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ASPECTS OF THE DEVELOPMENT OF MODERN CONTROL SYSTEMS

IMPROVING THE QUALITY OF ELECTRIC ENERGY IN THE DISTRIBUTION NETWORKS OF IRON ORE ENTERPRISES

Monograph

Under the editorship of Candidate of Technical Sciences, associate professor I.O. Sinchuk

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The monograph presents the materials of the author's research and his vision regarding the solution of the scientific task of theoretical justification and development of the principles of determination, control of the parameters of the quality indicators of electric energy and the construction of systems for adjusting the energy indicators of electric energy by means of a controlled influence on the operation of the network inverter, due to the application of the theory of neuro-fuzzy networks in the system of managing its operation according to the current value of the main indicators of the quality of electric energy and imperially calculated indicators of losses of electric energy in the distribution network.

An analysis of the current state and prospects for the development of systems for maintaining the quality of electric energy in Ukraine is given. The management structure of the electrotechnical complex of control and management of electric energy quality levels is proposed for implementation in the conditions of distribution networks of iron ore enterprises.

The monograph is intended for students of higher education of the 2nd and 3rd levels of the relevant universities, and it can also be useful for organizations and enterprises that are engaged in the development, design and installation and operation of control systems by means of improving the quality of electrical energy in electrical networks.

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INTRODUCTION

To date, in most cases of world practice, a centralized structure of generation and distribution of electrical energy is used. It should be noted that such traditional sources of energy have a finite supply, which may be exhausted in the near future. Meanwhile, the use of traditional energy sources causes significant damage to the environment, causing such effects as air pollution, global warming etc [1].

To eliminate these shortcomings, traditional energy sources should be replaced by renewable energy sources, such as wind energy, solar energy etc. Since these sources are connected to the power supply network at the level of distribution of electrical energy, such sources are called sources of distributed generation.

However, the integration of renewable sources into existing networks creates problems with the quality of electrical energy. A typical distribution network has a stochastic character. The power consumption of each bus, as well as the location and instantaneous power values of renewable electrical energy sources, are random. Due to this uncertainty, indicators of the quality of electrical energy can significantly decrease [2].

Distributed generation produces electricity from many small energy sources. However, when integrating such sources into the network, a number of technical and economic problems arise. Technical problems arise in aspects of the quality of electrical energy, voltage stability, reliability, etc. Therefore, systems with distributed generation must satisfy a number of strict technical requirements to ensure efficient, reliable and safe functioning of the general power supply network. The rapid development of power electronics and digital control systems makes it possible to develop devices that will provide active management of the energy characteristics of distributed generation sources in order to improve the operation of the power supply system by improving the power quality indicators at the point of common connection of loads [3].

It should be noted that the use of equipment containing power semiconductor switches generates harmonic components of currents at the point of common connection of loads, i.e. it is a non-linear load from the point of view of the network, i.e. it worsens the quality of electric energy.

Another aspect of the operation of such systems is that electrical energy is generated, transported, distributed and used in the form of alternating current. However, the use of alternating current, along with a number of positive sides, has certain disadvantages. The first of them is related to the presence of reactive power, which flows in the network in series with active power. At the same time, reactive energy cannot be used by converting it into other types of energy. Therefore, the level of its circulation in the network is tried to be minimized, and therefore, the provision of reactive power compensation is required from the sources of distributed generation [4].

The work includes the development of a new control system for network inverters when used in a three-phase, 4-wire power distribution system, which allows solving the issue of power quality and reactive power balance. At the same time, the inverter is considered as a multifunctional device, since, in addition to the function of converting the parameters of electrical energy, it relies on the functions of an active filter. Thus, the grid inverter can be used to ensure high quality and symmetry of the sinusoidal voltage in the power supply network, as well as to compensate for reactive power without compromising its main function [5].

CHAPTER 1.
ANALYSIS OF THE CURRENT STATE OF ELECTRICAL ENERGY QUALITY IN NETWORKS WITH DISTRIBUTION GENERATION

1.1. Analysis of the development of world energy

Modern energy systems include tens of thousands of elements that work in pairs at different nominal voltages, include thousands of power lines and substations, heat networks that are connected into one whole by the ash regime and the continuity of the production process, distribution and consumption of electrical and thermal energy. The construction of the power system, and later the combined national and international power systems with strict centralized management, had a great social and technical and economic significance at the time [6].

Modern industrial electricity was practically formed in the 1960s. Over time, a significant part of the electrical network equipment in use has reached the limit of the standard service life. Taking into account the social factor, the regulatory bodies of most countries objected to the increase of tariffs whenever possible, which did not allow to fully carry out large-scale expensive modernization of the infrastructure. Thus, power engineers were forced to continue working with equipment that had already reached the end of its useful life. In addition, energy companies focused on the development of the generation sector. In the mid-1970s in the USA, in the structure of investments for the development of energy, the share of costs for the transmission and distribution of electricity was less than 30%. This indicator grew to 45% by the end of the 1990s, but it was not enough to fully compensate for the backlog in increasing the capacity of electrical networks. As a result, the reliability of the operation of the entire electric power industry decreased [7].

In this regard, starting from the 1970s, most specialists in the field of energy focused on the serious disparities that have developed in the industry.

Thus, in many industrialized countries of the world, there were large-scale disruptions in electricity supply. For example, in June 1977, electricity supply to New York was stopped for 25 hours due to the disconnection of power lines due to a lightning strike, which led to a loss estimated at 10 million dollars; in August 1996, more than 15 million residents of the United States and some areas of Mexico were left without power supply for 10 hours as a result of overloading of power lines; in August 2003, the biggest accident in the history of energy occurred, which was called the "great blackout". Large-scale power outages affected megacities in the states of New York, Ohio, Michigan, Pennsylvania, Connecticut, New Jersey, as well as in Canada (Toronto, Ottawa). The total load loss was 61,800 MW. During the development of the accident, 263 power plants were shut down, including 10 nuclear power plants; in September 2003 – damage to the Italian power system; in May 2005 – an accident in the power system of Russia; in November 2006, problems in the German power system left millions of people without electricity not only in Germany, but also in Italy, France, and Belgium; in November 2009, there was damage to the transmission line connecting the world's largest HPP Itaipe (Brazil) with the center of the country [7].

The most important changes in the energy sector were associated with the active use of sources of generation and accumulation of energy of small and medium capacity. This is due to the fact that the global consumption of organic fuel is constantly increasing, while its price is constantly increasing, largely due to the insufficient efficiency of traditional energy. In addition, environmental restrictions, the increasing cost of land and water, government regulation and other factors are important objections to the construction of new powerful power plants and the development of centralized energy. With the emergence of competitive energy production technologies in the world, a fairly active intervention of "green" energy (based on renewable sources) in energy supply began.

Most of the articles are devoted to the application of distributed generation. These works related to the analysis of advanced technologies of energy generation and accumulation [1-3], considered the conditions of integration of individual means of distributed generation in the power system [1-3], their influence on the regimes of electric networks [2].

According to the White Book (distributed energy resources and technologies. Creating conditions for their optimal use in Ukraine), the term "distributed energy technologies" derives from the content of EU Directive 2019/9443, which defines distributed energy resources through the prism of technologies: generation, storage) and demand response management. For implementation in Ukrainian conditions, it is appropriate and practical to use the term "distributed energy technologies". The authors of this document suggest using this definition:

Distributed energy technologies (DET) are technologies that enable interaction with electrical installations connected to the distribution system (or the implementation of which is a part of such electrical installations) and provide a technical possibility to produce and/or store electrical energy for the purpose of releasing it to the network and/or provide demand management services.

Of course, the world experience of using DET contains a large number of the most diverse business models and their combinations, but within the framework of such a document it is not worth trying to describe them all. Especially since entrepreneurs in different countries are constantly inventing and implementing new business models [8].

An important characteristic of the target state of the market is the maximum involvement of prosumers and active consumers in participating in various segments of the electricity market in the spirit of the Fourth EU Energy Package. Today, only one type of prosumer has gained significant popularity in Ukraine - the owners of home solar electricity systems operating under a "green" tariff. The authors of this document believe that it is necessary to unlock opportunities for other (not "green tariff") work models.

To solve problems related to the use of distributed generation (DG) in the energy sector of Ukraine, it is necessary to ensure the fulfillment of a number of conditions, the main of which are [9]:

- the formation of a legislative field and a regulatory framework that allows to minimize administrative and narrow-departmental barriers in the implementation of innovative projects, which would create conditions for stimulating investments in this sphere of the economy, which would ensure the transparency of the technical conditions necessary for the implementation of relevant projects;
- ensuring the correct control of the real information environment in which the design and operation of small energy facilities is carried out, in order to achieve the actual effectiveness of the planned results;
- creation of an adequate decision-making methodology, in accordance with the optimal form of application of WG tools, which will allow taking into account a combination of various factors, the most relevant and characteristic conditions for the conditions of Ukraine, so that this procedure is as efficient, transparent and understandable as possible for all parties interested in this process;
- development of a strategy for the use of power electronics (PE), which are built on a modern element base, as well as local control and protection systems.

For Ukraine, the task of increasing energy efficiency today has shifted from a number of purely economic issues to the sphere of ensuring energy and even national security.

The optimal structure of the electricity industry should take into account powerful power plants, without which it is difficult to fully supply large consumers with electricity, and developing distributed generation, which, integrated into the structures of centralized electricity supply, will lead to the formation of integrated electricity supply systems.

Therefore, the transition from exclusively centralized energy to distributed network intelligent energy is a strategic long-term vector of changes in the energy contribution to the world. In this regard, Ukraine needs to quickly review the philosophy of the future development of the energy industry, paying due attention to the use of distributed generation, the creation of microgrids as an important component of Smart Grid technology.

In the conditions of extremely limited investment resources, even the point-by-point implementation of individual projects for the implementation of DG means requires careful analysis and argumentation in order to achieve the maximum, most importantly, real effect. Therefore, special attention should be paid to the creation of methodical and algometric support that allows effective and well-founded decisions to be made in a real information environment when forming projects for the use of DG tools, especially in the case of their complex application, in time, in the form of a micro network.

Distributed generation produces electricity from many small energy sources. However, when integrating such sources into the network, a number of technical and economic problems arise. Technical problems arise in aspects of the quality of electrical energy, voltage stability, reliability, etc. Therefore, systems with distributed generation must satisfy a number of strict technical requirements to ensure the efficient, reliable and safe functioning of the general power supply network [10].

