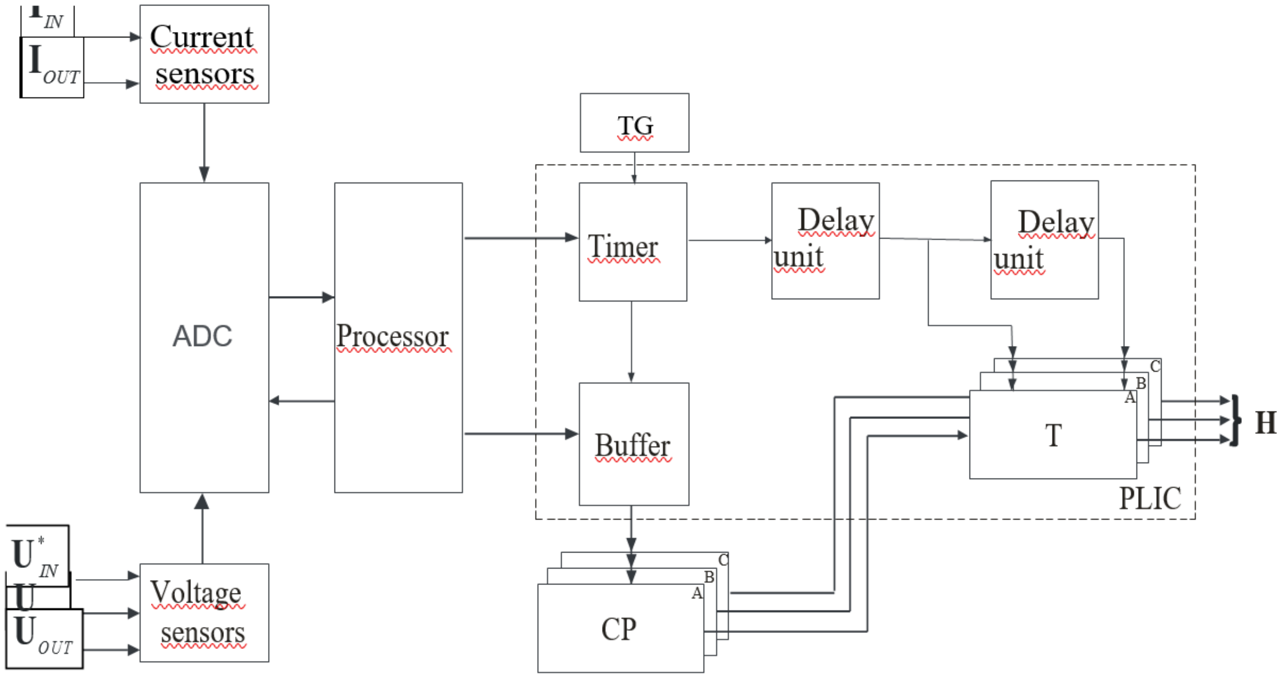


Fig. 3.1. Functional diagram of a microprocessor-based system for automated control of electric power conversion in autonomous power systems

The input and output currents and voltages, as well as the setpoint voltages, are measured by appropriate sensors. To measure currents, it is advisable to use the resistive method with a current shunt or sensors based on the Hall effect. The latter provide electrical isolation of the measurement subsystem from the power circuit, a wide frequency range, low energy losses, but require an external power supply. The input and output voltages and currents are digitized using an ADC and sent to a microprocessor [1]. To implement the proposed algorithm for controlling the electrical energy conversion system, the microprocessor inputs data from the ADC, analyzes it, determines the configuration of the matrix switch keys, which ensures a minimum of input current distortion at a given output voltage, and sends the result of calculations to a programmable logic integrated circuit that performs the functions of temporal and logical coordination of the microprocessor with the power keys of the matrix switch.

The programmable logic integrated circuit stores the states of all variables during the following subintervals in real time. The signals from the programmable logic integrated circuit are transmitted via optically decoupled drivers to the gates of the IGBT (insulated gate bipolar transistors) of the power section. In order to avoid cross-coupling of IGBT transistors, which can lead to a short circuit through the IGBT, the microprocessor first analyzes the current states of the keys. Digital filtering functions can be realized both on the basis of the use of a programmable logic integrated circuit and by microprocessor software [10].

An example of a processor that supports fuzzy logic commands is the 68HC12 family of microcontrollers manufactured by Motorola. The 68HC12 is a 16-bit microcontroller with an instruction system that includes 208 instructions, including commands for selecting the maximum and minimum numbers, as well as five division commands with 16/16 and 32/16 data bits in fixed and floating point formats, which allows the controller to be used in digital signal processing tasks. A feature of the 68HC12 is the ability to implement fuzzy algorithms due to the availability of specialized commands: MEM phasing commands, REV and REVW fuzzy variable processing commands, and WAW defuzzification commands [8].

3.2 Requirements for the practical implementation of digital filters in an adaptive control system for the process of electric power conversion

When microprocessors are used in control systems, physical limitations must be taken into account. Firstly, in any digital system, computational procedures require a certain amount of time, and, therefore, the controlling influences on the output of the microprocessor control device of the system will be carried out with a certain time lag relative to the input values. The execution time of any procedure depends on the number of machine cycles (elementary microprocessor actions) required to determine the output values at different times under different conditions, the waiting time for processing interrupts from external devices, etc. Taking into account time delays in the design and analysis of microprocessor control systems, as well as studying their impact on the dynamic properties of the system, are thus challenging tasks.

Secondly, it is necessary to take into account the effects associated with the sampling of input signals and the finite length of words processed in the microprocessor [4], the influence of which can increase when performing any mathematical operations. In the study of digital systems, level discretization is neglected in order to reduce the solution to a linear problem with a pulse system, without taking into account its impact on the accuracy and stability of the system due to the nonlinearity of the quantization process itself.

The magnitude of the quantization error is different for different algorithms and, in addition, for different implementations of the same algorithm obtained by using different programming methods. Based on this, it is possible, after analyzing the effect of quantization errors on the metrological properties of systems, to formulate practical recommendations for the optimal choice, taking into account the accuracy of the control algorithm and approaches to its implementation [2].

To study the effect of quantization on the metrological properties of control systems, digital links can be considered as linear, and level quantization can be taken into account by introducing additional noise sources into the system with an amplitude equal to the value of the quantization error limit $\Delta = X_{max} / 2^{N+1}$, where $X_{\max}$ - is the maximum value of the converted value, N is the number of bits. Then the upper limit of the quantization error of a digital system consisting of a set of links with the corresponding transfer functions W (z) can be estimated by applying known methods and rules for transforming the structural diagrams of automatic control systems. It should be borne in mind that to determine the transmission coefficient of a particular link relative to the input quantization error, it is necessary to choose its maximum value over the entire frequency range:

$$K = \max(|W(j\omega)|), \omega \in (0, \frac{\omega_T}{2}) \qquad (3.1)$$

where ω_{T} – is the quantization frequency of the digital link.

It can be shown that for a sequential connection of links with transfer functions W_1 (z) and W_2 (z), the total error is equal to the sum of the absolute errors caused by each individual link [3]:

$$\Delta = \Delta_2 + \Delta_1 \cdot K_2 \quad (3.2)$$

With a parallel connection, the total error is defined as:

$$\Delta = \Delta_1 + \Delta_2 \quad (3.3)$$

In the case when the link W_2 (z) is included in the feedback loop of the link W_1 (z), the following expression can be obtained by making additional transformations of the circuit:

$$\Delta = \Delta_1 \left(1 + \frac{1}{1 \mp K_1 K_2}\right) + \frac{\Delta_2}{1 \mp K_2 K_1} \quad (3.4)$$

where the "+" or "-" sign depends on the type of feedback: negative or positive. Some conclusions can be drawn from these examples.

First, parallelization of the computing process can lead to an increase in the error of the microprocessor control system. Secondly, the error in a serial connection, i.e., when performing actions on data sequentially, has certain limits. And thirdly, in the case of a feedback connection (i.e., in the case of implementing recursive computing procedures), the degree of error increase depends on the sign of the feedback.