1.2 World practice of implementation of intellectualization of electric power systems

Today, we are already on the threshold of the next stage of development of Internet technologies - the Internet of Things. This technology enables a global combination of control objects and people. So, this should lead to increased automation and efficiency of their functioning as a whole.

This approach should increase the level of intellectualization of processes and the development of "intelligent" networks aimed at ensuring the management of power system operation modes, creating conditions for information exchange and ensuring the reliability of their operation [11].

The scientific community predicts rapid further development and implementation of connecting objects to the Internet. If the forecasts come true, this technology will literally change the principles of interaction between people, industrial facilities, infrastructure facilities, and society. Management and monitoring of such objects in real time from any location without direct interaction will provide an opportunity to build radically new approaches to management. This state of affairs should strengthen the optimization processes in the systems and give them new properties, which should lead to saving time, resources and improving the quality indicators of interaction.

Today, the global trend of modernization of industrial enterprises with the aim of increasing the efficiency of production and the efficiency of energy consumption should be noted. Such modernization approaches are aimed at increasing the overall efficiency of the equipment of these enterprises by reducing energy costs for the technological production cycle. It should also be noted the introduction of the latest computerized systems in the conditions of industrial production complexes with a connection to the Internet.

Modern control systems at industrial enterprises increase the level of intellectualization due to the ability to transmit a large volume of data in real time. Connecting devices to the Internet is widespread among industrial facilities, infrastructure facilities, and personal use [12].

It should also be noted the implementation of the following technologies in electric power systems. They became widely used in lighting and signaling systems, which increased their level of energy efficiency and functionality.

Meanwhile, it should be noted that reliability of electricity supply, energy efficiency and energy security are determined among other areas of energy industry development. The global energy industry is currently characterized by processes of reconfiguration and implementation of intellectualization based on the modern Smart Grid concept.

The experience of the developed countries of the world shows that the solution of today's issues in the energy industry is possible only with the use of advanced technologies. For this purpose, the direction of the development of the world energy industry was determined within the framework of the introduction of modern energy-efficient technologies, decarbonization and intellectualization of the industry [13].

Thus, the active intellectualization of the energy industry is due to the corresponding structural changes in the structure of electric power systems, through the introduction of distributed generation based on renewable sources of electric energy.

Modern trends in the development of the energy industry within the framework of the modern concept of Smart Grid should also include power system mode control systems, distributed generation and power consumption systems, power distribution automation systems for medium and low voltage classes, electricity consumption accounting technology and mode load control.

The rapid development of power electronics and digital control systems makes it possible to develop devices that will provide active management of the energy characteristics of distributed generation sources in order to improve the operation of the power supply system by improving the power quality indicators at the point of common connection of loads.

Adaptive automatic control systems (ACS) in which the incompleteness of a priori information is supplemented by more complete use of current information with simplified process models [14].

Among the most significant changes in the development of society and the economy, which affect the energy sector, among others, are the following: a shortage of sources of electrical energy, constantly growing demands for the reliability and quality of electricity supply from consumers, and a decrease in overall system costs.

At the same time, a fully integrated distributed generation and an activated end-consumer consumption management system will allow taking over part of the system services, reducing the role of centralized generation. This circumstance will also help ensure more efficient transmission and distribution of electricity.

This requires a change in the power system management paradigm – from the concept of centralized management – to the concept of distributed management.

Thus, the main factors that determine the need for radical transformations in the electric power industry under the influence of difficult conditions can be grouped as follows [15].

It should be noted that in the domestic electric power industry, over many years, technologies have been developed, which are essentially elements of the Smart Grid. This primarily concerns systems of automated and automatic control of processes in electric power systems (EPS). As an example, due to active-adaptive systems of optimal control, the reliability of electricity supply and the quality of electricity were maintained at the appropriate level.

The development of modern electrical networks requires constant improvement of the technical means used for optimal management of modern EPS, which in turn creates opportunities for improving the functioning of EPS and causes the development of methods and algorithms that are the basis of modern ACSs.

Modern operating conditions of EPS lead to the occurrence of many complications that arise during the operation of ACS [16]:

– in the process of evaluating the current mode, sometimes anomalous measurements occur, which are caused by telemetry failures;

– existing methods and algorithms included in ACS operation do not take into account all influencing factors on the EPS operation mode, therefore the control influences are inaccurate;

– the technical condition of the regulatory devices does not allow all control influences to be fully implemented.

If we specify the concept of Smart Grid as a concept for the development of energy systems at different levels, then it should be noted, first of all, the fact of the use of such terms as Regional Smart Grid and Micro Smart Grid, which are characteristic for the description of energy systems of industrial importance and regional in conditions of active urbanization. The functional capabilities of these systems are determined by the tasks that were assigned to them, as a rule, at the design stage. To date, the solution of tasks of various levels in electric power systems of various levels of complexity can be due to the introduction of power electronics elements, a common example of this is the introduction of devices for converting electrical energy parameters into the system. Therefore, the elements of power electronics are typical elements of electric power systems built on the basis of the concepts of Regional Smart Grid and Micro Smart Grid [17].

It should be noted that Regional Smart Grid and Micro Smart Grid systems have a number of characteristic features and differences. Thus, Regional Smart Grid systems of relatively low power are characterized by great instability of electrical parameters. While the Micro Smart Grid, which includes sources of electrical energy based on renewable energy sources and a large number of consumers of electrical energy, which are characterized by different modes of operation and energy parameters, are characterized by different speeds and are not limited by the range and time of changes in electrical parameters energy, which may have a stochastic character due to the high complexity of the system.

Meanwhile, it should be noted the peculiarities of the interaction of electric power systems built according to the Smart Grid concept. Such systems have an unconditional compatible influence of one system on another with the definition of leading and slave systems. Such mutual influence prompts the determination, during the design and modernization of existing electric power systems, of the features of the construction of their control systems and methods of construction of information channels in such systems.

One of the modern methods of transmission of control signals in electric power systems is their transmission by power electrical networks [18].

1.3 General assessment of the impact of distributed sources of electricity on the operation of distribution networks

In the course of the transition from the wholesale electricity market of a single buyer to the balancing one and to electricity supply under bilateral contracts, in recent years and for the future, a trend of transition from a purely centralized electricity supply to a combined one is observed in Ukraine, when the number of local sources of electricity increases. Local sources of electricity operating directly in 10–6–0.38 kV networks include both traditional low-power sources and alternative ones. Renewable sources of electricity (RSE), cogeneration plants, gas and steam-gas plants, etc. are being developed as an alternative to traditional ones.

At the same time, electric networks (EN) of energy systems were designed and built under the conditions of centralized power supply, when electricity from large thermal and nuclear power plants was transformed and transferred to consumers [19].

With the development of decentralized sources of electricity (DSE) in distribution networks, new tasks arise, such as the need to optimize the combined power supply from EPS and decentralized generation, coordination of the coverage of the load schedule by distributed sources that, due to their physical characteristics, can produce power according to different schedules, evaluation impact of DSE on the value of short-circuit currents and, accordingly, on the operation of relay protection and automation, assessment of the impact on technical and economic indicators of distribution electric networks (DEN) etc.

The influence of DSE on DEN modes depends significantly on the value of the total distributed generation in it, on the unit installed power of DSE and their type, as well as on their connection location in the electrical network (these can be lower voltage buses of substations or branches of power transmission lines).

In addition, it should be taken into account that at the same time the economic conditions of the operation of the electric power industry as an industry are changing, in particular, the model of the wholesale market is changing. In the case of implementation of electricity supply under bilateral contracts with the participation of DSE, when the latter supply power to the electric network, there is a need to coordinate their work with the power system from which centralized power is supplied [20].

This becomes mandatory when the installed capacity of the DSE in EN is a significant proportion of its total load (for example, 20% or more). In this case, the DEN can and should be considered as a local electrical system (LES), in which, in addition to the above-mentioned tasks, there are the tasks of studying the static and dynamic stability of the DSE and others that are characteristic of the electrical system.

The urgent task is to obtain the maximum profit from the operation of RSE for their development, provided that electricity losses are reduced and its quality is improved in DEN, as well as the reliability of electricity supply is increased. At the same time, taking into account that electricity from DSE is transmitted by DEN lines simultaneously with electricity from other sources, it is necessary to allocate from the total losses of electricity the share that concerns transit from DSE.

Today, electricity losses in the electrical networks of energy supply companies of Ukraine amount to 11.5–12.1% of its release into the electrical network, which is significantly more than in the USA (6.5%), England (8.6%), France (4.5%). It is recognized that distribution networks are the most problematic and costly factor in the electricity supply of territories [21].

DSE is an important area of influence on power losses in distribution networks. It is obvious that both DSE parameters and their connection schemes, as well as the volume and consumption schedule of adjacent loads, affect the value of losses in EN.

Possible schemes for connecting DSE to DEN are presented, which differ significantly in their impact on power flows and, accordingly, on power and electricity losses in the network. In fig. 3.1, and DSEs are connected to the busbars of the substation. In this case, the transformer is unloaded to the power produced by the DSE, and as a result, the load losses in the transformer are reduced. In power transmission lines, losses do not change. In the version shown in fig. 3.1, b, both the transformer of the substation and part of the power line are unloaded, which provides an additional reduction in power losses. Since the power flow is reduced, the voltage losses are also reduced, which helps to improve the voltage levels at the 10/0.4 kV substation buses [22-29].

Based on the typical DSE connection schemes to distribution networks, at certain generation capacities, they partially compensate for the power flows caused by the load of consumers, and the supply of electricity from the system decreases. At the same time, electricity losses in distribution networks are reduced.

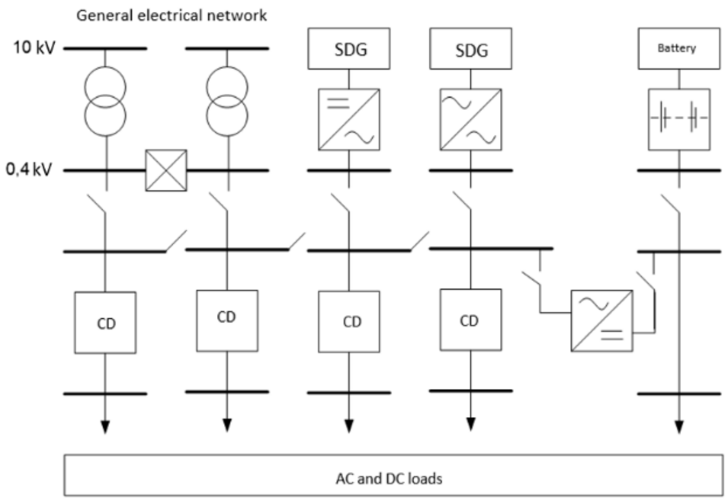

Figure 1.1 – A typical DSE connection scheme to distribution networks

Meanwhile, when connecting a wind energy turbine (WET) to the distribution network, it is necessary to analyze their interaction in order to find out what effect the WPE will have on the operation of the power system and what are the requirements for the protection and control equipment of the electrical system and the generator [29-37].