Reducing the impact of restrictions related to the finite length of words processed in a microprocessor is possible by using a floating-point format for data processing, which requires additional resources and increases time delays in the microprocessor system.

The total error of a digital filter consists of the methodological error and the quantization error. The methodological error of a digital filter decreases with the relative frequency $\bar{f} = f_0 / f_T$ (where f_0 and f_T are the cutoff and quantization frequencies, respectively), and the quantization error, due to the dependence of the filter coefficients on the relative frequency, increases.

To analyze the effect of quantization on the accuracy of the digital filter, we simulated computational algorithms using the “MVTU 3.5” PACKAGE. A general model for determining the dependence of the relative error of the digital filter δ on the relative frequency $\bar{f}$ is shown in Fig. 3.2.

The model contains subsystems of digital filtering with processing of fixed and floating point numbers (Fixed and Float, respectively), which receive a sinusoidal signal of variable frequency and unit amplitude $x(t)$. The signals $y`(t)$ and $y``(t)$ transformed by the filters are compared with the reference signal $y(t)$, which is defined as the output of the ideal filter.

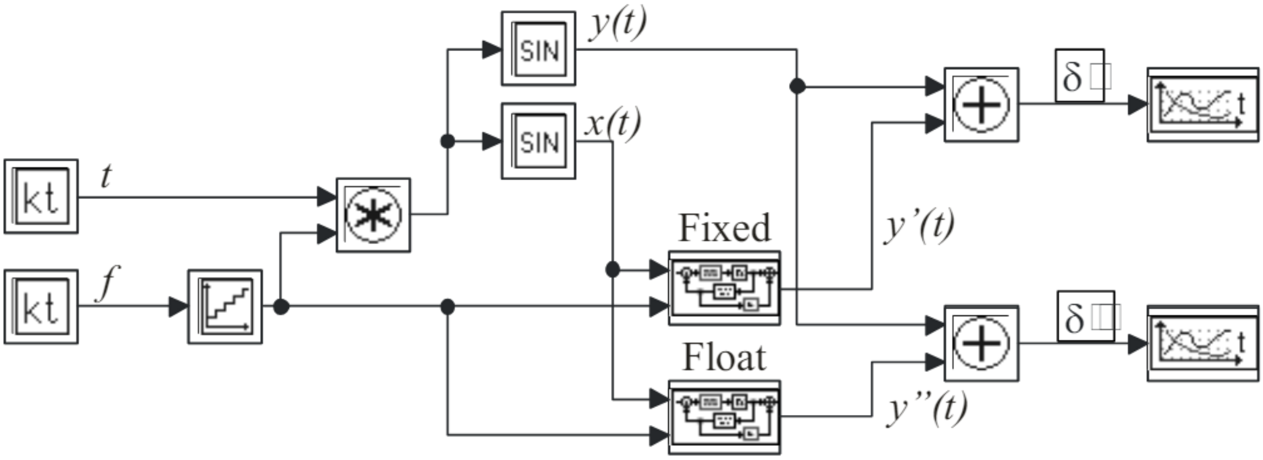


Fig. 3.2. General model for determining the dependence of the error of a digital filter δ on the relative frequency $\bar{f}$

The structure of the Fixed subsystem is shown in Fig. 3.3.