The results show that the wind energy turbine generator should be disconnected from the distribution network in case of any damage. Changes in voltage in the distribution network due to changes in wind speed are greater if the synchronous generator is connected to the line at a point far from the substation. The change in voltage is also greater with sudden decreases in wind speed than with wind gusts of the same amplitude [38].

If the generator is connected to the power system at a substation, the voltage variation on any line fed from that substation is less than 0.5% for the most severe conditions tested. If the generator is connected closer to the end of the line, sudden decreases in wind speed and its gusts cause voltage fluctuations in the distribution network equal to 2.2%.

A decrease in the voltage in the network in connection with the connection of wind energy turbines to it can occur during the start and stop of wind energy turbines and as a result of fluctuations in their power due to changes in wind speed. For wind turbines with synchronous generators, the voltage reduction that occurs at start-up can be completely prevented as a result of the application of automatic synchronization, which is widely used in power systems. In the case of wind energy turbines with asynchronous generators, the reason for reducing the network voltage will be the connection to the generators of a battery of capacitors used to improve cos φ.

Simultaneous or independent frequency fluctuations and large voltage fluctuations are undesirable for consumers and should be prevented. Large voltage fluctuations due to the operation of wind energy turbines can be assumed if they rarely occur. Frequent fluctuations in voltage will cause complaints from consumers of the power system, if the voltage fluctuation does not meet the established requirements [39].

CHAPTER 2.
ANALYSIS OF PARAMETERS OF DISTRIBUTION NETWORKS OF ELECTRICAL SUPPLY SYSTEMS OF IRON ORE ENTERPRISES AND WAYS OF THEIR IMPROVEMENT

2.1. Results of simulation of the enterprise's power supply system

The figure shows a model built in the Mat Lab environment. It includes a general network of 35 kV, a 35/6 kV step-down transformer substation, a 10 km long line to a 6/0.4 kV step-down substation, a 6/0.4 kV step-down substation, a 1 km long line to the consumer of electricity, a block 2 IGBT converters for each phase and a consumer of electrical energy, which is represented by a three-phase asynchronous motor of 15 kW.

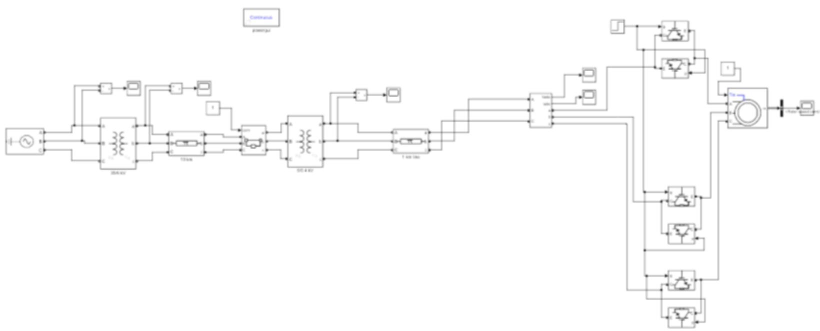

Figure 2.1 – Model of the power supply system of the load of the industrial object 35/0.4 kV

Thus, in fig. 2.2-2.10 it is possible to observe the peculiarities of the influence of transient processes of one of the most widespread and powerful consumers of electric energy - electric motors.

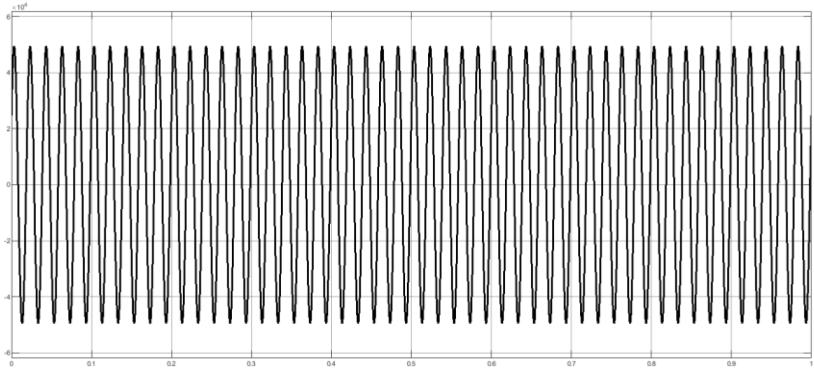

Figure 2.2 – Voltage graph on the 35kV side between phases a and b

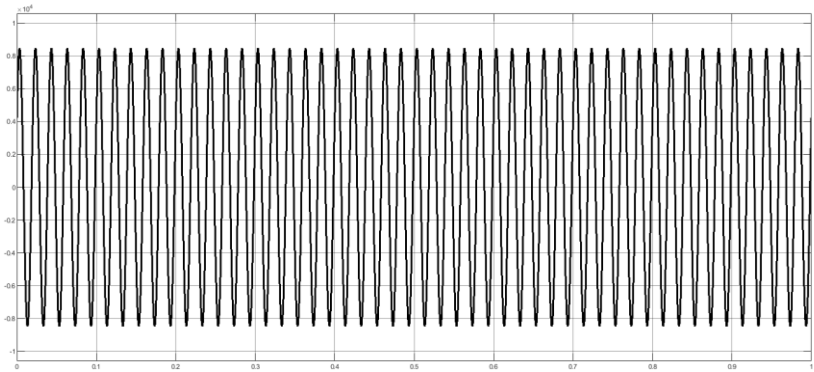

Figure 2.3 – Voltage graph on the 6kV side between phases a and b

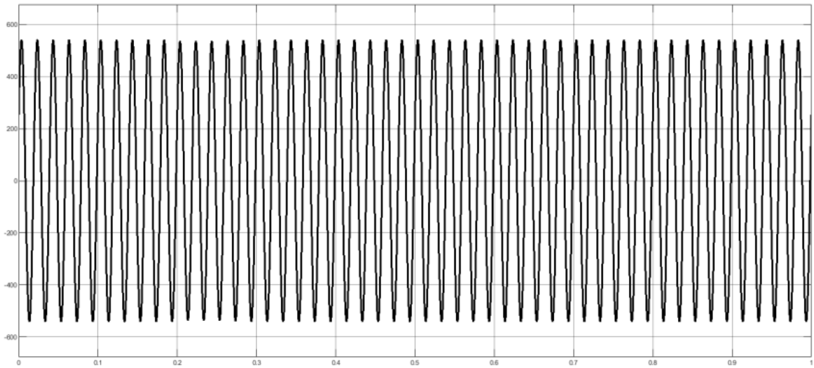

Figure 2.4 – Voltage graph on the 0.4 kV side between phases a and b

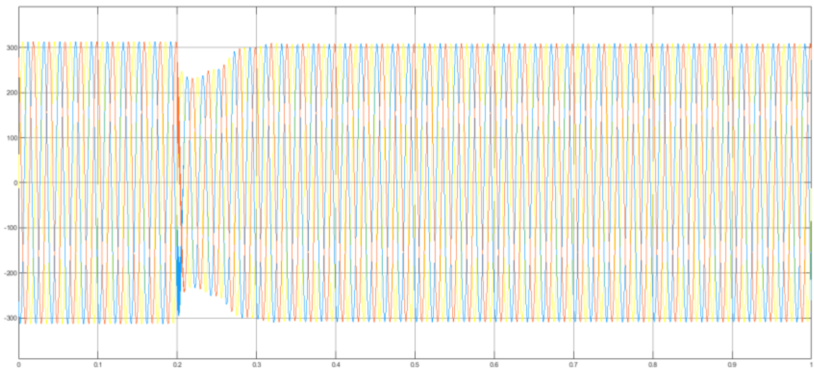

Figure 2.5 – Voltage graph on the 0.4 kV side of the load in phases a, b, c

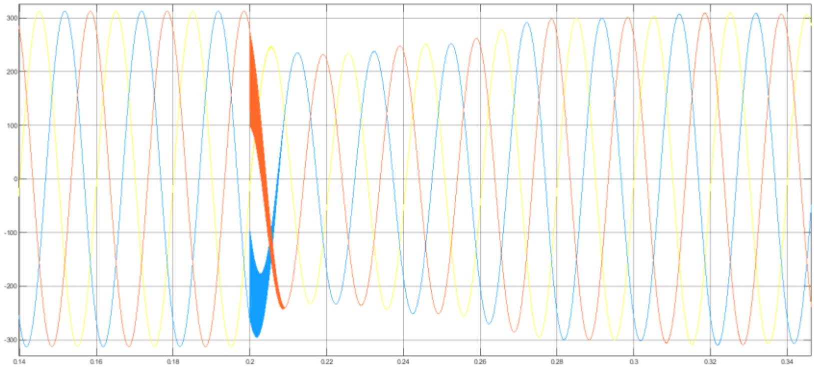

Figure 2.6 – Voltage graph on the 0.4 kV side of the load in phases a, b, c (interval of the transient process)

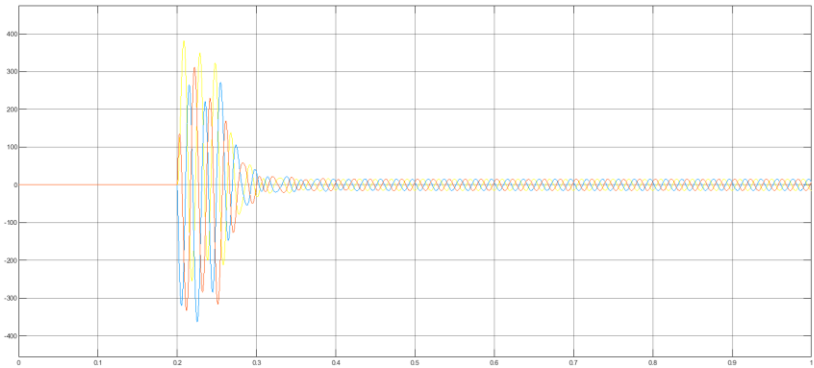

Figure 2.7 – Current graph on the 0.4 kV side of the load by phases a, b, c

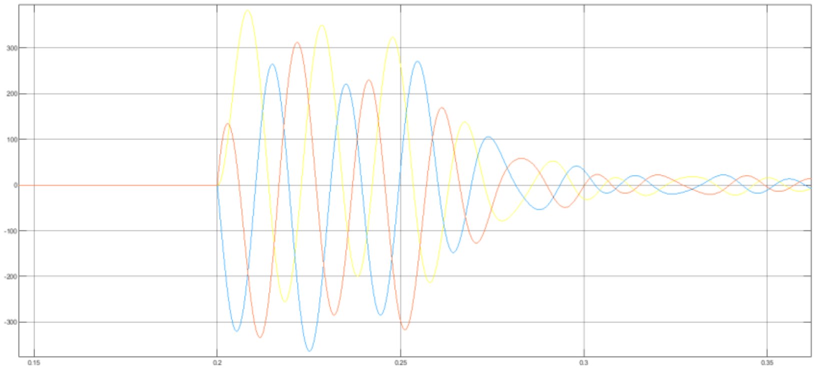

Figure 2.8 – Current graph on the 0.4 kV side of the load in phases a, b, c (interval of the transient process)

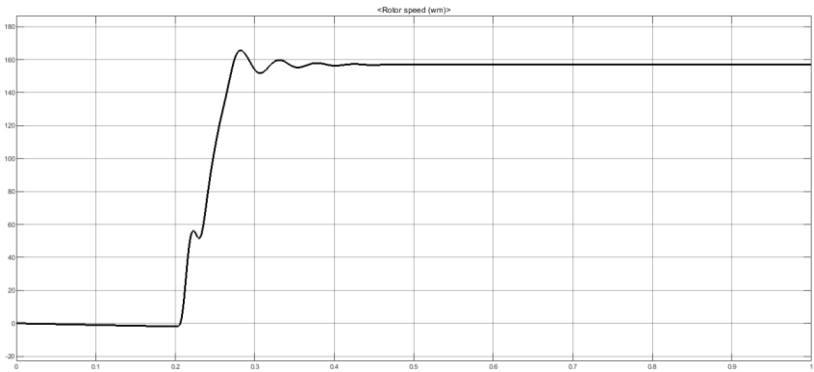

Figure 2.9 – Engine rotor speed graph (start-up mode)

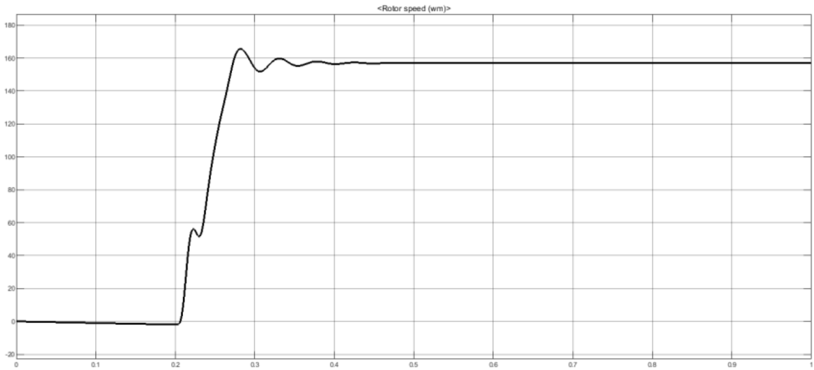

Figure 2.10 – Graph of the speed of rotation of the rotor of an asynchronous motor (starting mode) (interval of the transient process of starting the motor)

As can be seen from fig. 2.2-2.10, the transient processes of starting electric motors have exactly the section of the network to which they are connected. The transient process does not have a significant impact on other sections of the network on the higher voltage side and does not spread to the general network. Meanwhile, it has a significant impact on the section of the network to which it is connected, negatively affecting the quality indicators of both current and voltage components.

2.2 Aspects of the influence of network inverters of distributed generation sources on indicators of the quality of electric energy

Despite the fact that the term "quality of electric energy" refers to a whole range of indicators, it is most often attributed to the quality of the supply voltage, since in traditional electric power systems voltage sources act as power sources, and the current forms are determined by the characteristics of the load. The low quality of electrical energy can be reflected in the form of various indicators, such as amplitude and frequency fluctuations, transient processes, the content of harmonics in the form of signals, power factor, phase asymmetry, power continuity, etc. Low quality of electrical energy can occur for various reasons, for example, due to the influence of non-linear loads. Since the electric power system is interconnected, a decrease in quality indicators at one point of the network can lead to a decrease in quality indicators in other parts of the network. An important stage in the development of power supply systems at present is the transition from centralized models to systems with distributed generation with integration into the network of renewable energy sources based on the use of solar, wind, water, etc. energy. At the same time, such microgrids can either work isolated from the centralized power supply, or connect to it. At the same time, the main element that ensures the interaction of sources of distributed generation and the network are inverters, the work of which, due to the key mode of operation of semiconductor elements, is associated with the appearance of harmonic voltage components, which leads to the need to analyze the issue of the quality of electrical energy in networks with distributed generation. At the same time, it is important to take into account the aspect that sources of harmonics in such networks are not only inverters of distributed generation sources, but also other loads. A significant number of consumers of electrical energy can be considered as non-linear loads, since they contain semiconductor converters that lead to the creation of harmonic currents even when powered by a purely sinusoidal voltage. These harmonic currents flow through the resistances of the distribution network, including the internal resistances of the power source, and cause the appearance of harmonic voltage components. In the future, voltage harmonics lead to current harmonics even in linear loads. Thus, current national and international standards of electrical energy quality impose restrictions on both the level of individual harmonic components and general indicators of harmonic pollution, such as the total harmonic distortion (THD). Therefore, control systems for inverters of distributed generation sources must have the ability to eliminate or minimize harmonic components in order to meet the requirements of standards and reduce energy losses.

In the literature, a number of closed control systems are considered, which allow to reduce the harmonic distortion of signals by inverters of distributed generation sources [40-50]. The task of such systems is to approximate the output voltage of the inverter to the sinusoidal signal of the task with the elimination of other harmonic components. In [60], aperiodic digital (deadbeat) controllers for controlling inverters are considered. In [51], an analysis of the control system using hysteresis control was performed. Considerable attention of researchers is devoted to systems of repetitive (repetitive) control of network inverters [52], which use simple learning methods that allow eliminating periodic errors in dynamic systems using an internal model. The advantage of this approach is that it can take into account a large number of harmonic components, providing low indicators of the coefficient of total harmonic distortion. The disadvantage of this approach is the need to carry out a significant amount of experimental research to determine the harmonic signal.

In addition, an important component of the analysis of ways to improve the quality of electric energy is to find out the reasons for their deterioration. As is known, the value of the output resistance of the inverter plays a decisive role in reducing the coefficient of total harmonic distortion of the voltage. Therefore, it is advisable to consider approaches to reducing this coefficient by reducing the value of the output resistance. If we consider the issue of the quality of electrical energy in the context of the coefficient of total harmonic distortion of the current, then the development of the structures of power active filters is an actual direction of the development of this issue.

The purpose of the synthesis of current regulators of the network inverter control system is to ensure the output current of the inverter with a minimum content of harmonics under the condition of simple implementation of synchronization with the network. When using a three-phase reference system *abc*, separate current regulators are used for each phase. At the same time, the network current assignment signal i^* is obtained from the current assignment signals along the d and q axes (I_d^* and I_q^*) by means of coordinate transformations. To obtain phase information about the current vector of the mains voltage, it is possible to apply the block of phase auto-adjustment of the frequency. Thus, with proper synchronization of the network voltage vector and the rotating coordinate system dq, the components of the task current vector I_d^* and I_q^* will affect the exchange of active and reactive power between the network and the inverter. Provided that the current operating mode of the system does not involve the transfer of energy from the inverter to the network or vice versa, then the task signals of the component currents I_d^* and I_q^* should be set equal to zero, and for the absence of energy exchange, the output voltage of the inverter should be equal to the voltage in the network. To achieve this, it is necessary to add the measured values of the voltage in the network to the output signals of the current regulators, which can be additionally filtered.

For the further synthesis of control systems, consider a single-phase substitute scheme of the control object "inverter - filter - alternating current network" (Fig. 2.11). The control object contains an inverter, an LC filter formed by the inductances L_f and C_f, as well as the active resistance R_g and the network inductance L_g.

The currents in the two inductive branches, as well as the voltage on the capacitor, can be considered as state variables, the network voltage and the task current as input signals, and the inverter voltage task signal as a control variable:

$$x = \left[i_i \; i_g \;\; u_f\right]^T; \tag{2.1}$$

$$w = \left[u_g \;\; i^*\right]^T. \tag{2.2}$$

As the output signal of the control object, the control error of the current value can be considered, that is, the difference between the set value of the current i^* and the real value of the current flowing from the inverter to the network:

$$e = i^* - i_g. \tag{2.3}$$

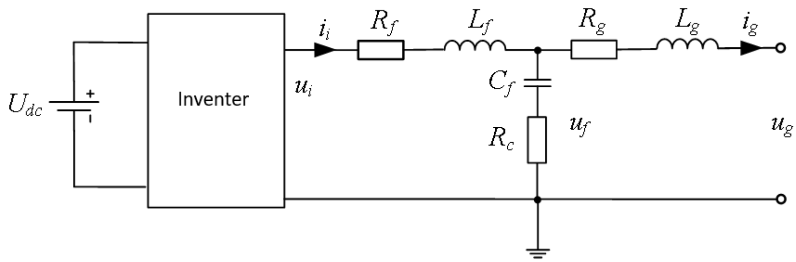

Figure 2.11 – Single-phase alternate scheme of the control object "inverter - filter - alternating current network"

Then the control object in the state space can be described by the following equations:

$$\frac{dx}{dt} = Ax + B_1 w + B_2 u; \tag{2.4}$$

$$y = C_1 x + D_1 w + D_2 u; \tag{2.5}$$

$$A = \begin{bmatrix} -\dfrac{R_f + R_c}{L_f} & \dfrac{R_c}{L_f} & -\dfrac{1}{L_f} \\ \dfrac{R_c}{L_g} & -\dfrac{R_g + R_c}{L_g} & \dfrac{1}{L_g} \\ \dfrac{1}{C_f} & -\dfrac{1}{C_f} & 0 \end{bmatrix}; \tag{2.6}$$

$$B_1 = \begin{bmatrix} \frac{1}{L_f} & 0 \\ -\frac{1}{L_g} & 0 \\ 0 & 0 \end{bmatrix}; \; B_2 = \begin{bmatrix} \frac{1}{L_f} \\ 0 \\ 0 \end{bmatrix}; \tag{2.7}$$

$$C_1 = [0 \quad -1 \quad 0]; \tag{2.8}$$

$$D_1 = [0 \quad 1]; \; D_2 = 0. \tag{2.9}$$

Since the network inverter control system must ensure stability in conditions of uncertainty of network resistance parameters, it is advisable to use an H∞ regulator in the current control circuit.