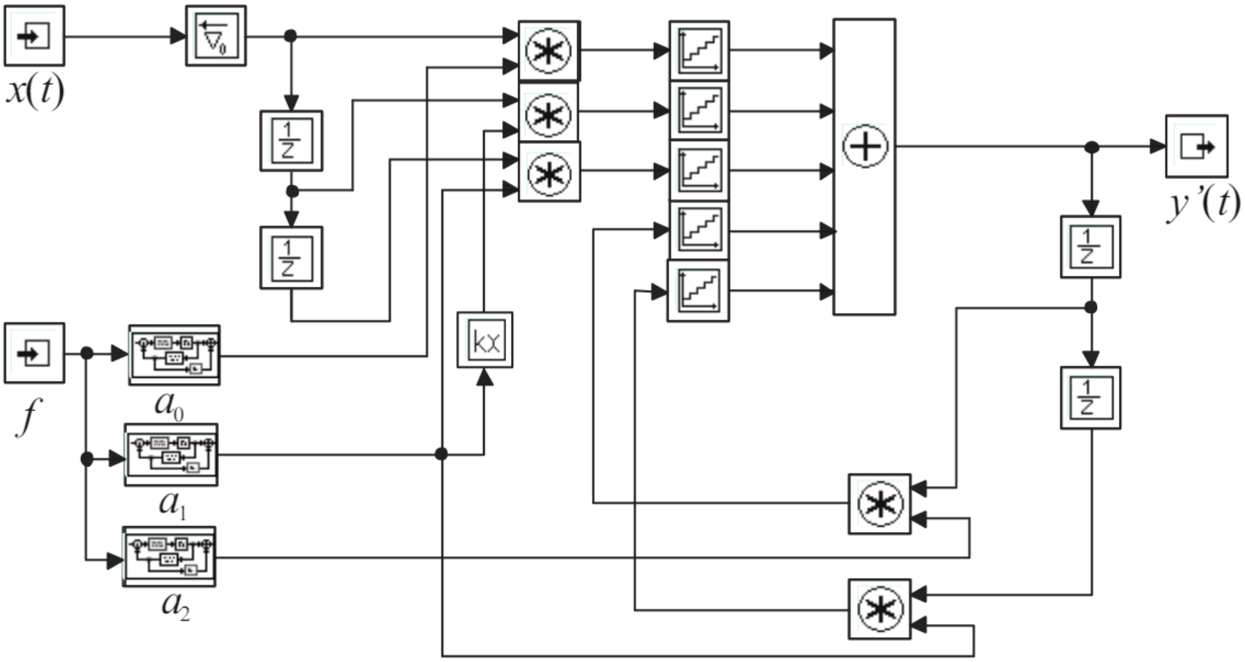


Fig. 3.3. Structure of the Fixed subsystem for digital filtering with processing of numbers in fixed-point format

The model implements the impulse transfer function of the Butterworth selective filter [3], which can be obtained by substituting

$a_0 = 4 \cdot \pi^2 \cdot f_{IN}^2$, $a_1 = \frac{2 \cdot \pi \cdot f_{IN}}{Q}$ and $s = \frac{1 - z^{-1}}{T_0}$, where $T_0 = {}^{\bar{f}}\!\big/_{\dot{f}_{IN}}$ - sampling time:

$$W_F(z) = \frac{a_0 - 2 \cdot a_1 \cdot z^{-1} + a_1 \cdot z^{-2}}{1 + a_2 \cdot z^{-1} + a_1 \cdot z^{-2}} \tag{3.5}$$

The coefficients of the transfer function W_F (z) are defined as:

$$a_0 = \frac{4 \cdot \pi^2 \cdot \overline{f^2} \cdot Q + Q}{4 \cdot \pi^2 \cdot \overline{f^2} \cdot Q + 2 \cdot \pi \cdot \overline{f^2} + Q}, \tag{3.6}$$

$$a_1 = \frac{Q}{4 \cdot \pi^2 \cdot \overline{f^2} \cdot Q + 2 \cdot \pi \cdot \overline{f} + Q}, \tag{3.7}$$

$$a_2 = \frac{2 \cdot Q + 2 \cdot \pi \cdot \overline{f}}{4 \cdot \pi^2 \cdot \overline{f^2} \cdot Q + 2 \cdot \pi \cdot \overline{f} + Q}, \tag{3.8}$$

According to the obtained expressions in the model in Fig. 3.3, the values of the coefficients are calculated, i.e., the filter is rebuilt depending on the relative frequency $\bar{f}$.

To simulate the processing of floating-point numbers, instead of quantizers, the model (Fig. 3.3) uses submodels that define the components of the processed data (orders and mantissa) and take into account the discretization for each component separately. The structure of the submodel of the quantization process when processing numbers in floating point format is shown in Fig. 3.4.

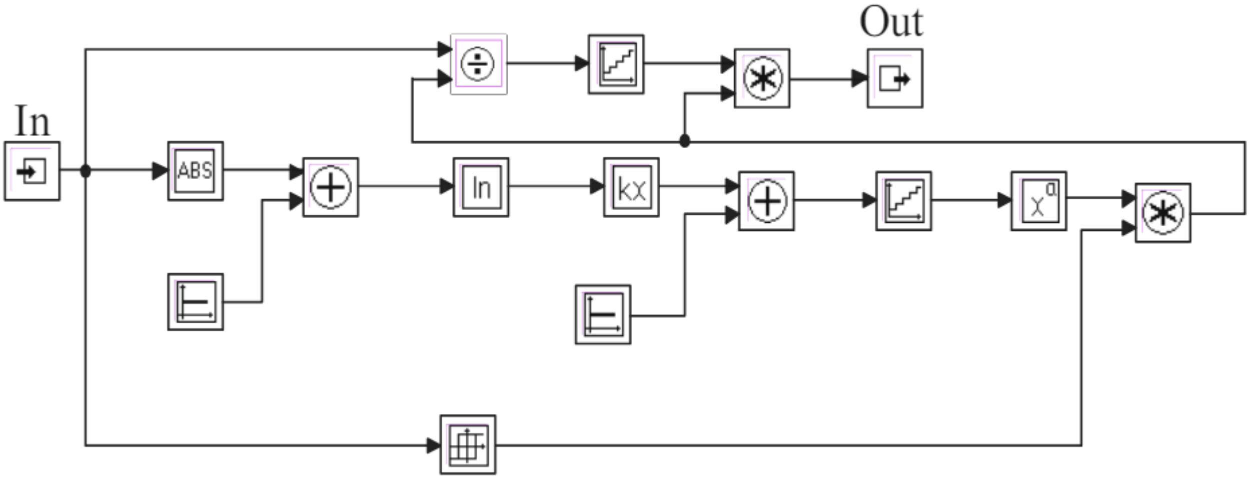


Fig. 3.4. Structure of the quantization process submodel when processing numbers in floating point format

In Fig. 3.5 shows the dependences of the total error of the second-order digital selective Butterworth filter according to expression (3.7), taking into account the effect of sampling depending on the relative quantization frequency $\bar{f}$ for the bit depth of the processed words 8 in fixed (a) and floating point (b) formats.