The task of its operation will be to minimize the control error and obtain low indicators of the coefficient of total harmonic distortion of the network current, provided that the value of the network resistance changes widely. The corresponding parameters of such a regulator were obtained using the Matlab environment function hinfsyn.

At the highest level of the control system, the static method was used, which allows you to control the power transmitted by each of the inverters of the network by influencing the frequency and amplitude of the output voltage. This concept follows the properties of similar systems used in networks with powerful synchronous generators having significant moments of inertia and allows them to work in parallel, sharing the load by reducing the frequency while increasing the active power in the network. However, unlike systems with synchronous generators, inverters of distributed generation sources do not have such significant inertial properties that ensure system stability during synchronization. At the same time, the control system provides flexible control of dynamic processes, demonstrating high speed. Therefore, in order to increase the stability of the network and to coordinate the power sources that work in parallel, the inertial properties of the synchronous generator are reproduced using the laws of statics, adjusting the voltage amplitude and frequency in proportion to the components of active and reactive power [54].

The main dependences describing the control of inverters when using the law of statics are as follows:

$$\omega_k = \omega_{nom} - m_k P_k; \tag{2.10}$$

$$U_k = U_{nom} - n_k Q_k, \tag{2.11}$$

where ω_k is the angular frequency of the k-th inverter, which varies depending on the measured value of its active power P_k; ω_{nom} – the nominal value of the angular frequency in the network; m_k – coefficient forming the law of statics for active power; U_k is the amplitude of the output voltage of the k-th inverter, which varies depending on the measured value of its reactive power Q_k; n_k is a coefficient that forms the law of statics for reactive power.

The value of the voltage frequency is a common state variable of the entire network, which means that its value is the same for all network converters in the static mode of operation, which leads to a uniform distribution of active power between them, when the static coefficients m_k are constant and the same for all inverters. So:

$$m_1 P_1 = m_2 P_1. \tag{2.12}$$

The value of the voltage amplitude is not a common variable of the state of the entire network, since its value may differ in different nodes of the circuit, and therefore, even with the same values of coefficients n_k, the ideal distribution of reactive power cannot be achieved. This is confirmed by the following dependence [55]:

$$n_1 Q_1 + U_1 = m_2 Q_1 + U_2. \tag{2.13}$$

2.3 Approaches to eliminate asymmetric modes of operation of sources with distributed generation

The use of sources with distributed generation allows efficient use of existing renewable energy sources, contributes to the reduction of harmful emissions in the case of traditional electricity generation, improves the quality of electricity for consumers and reduces overloading of transmission lines. In low-voltage networks with distributed generation, it is quite often necessary to provide a fourth (neutral) conductor by means of energy sources and corresponding network interfaces for powering single-phase and asymmetrical three-phase loads. At the same time, we should expect a decrease in the mutual influence of the load phases among themselves in the context of ensuring compliance with the indicators of the quality of electric energy, but this issue requires an appropriate analysis. Therefore, the neutral conductor is necessary to ensure the current flow of unbalanced loads, and therefore the traditional inverter interface of such networks must be converted to connect the neutral conductor [56].

Traditionally, microgrids with four-wire lines can work either with a connection to the centralized power supply network or in an autonomous (island) mode. At the same time, it should be taken into account that not all inverters in such a network must be able to connect to a four-wire network, since some of them can work in a symmetrical three-phase mode. In this work, we consider the option that the neutral conductor is powered by one inverter, and in the future it is necessary to develop a control system that would allow dividing the current in the neutral conductor between several inverters connected in parallel.

The simplest way to provide a neutral point for connecting the neutral conductor is to use two capacitors with balancing resistors connected in parallel, that is, to create a zero voltage by dividing the total DC link voltage in half. Circuits with voltage separation in the direct current circuit are widely used in electric drives with three-level energy converters, since in this case there is no need to connect the neutral point directly to the load, and the main purpose of this electrical circuit is to obtain equal halves of the total voltage in the direct current circuit. Also, this solution finds its use in the structures of power active filters, since in this case the current in the neutral conductor does not contain a constant component, and the other components in this conductor are relatively small. For such inverters, it is possible to develop methods of pulse-width modulation suitable for balancing the voltages on the voltage divider capacitors. The disadvantage of such a circuit solution is that the current of the neutral conductor flows through the capacitor divider. If this current is of a significant value, then capacitors of a significant capacity are needed to reduce the level of voltage ripples on them, and therefore the voltage at the zero point deviates from the set level, which leads to an asymmetry of the output voltages, which is especially noticeable when the neutral conductor current has a constant component [57].

Another option for powering asymmetrical loads in networks with distributed generation is the use of inverters with four arms. Such an inverter can be controlled using three-dimensional pulse width modulation. The advantage of such a system is a more efficient use of the voltage in the direct current circuit, but the control of the fourth arm of the inverter is also carried out at the level of the overall pulse-width modulation of the output voltage, and therefore ensuring the ability to control the current level in the neutral conductor requires the development of a complex control system. The disadvantage of this scheme is that the formation of the zero voltage is carried out due to pulse-width modulation using higher levels of pulse voltages, and therefore the switching of high voltages with a high frequency can lead to problems with compliance with electromagnetic compatibility standards.

CHAPTER 3.
APPROACH TO THE CONSTRUCTION OF THE LAW FOR CONTROLLING THE ELECTRICAL ENGINEERING COMPLEX OF CONTROL AND CONTROLLING THE NORMAL QUALITY LEVEL OF ELECTRICAL ENERGY

3.1. SWOT analysis of the application of Smart Grid technology in improving the quality of electricity

It should be noted, first of all, that any implementation of advanced technologies has its own strengths and weaknesses, opportunities and threats during their implementation. Therefore, for a detailed study of issues in global practice, it is customary to use a SWOT analysis in order to identify the features of the introduction of the latest technologies and the introduction of new projects.

The strengths of using Smart Grid technology in improving the quality of electricity include [58]:

1) spread of the digitalization process in industry;
2) development of decarbonization processes in industry;
3) increasing the level of energy efficiency of technological processes;
4) sustainable development of the technological level of the industry;
5) implementation of the principles of decentralization of power supply of energy facilities of industry;
6) increasing the level of involvement of high-tech processes in the production processes of industrial enterprises.

Weaknesses of the use of Smart Grid technology in improving the quality of electricity include:

1) large capital investments;
2) budget restrictions during modernization in production;
3) insufficiently equipped auxiliary infrastructure;
4) limited number of specialists for modernization and maintenance of modern high-tech systems for managing production processes in industry;
5) insufficient legislative provision and regulation of the introduction of modern high-tech systems for managing production processes in industry;
6) territorial and information technology discrepancies are possible.

The possibilities of using Smart Grid technology to improve the quality of electricity include [59]:

1) innovative technologies and mechanisms;
2) operational management of the reliability of electricity supply;
3) introduction of new forms of worker participation in technological and production processes at the factory;
4) increased resistance of the energy system to external and internal disturbances;
5) maintenance of the standardized quality of electrical energy in all areas of the power grid of the industrial enterprise;
6) operational monitoring of the condition and diagnosis of electrical networks and electrical consumers;
7) reduction of environmental pollution;
8) professional growth of engineering and technical personnel;
9) reducing the number of emergency situations due to the introduction of artificial intelligence;
10) the possibility of effective use of sources of distributed generation based on alternative and renewable sources of electrical energy as part of the distribution networks of industrial enterprises;
11) increasing the duration of operation of electrical equipment involved in technological processes.

Threats of using Smart Grid technology to improve the quality of electricity include [60]:

1) possible misuse of data;
2) increasing vulnerability to cyber attacks;
3) risks for the labor market due to the spread of automation and robotization of production processes;
4) increasing the scale of the collapse in case of a global failure of programs;
5) the risk of the human factor during maintenance by maintenance personnel of high-tech elements of production processes, which can lead to large losses.

Thus, using the symbiosis of digitalization and other advanced technologies in the field of energy, the Smart power grid has the ability to control the processes of transmission of electrical energy generated from generating plants and, if necessary, its redistribution, accounting, accumulation and storage.

Meanwhile, it should also be noted that the processes of decentralization of power supply systems through the implementation of

Smart power grids are designed to contribute to the solution of tasks related to uninterrupted power supply and the active implementation of renewable sources of electric energy. Among other things, the key to the active development of this direction in the field of energy is possible only from the level of digitization of the energy sector of the state as a whole.

3.2 Peculiarities of transmission of information on power lines of electricity supply

Today, in connection with the intensive development of digital technologies, wireless data transmission networks - WI-FI and Bluetooth - are becoming more and more relevant. They are based on the transmission of digital data over a radio channel.

Wireless WLAN networks (Wireless Local Area Network) are recommended in those places where installing a cable network is impossible or impractical. They are especially effective in companies where personnel actively move around a certain area of the enterprise during the working day. These can be: sales offices, healthcare institutions, agencies, large warehouses, etc.

There is another type of wireless data transmission system - this is Bluetooth technology. It allows you to connect almost any devices with each other: laptops, mobile phones, digital cameras, printers, and even such household appliances as air conditioners, microwave ovens, washing machines.

Every year, information and communication technologies (ICT) play an increasingly important role in people's lives, while increasing their influence on the socio-economic development of the country. Recently, both separate telecommunication services (Internet access, video surveillance, remote control of heating, lighting, etc.) and modern concepts designed to automate certain household processes, diversify leisure time, simplify access to social services and etc. ("Smart Home", "Smart City" and "Internet of Things" (IoT)).

A necessary condition for full-scale use of the potential of the listed concepts is the availability of high-speed networks capable of providing high bandwidth. Today, the basis for the construction of high-speed networks is public telephone networks (PTN), fiber optic networks, cable networks, mobile and satellite networks, as well as electrical wiring networks (PLC technology). Each of them has its advantages and disadvantages, which determine the expediency of their use in certain conditions. In particular, electrical wiring networks (EWN) are used as a signal propagation medium during the construction of infrastructure according to the "smart city" concept for the organization of remote control services based on the readings of various sensors installed in the building, as well as when deploying a "smart home".

PLC technology is a promising telecommunication technology, which, working on power grids, allows organizing high-speed information exchange. Depending on the transmission speed, PLC is divided into broadband (BPL) with a speed of more than 1 Mbit/s and narrowband (NPL).

At the same time, PLC devices can "see" and decode information, although ordinary electrical devices at the same time work in normal mode.