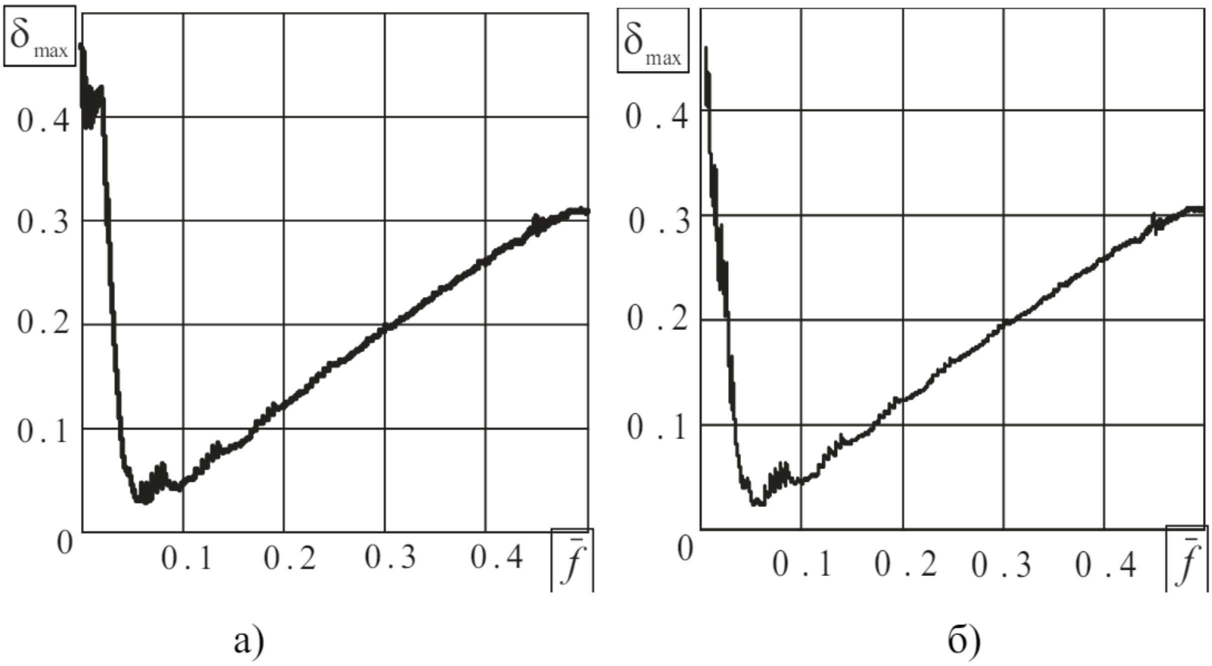


Fig. 3.5. Dependence of the relative error of the selective filter Butterworth filter:

a) fixed-point format; b) floating-point format

Increasing the number of bits significantly reduces the error value; at the number of bits of 16 and the fixed-point data format, the dependence of the error on the relative frequency is almost the same as in Fig. 3.5 b. As can be seen from the results obtained, there is an optimal value of the relative frequency of the digital filter at which the error has the lowest level. Taking into account the proposed recommendations for selecting the optimal frequency allows us to improve the accuracy of the functioning of the microprocessor-based control system for converting electrical energy.

3.3 Control of actuators of technological machines

The majority of mass applications of drives (pumps, fans, conveyors, compressors, etc.) of technological machines require a small speed control range (up to 1:10, 1:20) and relatively low speed. In this case, it is advisable to use classical automated control structures.

The use of AC motors in the actuators of light industry production is often associated with certain difficulties due to the peculiarities of technological processes [8]. For example, the following requirements are imposed on the drive of a grinding machine [4]: a wide range of rotational speed control to ensure the constancy of the warp tension and grinding speed when the radius of the warp changes; high smoothness of operation and speed control to prevent fluctuations in tension along the length of the warp, which lead to increased thread breakage. The development of an asynchronous drive that would fulfill all these conditions while ensuring high energy performance requires special and fundamentally new approaches to the construction of such a drive.

The implementation of wide-range drives (up to 1:10000) is possible due to the use of more complex vector control structures implemented on the basis of digital controllers operating on the principles of fuzzy logic. The vector control method is the basis of special control of induction motors [5]. Currently, this method has become an advanced one in high-precision drive control due to its efficiency and high reliability. Systems based on the vector principle are characterized, among other things, by simplicity and low cost. Asynchronous motors require complex control algorithms because they have a nonlinear relationship between stator current and torque or magnetic flux [3].

The vector control method involves controlling the flow, but since it cannot be measured directly, the rotor flow must only be calculated. The job of a microprocessor-based system is to keep the rotor flow amplitude constant. The complexity of the vector method is offset by its advantages. The method allows processing instantaneous electrical quantities, which allows for more accurate control both in transient modes and in steady state. This method controls the stator currents represented as a vector, which requires the conversion system operating as part of the automated drive to generate motor supply voltages not only with the required amplitudes and frequencies, but also with certain phases.

The ability of conversion systems based on matrix converters with a fuzzy controller to change the parameters of the converted electricity in real time opens up prospects for their use in asynchronous drives with vector control. The low level of distortion of input currents facilitates the solution of the problem of electromagnetic compatibility of the drive with the power supply network.

A modern tracking drive must provide a large range of speed control (up to 1:1000), high feed rates (up to 5-10 m/min), and specified dynamic characteristics (acceleration and deceleration times, magnitude of the mismatch) [5]. The requirements for dynamics are determined by the law of motion of the object and the conditions for the best filtering of the random component of the input signal [5].

In drives with a variable total moment of inertia (tippers, robotic manipulators, lifting and swinging tables, excavator support and rotary mechanisms, forging and pressing machines, etc.), changes in the input torque significantly affect transients in the electric drive, which leads to a significant underutilization of its capabilities [4]. Reducing the impact of changes in the input torque is possible by introducing positive speed feedback to the input of the current controller. In Fig. 3.6 shows a block diagram of a variable moment of inertia tracking electric drive with positive speed feedback [5].