Nowadays, the technology is widely used both in Ukraine and in Europe and America.

The basis of the PowerLine technology is the use of frequency division of the signal, in which a high-speed data stream is divided into several relatively low-speed streams, each of which is transmitted on a separate frequency and then combined into a single signal. In reality, PowerLine technology uses 84 frequencies in the range of 4-21 MHz.

PLC technology in the MicroGrid system can be used to automatically collect data from electricity meters, which makes it possible to analyze, process and forecast data on electricity consumption [51]. PLC modules are communication elements of household and industrial electronics devices in a unified information infrastructure.

The most effective is combined management, which contains elements of centralized and decentralized strategies. In this case, it is assumed that there is a central control unit in the system, but it performs the function of control and management at a generalized level - it determines the trends of the quality of work, the current state of electricity consumption, produces general evaluation signals about the state of the system and the need to take measures to reduce consumption by switching in a more economical mode. Thus, a flexible information infrastructure capable of adapting to changing parameters and the current level of consumption is formed.

The combination of centralized and decentralized principles of construction of control systems with a communication environment for information transmission allows to take into account such aspects that are not fully taken into account in the usual construction of control systems, namely [60]:

1. Individual properties of electrical equipment; the qualification of the operator servicing the equipment; cost function; production function;

tariff rates and other economic indicators.

2. Time dependences of the vector of the tariff cost of costs, which can be different not only for different devices, but also for the same ones, if used in different areas or enterprises.

3. The change in the values of the cost vector and the production function depending on the amount of electrical equipment involved in the work.

Let's consider the possibilities of introducing elements of decentralization when creating the MicroGrid information infrastructure based on the X10 protocol.

X10 is an international open industry standard used for communication of electronic devices in home automation systems. The X10 standard defines the methods and protocol for transmitting control signals to electronic modules to which electrical devices are connected, using existing electrical network lines or wireless channels.

The X10 standard was developed in 1975 by Pico Electronics to control household electrical appliances.

Today, the standard remains one of the most popular, although there are a number of alternatives with more extensive capabilities.

An ordinary electrical network is used to connect the modules of the X10 network. Encoded digital data is transmitted using radio frequency pulses with a central frequency of 120 kHz, duration of 1 ms, synchronized with the moment of the alternating current crossing through the zero value.

The network PLC modules themselves are connected as "intelligent switches" to the power grid, although there are more complex built-in modules, such as replacement sockets, switches, etc..

The relatively high carrier frequency does not allow the signal to propagate through transformers or between phases in multi-phase and split-phase networks. In split-phase networks, a simple capacitor can be used to transfer the signal from phase to phase, but for multi-phase and split-phase networks, where a simple capacitor is not enough, an active repeater must be used. When transmitting a signal from phase to phase, it is necessary to take into account the above-mentioned condition - bit transmission begins at the zero crossing. It is for this reason that when changing from phase to phase, the signal is shifted by 1/6 of the period.

Another important point is the possibility of blocking signals outside the range of the network. Inductive filters are used to neutralize the influence of modules of one X10 network on another.

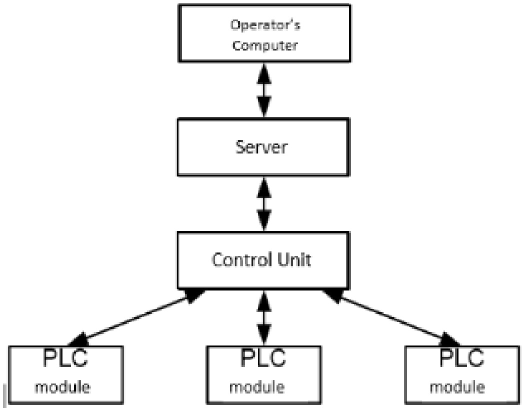

Figure 3.1 - Scheme of the information transmission system using PLS technology in the MicroGrid system based on a centralized hierarchy

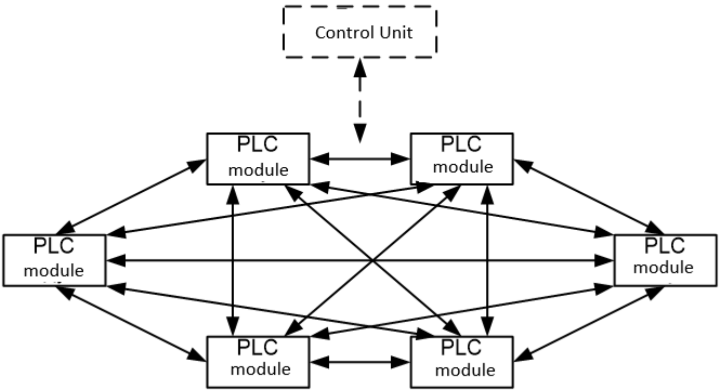

Figure 3.2 - Scheme of the information transmission system using PLS technology in the MicroGrid system according to the decentralized hierarchy

3.3 Control of the quality of electric energy in the aspect of the introduction of Micro Grid technology

Meanwhile, with such a construction of the control system, it is necessary to take into account not the general indicators of the quality of electric energy in the network of the system, but also its individual sections, which will be used to transmit the controlled signals of the system.

However, the integration of renewable sources into existing networks creates problems with the quality of electrical energy. A typical distribution network is stochastic in nature. The energy consumption of each bus, as well as the location and instantaneous power values of renewable electrical energy sources, are random and difficult to predict. Due to this uncertainty, indicators of the quality of electrical energy can significantly decrease [2].

In a number of publications, a lot of attention has been paid to the issue of introducing distributed generation sources to the power supply systems of enterprises and the introduction of Micro Grid technology. However, the issue of long-distance transmission of information during the introduction of Micro Grid and especially during the installation of additional power generation capacities based on renewable sources of electrical energy at enterprises, with the aim of optimal management and dispatching, remains unresolved [1-13].

PLC technology in the MicroGrid system can be used to automatically collect data from electricity meters, which makes it possible to analyze, process and forecast data on electricity consumption. At the same time, PLC modules are communication elements of industrial electronics devices in a unified information infrastructure [9].

One aspect of the integration of distributed generation sources is their connection to the grid. In low-voltage networks with distributed generation, it is quite often necessary to provide a fourth (neutral) conductor by means of energy sources and corresponding network interfaces for powering single-phase and asymmetric three-phase loads. At the same time, we should expect a decrease in the mutual influence of the load phases among themselves in the context of ensuring compliance with the indicators of the quality of electric energy, but this issue requires an appropriate analysis [9].

However, for such possible options for connecting sources of distributed generation to the enterprise's electrical network, and taking into account the stochastic nature of the operation of renewable energy sources, on the capacities of which they should be based, attention should be paid to aspects of the quality of electrical energy, as a local indicator, and not a general indicator in the enterprise's network [60-70].

Thus, taking into account all the mentioned aspects, conditions and factors, the scheme of the system of control and management of the level of electrical energy quality (Fig. 3.3) and the algorithm of its functioning are proposed.

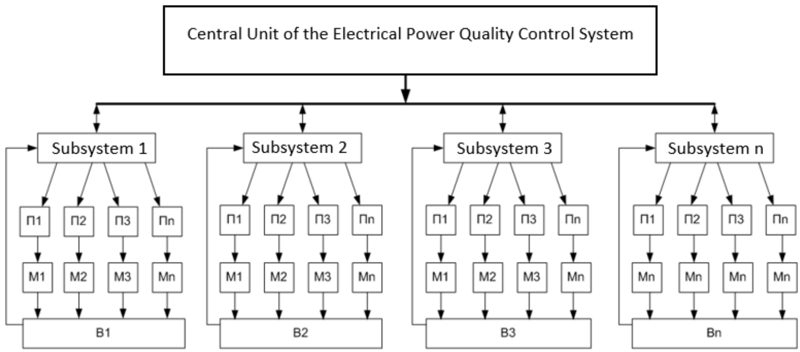

Figure 3.3 – Scheme of the system of control and management of the level of electrical energy quality

Figure 3.3 shows the proposed scheme of the control and management system for the level of electric energy quality, where B1-n are measuring blocks of the corresponding indicators of the quality of electric energy in the sections of the M1-n network, which are regulated by the corresponding devices П1-n

The proposed algorithm makes it possible to adjust the relevant indicators of the quality of electric energy in a centralized-decentralized way of management in the appropriate sections of the network with the connection of distributed sources of electric energy based on renewable energy sources.

Taking into account the possibility of adaptive management of the quality of electrical energy in the network in a centralized-decentralized way, it is possible to implement PLC technology for information transfer in the aspect of intellectualization of power supply management systems and the introduction of Micro Grid technologies.

Considering the relevance of the intellectualization of power supply management systems, it is possible to implement PLC technology to transmit information to the Micro Grid, which will eliminate difficulties with the transmission of the control signal and data transmission to the control system [2].

3.4 Construction of a power quality control system based on fuzzy neural networks in power distribution networks

The quality of electrical energy is characterized by a set of properties of electrical energy that determine its suitability for the normal operation of electrical equipment in accordance with their purpose at normalized functional capacity [7].

Indicators of the quality of electrical energy are divided into two groups: basic and additional.

The main indicators of the quality of electric energy determine the properties of electric energy that characterize its quality. Additional indicators of the quality of electric energy are forms of recording the main indicators of the quality of electric energy, used in regulatory and technical documents.

The main indicators of the quality of electrical energy include: voltage deviation δ U, the range of voltage changes δU_t, the dose of voltage fluctuations Ψ, the coefficient of non-sinusoidality of the voltage curve k_{nsU}, the coefficient of the ν-th harmonic component $\mathrm{K}_{\mathrm{U}(\nu)}$, the coefficient of the reverse sequence of the voltage $\mathrm{K}_{2\mathrm{U}}$, the coefficient of the zero sequence of the voltage $\mathrm{K}_{0\mathrm{U}}$, the frequency deviation Δf, the duration of the voltage dip Δt_p, pulse voltage U_{ipn} [8-9].

Additional indicators of the quality of electrical energy include: amplitude modulation coefficient K_{mod}, interphase voltage unbalance coefficient K_{neb}, phase voltage unbalance coefficient $K_{neb.f}$.

Based on the logical conclusion tree of constructive and technological factors, we will model the structure of a hierarchical neurofuzzy network (Fig. 3.4).