The drive contains a controlled matrix converter, an induction motor (IM), a reducer (R), a control object (CO), a speed sensor (SS), a position sensor (PS), a current sensor (CS), a current controller (CC), a self-tuning speed controller (SC), a position controller (PC), a reference voltage source (VSS), adders Σ_1 and Σ_2, a multiplication unit, and an integrator.

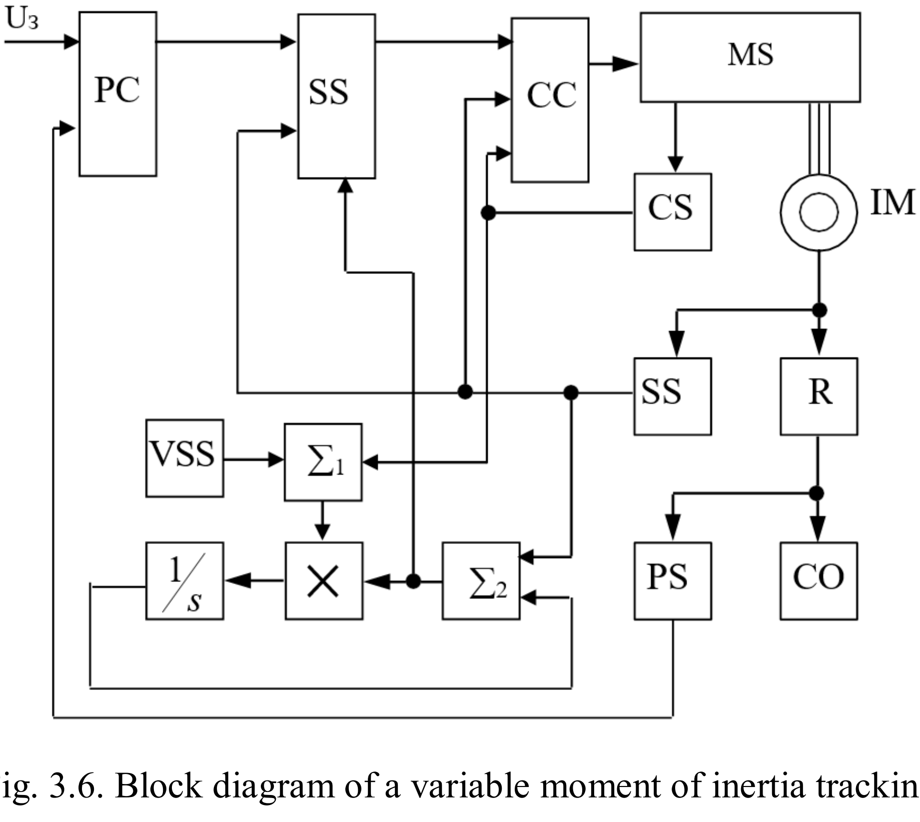


Fig. 3.6. Block diagram of a variable moment of inertia tracking electric drive with positive speed feedback

The control input of the self-tuning speed controller SC receives a signal inversely proportional to the value of the total input moment of inertia J_Σ from the output of the totalizer Σ_2 . The second input receives a speed error signal. When the moment of inertia of the drive changes, the value of the signal $1/J_\Sigma$ changes, which is equivalent to changing the parameters of the self-tuning speed controller. The signal from the speed sensor SS is fed to the input of the current regulator CR, providing positive speed feedback. The signals from the outputs of the adders Σ_1 and Σ_2 are fed to the inputs of the multiplication unit, which, together with the integrator, the adder Σ_2, and the speed sensor of the motor, form a feedback on the motor speed. The integrator time constant is determined from the condition of higher speed of the tracking system than the speed loop of the tracking electric drive.

The signal at the input of the integrator is proportional to the value of $dt/d\omega$, thus the output of the summator Σ_2 is an estimate of the parameter $1/J_\Sigma$, because from the equation of motion of the electric drive we obtain:

$$\frac{d\omega}{dt} = \frac{M_{\partial yn}}{J_\Sigma} \qquad (3.9)$$

Where M_{dyn} - is the dynamic torque on the motor shaft.

Or $$\frac{1}{J_\Sigma} = \frac{d\omega}{M_{dyn}\cdot\partial t} \qquad (3.10)$$

The structure of the microprocessor control system for a tracking electric drive imposes additional requirements on the dynamics and response speed of the converter, which is part of the system. Due to positive feedback, there may be abrupt changes in the setpoint from the output of the current regulator, which the converter, together with its microprocessor control system, must promptly respond to.

The application of matrix converters with closed-loop automated control systems in asynchronous tracking drives allows for significant improvement in the dynamic properties of the drives, reduction in weight and size parameters, and an increase in their operational reliability.

3.4 Conclusions to Chapter 3

1.The issues arising during the practical implementation of control systems for the conversion of electrical energy in autonomous power systems, as well as the ways to further enhance their efficiency, were examined.

2.A functional diagram of a fuzzy controller for a microprocessor-based system for converting electrical energy in autonomous power systems on a modern component basis was presented, and the requirements for its components were formulated.

3.The impact of quantization effects on the accuracy of calculations was analyzed for the implementation of digital filters using microprocessor-based means. These filters are intended to determine the degree of distortion in the input current of the converter. The relative frequency range was determined within which the minimum sampling error is ensured. Practical recommendations were developed for selecting the quantization frequency, which can be used in the design of various digital signal processing devices.

4.The application of an adaptive control system for the process of electrical energy conversion to power controlled asynchronous drives of various mechanisms and machines enables the provision of smooth operation and frequency regulation within wide limits. Due to the ability of the electrical energy conversion system based on a matrix converter with a fuzzy controller to generate high-quality output voltages with required amplitudes, frequencies, and phases, it can be applied in implementing scalar and vector control of alternating current drives.

CONCLUSIONS

1.Increasing the efficiency of control processes for converting electrical energy in autonomous power systems is one of the ways to address the challenges of coordinating the parameters of generated and consumed electrical energy, as well as ensuring the reliable operation of conversion systems under various operating conditions.

2.The analysis of existing models and control methods for the processes of electrical energy conversion in autonomous power systems has highlighted the necessity of constructing an adaptive control system for conversion processes. This need is justified by the aim to improve quality metrics and enhance the efficiency of the conversion process through the coordination of autonomous power units and consumers.

3.A generalized criterion for assessing the quality of input currents in a multi-phase matrix converter has been proposed to account for distortions in each input phase of the converter. Based on this criterion, the problem of optimal control of the electrical energy conversion process has been formulated.

4.A method for optimal control of a three-phase matrix converter based on minimizing input current distortions while maintaining a specified output voltage has been proposed. This method ensures a lower level of current distortions at the converter input and high-frequency components in the converted voltage, all achieved through a relatively simple control algorithm.

5.It has been proven that the use of the developed method for controlling the process of electrical energy conversion in matrix converters allows for: significant reduction of harmonic amplitudes in the input current; improvement of the quality indicators of electrical energy in autonomous power systems by reducing the distortion coefficient of the input current by 7-38% depending on the relationship between input and output amplitudes and frequencies; ensuring the operability of the conversion system during emergency situations.

6.An analysis of the influence of nonlinearities on the accuracy of computational procedures in digital control loops for the process of electrical energy conversion has been conducted. Additionally, the method for evaluating the level of quantization errors has been refined, allowing for the selection of optimal tuning parameters for microprocessor control systems in the process of electrical energy conversion to ensure low levels of errors associated with quantization processes and high-speed performance of microprocessor control systems.

7.The issues related to the implementation of the proposed control method based on modern electronic components have been discussed. Requirements for the main functional components have been formulated. Moreover, ways for further improvement of control methods for electrical energy conversion systems based on matrix converters have been identified.

8.The application of an adaptive control system for the process of electrical energy conversion to power controlled asynchronous drives of various mechanisms and machines enables the provision of smooth operation and frequency regulation within wide limits.

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