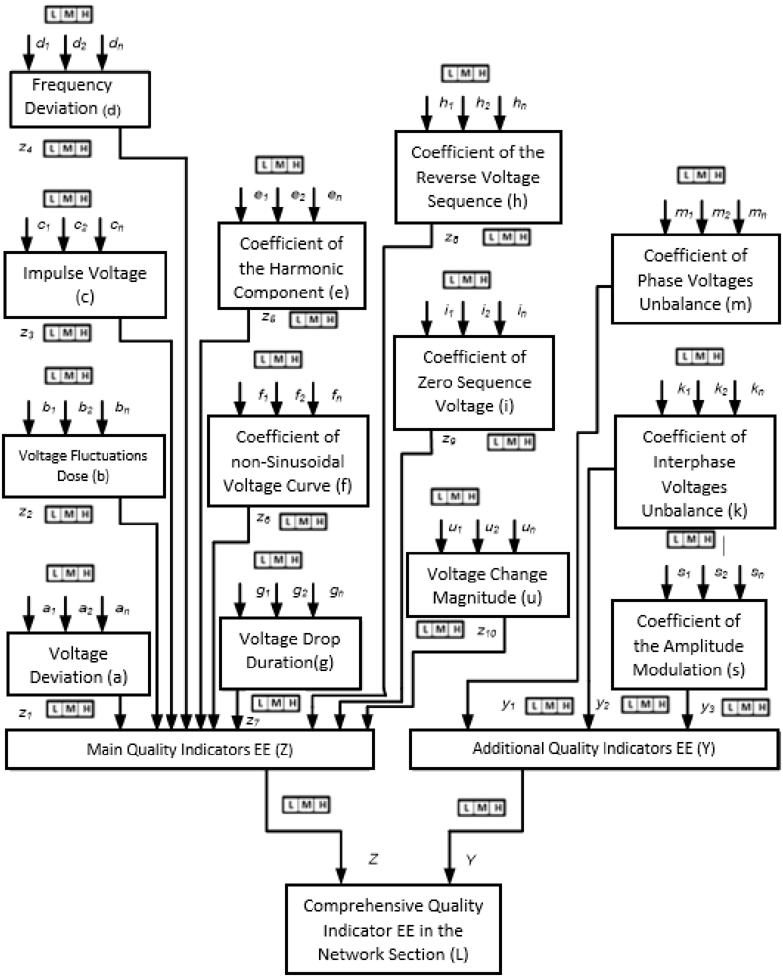

Figure 3.4 – The structure of a hierarchical neural fuzzy network for determining and controlling quality indicators of the power supply system

Each element of this structure represents a certain level of the logical tree of influence on the quality of the power supply system. Each element has a term-set of expert evaluations, which is indicated at the input of the parameters in the line: "L - low", "M - medium", "H - high".

Factors affecting the quality of the power supply system

$$Z = f_z(z_1, z_2, z_3, z_4, z_5, z_6, z_7, z_8, z_9, z_{10}), \quad (3.2)$$

$$Y = f_Y(y_1, y_2, y_3), \quad (3.3)$$

$$z_1 = f_{z1}(a_1, a_2, a_n), \quad (3.4)$$

$$z_2 = f_{z2}(b_1, b_2, b_n), \quad (3.5)$$

$$z_3 = f_{z3}(c_1, c_2, c_n), \quad (3.6)$$

$$z_4 = f_{z4}(d_1, d_2, d_n), \quad (3.7)$$

$$z_5 = f_{z5}(e_1, e_2, e_n), \quad (3.8)$$

$$z_6 = f_{z6}(f_1, f_2, f_n), \quad (3.9)$$

$$z_7 = f_{z7}(g_1, g_2, g_n), \quad (3.10)$$

$$z_8 = f_{z8}(h_1, h_2, h_n), \quad (3.11)$$

$$z_9 = f_{z9}(i_1, i_2, i_n), \quad (3.12)$$

$$z_{10} = f_{z10}(u_1, u_2, u_n), \quad (3.13)$$

$$y_1 = f_{y1}(m_1, m_2, m_n), \quad (3.14)$$

$$y_2 = f_{y2}(k_1, k_2, k_n), \quad (3.15)$$

$$y_3 = f_{y3}(s_1, s_2, s_n), \quad (3.16)$$

where Y is a linguistic variable describing the main indicators of the quality of electric energy; Z is a linguistic variable describing additional indicators of the quality of electrical energy; z_1 - voltage deviation; z_2 - dose of voltage fluctuations; z_3 - impulse voltage; z_4 - frequency deviation; z_5 - the coefficient of the harmonic component; z_6 - non-sinusoidal coefficient of the voltage curve; z_7 - duration of voltage drop; z_8 - coefficient of reverse voltage sequence; z_9 - coefficient of zero sequence voltage; z_{10} - voltage change range; y_1 - coefficient of unbalance of phase voltages; y_2 -

unbalance coefficient of interphase voltages; y_3 - coefficient of amplitude modulation; a, b, c, d, e, f, g, h, i, u, m, k, s are the corresponding parametric inputs of the quality indicators of electric energy on the corresponding 1, 2, n sections of the distribution network.

Based on the logical tree of conclusions of the parameters of the quality indicators of electric energy and the structure of the hierarchical neural fuzzy network, we will evaluate the levels of linguistic variables.

Table 3.1 - Fuzzy knowledge matrix about system-level relations

	IF		THEN
(e_1)	(e_2)	(e_3)	(e)
Low	Low	Low	Low
Low	Medium	Low	
Low	Low	Medium	
Medium	Medium	Low	Medium
Low	Medium	High	
Medium	Low	High	
Medium	Medium	Medium	
Low	High	Medium	
High	Low	Medium	
Medium	Medium	High	
High	Medium	High	High
High	High	Medium	
High	High	High	

The following system of equations of fuzzy logic corresponds to the linguistic statement describing the influence of various parameters of the electrical network on the quality of the power supply system (Table 3.1):

$$\mu_{\text{H}}(e) = \mu_H(e_1) \wedge \mu_H(e_2) \wedge \mu_H(e_3) \vee \mu_H(e_1) \wedge \mu_H(e_2) \wedge \mu_H(e_3) \vee \mu_H(e_1) \wedge \mu_H(e_2) \wedge \mu_C(e_3), \tag{3.17}$$

$$\mu_C(e) = \mu_C(e_1) \wedge \mu_C(e_2) \wedge \mu_H(e_3) \vee \mu_H(e_1) \wedge \mu_C(e_2) \wedge \mu_E(e_3) \vee \mu_C(e_1) \wedge$$
$$\wedge \mu_H(e_2) \wedge \mu_E(e_3) \vee \mu_C(e_1) \wedge \mu_C(e_2) \wedge \mu_H(e_3) \vee \mu_H(e_1) \wedge \mu_E(e_2) \wedge \mu_C(e_3) \vee \mu_E(e_1) \wedge$$

$$\wedge \mu_{\text{H}}(e_2) \wedge \mu_C(e_3) \vee \mu_C(e_1) \wedge \mu_C(e_2) \wedge \mu_E(e_3), \tag{3.18}$$

$$\mu_2(e) = \mu_E(e_1) \wedge \mu_C(e_2) \wedge \mu_E(e_3) \vee \mu_E(e_1) \wedge \mu_C(e_1) \wedge \mu_C(e_3) \vee \mu_E(e_1) \wedge \mu_E(e_2) \wedge \mu_E(e_3). \tag{3.19}$$

The fuzzy logic inference technique, which was applied to the information in the previous stages, allows the calculation of indicators of the quality of electrical energy, which are predicted as fuzzy sets. Fuzzy sets determine the level of energy parameters of distribution electric networks and the parameters of electric energy quality indicators for a fixed vector. To go from fuzzy sets to quantification, a dephasing process is required. Among various dephasing methods, the "Centroid" method [1] will be used. The process of defuzzification at the level of indicators of the quality of electrical energy, we calculate the values of the membership functions of pairwise comparisons, and for the expert evaluation of the elements, we will use the Saati scale [2].

As a device, the matrix of pairwise comparisons of different levels of the corresponding indicators of the quality of electric energy from the point of view of their proximity to the term "low" is given in Table 2. The factor e - the coefficient of the harmonic component is defined on the universal set U (e) = {1, 2, 3} (o.u.). The linguistic values of this factor are given by the term set T (e) = <low, medium, high> [70-80].

Table 3.2 – Pairwise comparisons of the coefficients of the harmonic component according to their proximity to the term "low"

		e_1	e_2	e_3
$Alow(e) =$	e_1	1	6 / 9	1 / 9
	e_2	9 / 6	1	1 / 6
	e_3	9	6	1

1 When forming this matrix, only the third row was expertly determined, and the elements of the other rows were calculated based on the properties of the resulting matrix [80-90].

According to the data in Table 3.2, the degree of belonging of the elements to the term "low" was obtained:

$$e_{\text{low}}(e_1) = \frac{1}{1+\frac{6}{9}+\frac{1}{9}} = 0{,}5625, \tag{3.20}$$

$$e_{low}(e_2) = \frac{1}{\frac{9}{6}+1+\frac{1}{6}} = 0{,}375, \tag{3.21}$$

$$e_{low}(e_3) = \frac{1}{9+6+1} = 0{,}0625. \tag{3.22}$$

Similarly, the matrices of pairwise comparisons of the coefficients of the harmonic component are determined from the point of view of their proximity to the term "medium" and "high".

Table 3.3 – Pairwise comparisons of the coefficients of the harmonic component according to their proximity to the term "medium"

		e_1	e_2	e_3
$A_{medium}(e) =$	e_1	1	9 / 1	6 / 1
	e_2	1 / 9	1	6 / 9
	e_3	1 / 6	9 / 6	1

Table 3.4 – Pairwise comparison of the coefficient of the harmonic component according to their proximity to the term "high"

		e_1	e_2	e_3
$A_{high}(e) =$	e_1	1	1 / 6	9 / 6
	e_2	6 / 1	1	9 / 1
	e_3	6 / 9	1 / 9	1

According to the table 3.3 obtained degrees of belonging of elements e_1, e_2, e_3 to the term "medium":

$$e_{medium}(e_1) = \frac{1}{1+9+6} = 0{,}0625,$$
$$e_{medium}(e_2) = \frac{\mathbf{1}}{\frac{\mathbf{1}}{\mathbf{9}} + \mathbf{1} + \frac{\mathbf{6}}{\mathbf{9}}} = \mathbf{0}{,}5625,$$
$$e_{medium}(e_3) = \frac{1}{\frac{1}{6} + \frac{9}{6} + 1} = 0{,}375.$$

According to the data in Table 3.4, the degrees of belonging of elements e_1, e_2, e_3 to the term "high" were obtained:

$$e_{high}(e_1) = \frac{1}{1 + \frac{1}{6} + \frac{9}{6}} = 0{,}375,$$
$$e_{high}(e_2) = \frac{1}{6+1+9} = 0{,}0625,$$

$$e_{high}(e_3) = \frac{1}{\frac{6}{9} + \frac{1}{9} + 1} = 0{,}5625.$$

The obtained values of membership functions are normalized to unity by dividing by the largest degree of membership. As a result, different levels of coefficients of the harmonic component are represented in the form of such fuzzy sets:

- the harmonic component coefficient is "low"

$$e = \left\{ \frac{0{,}5625}{1}; \frac{0{,}375}{2}; \frac{0{,}0625}{3} \right\};$$

- alternative energy source "medium"

$$e = \left\{ \frac{0{,}0625}{1}; \frac{0{,}5625}{2}; \frac{0{,}375}{3} \right\};$$

- the coefficient of the harmonic component is "high"

$$e = \left\{ \frac{0{,}375}{1}; \frac{0{,}0625}{2}; \frac{0{,}5625}{3} \right\}.$$

Fuzzy sets characterizing membership functions for the linguistic variable "harmonic component coefficient" are shown in Fig. 3.5.

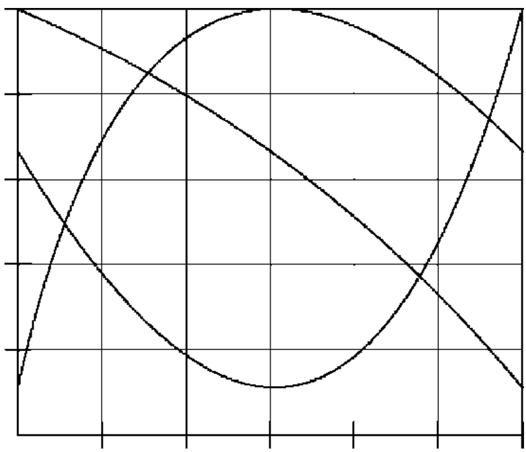

Figure 3.5 – Functional features for the linguistic variable "harmonic component coefficient"

The obtained knowledge base on the relations of fuzzy terms of input and output linguistic variables allows to optimize the control signal of the system of management and control of the quality of electric energy according to the relevant indicators in the specified controlled sections of the distribution network [91].

3.5 Modeling and study of the operation of the proposed control system

A mathematical model was developed in the Matlab/Simulink environment to study the modes of operation of the proposed control system, as well as the analysis of processes in network inverters of distributed generation sources. The general structure of the model is shown in fig. 3.6.
Results of simulation of the power supply system using distributed generation sources.

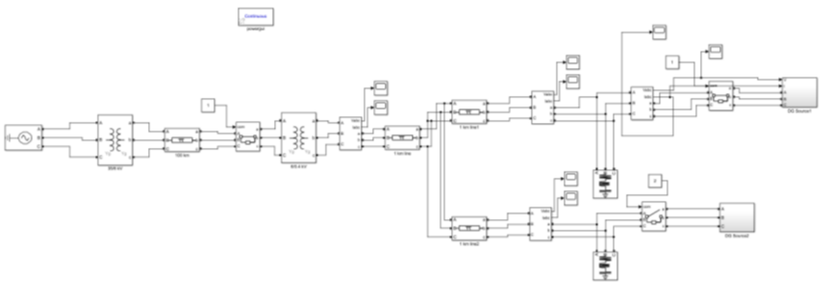

Figure 3.6 – Model of the power supply system in the Matlab/Simulink environment using one source of distributed generation

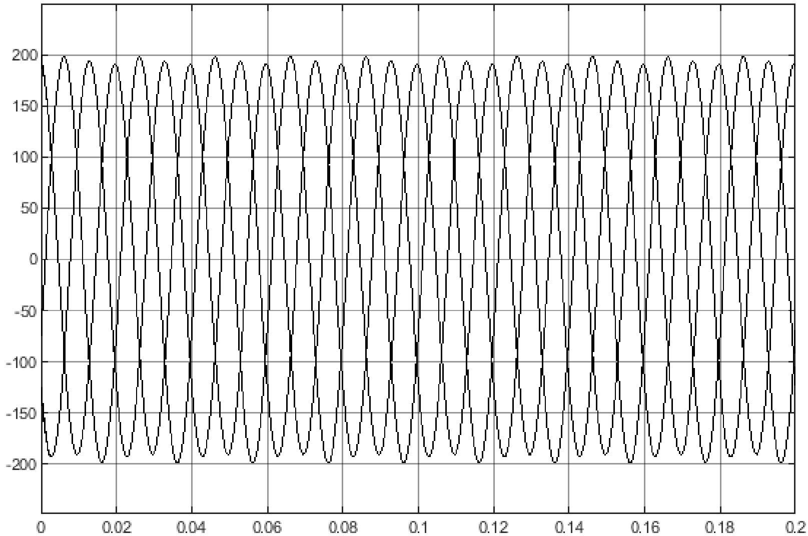

Figure 3.7 – Voltage graph of phases A, B, C 0.4 kV after the filter

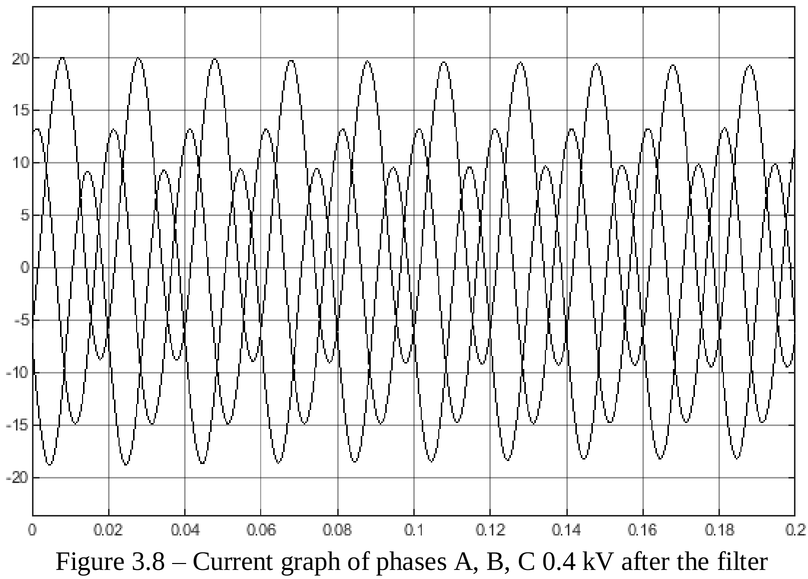

Figure 3.8 – Current graph of phases A, B, C 0.4 kV after the filter

Meanwhile, the following graphs show the current and voltage parameters after using the proposed inverter-based control system. Of course, the parameters are still far from ideal, but even with such voltage parameters, it is possible to use technologies for transmitting controlled and informational signals through the studied distribution network.

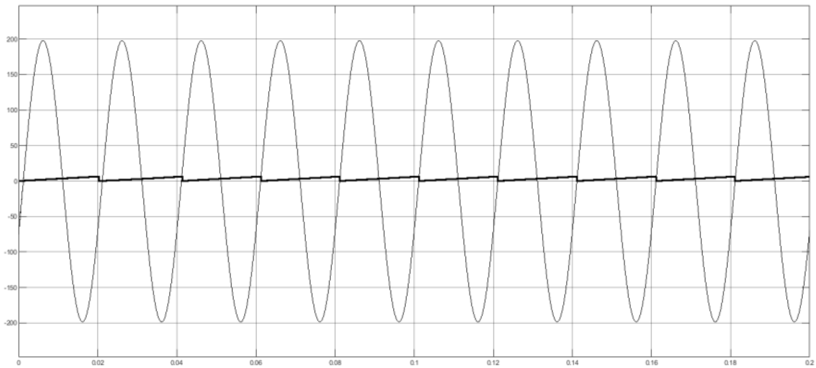

Figure 3.9 – Graph of current and voltage after the inverter 1

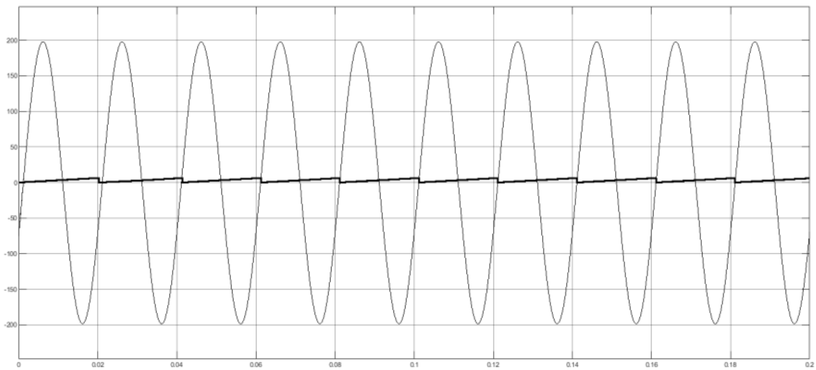

Figure 3.10 – Graph of current and voltage after the inverter 2

Such a configuration of current and voltage graphs will make it possible to transmit an information signal through power distribution networks.

3.6 Economic rationale for the development and implementation of a system of electrotechnical complex control and management of the quality of electrical energy in the distribution networks of enterprises

The term of the project is t=10 years, capital costs are CC=20717912 UAH, we accept a discount rate of 10%, annual savings (cash flow) CF=3690104.4 UAH.

Table 3.1 – Method of net discounted income at the discount rate of 10%

year / index	0 year	1st year	2nd year	3rd year	4th year	5th year
CF mlnUAH	-20,717	3,69	3,69	3,69	3,69	3,69
DCF mlnUAH	-20,717	3,35	3,04	2,77	2,52	2,29
Net DCF mlnUAH	-20,717	-17,367	-14,327	-11,55	-9,03	-6,74
year / index	6th year	7th year	8th year	9th year	10th year	
CF mlnUAH	3,69	3,69	3,69	3,69	3,69	
DCF mlnUAH	2,08	1,89	1,72	1,56	1,42	
Net DCF mlnUAH	-4,66	-2,77	-1,057	0,503	1,92	

$$DC = \frac{\Gamma\Pi}{CF} \text{ UAH},$$

where *CF* – cash flow; τ – discount rate, which depends on many factors, including inflation; *t* – number of years of project implementation.

$$DCF_1 = \frac{3690104,4}{(1+0,1)^1} = 3354640,3 \text{ UAH.}$$

$$DCF_2 = \frac{3690104,4}{(1+0,1)^2} = 3049673 \text{ UAH}$$

$$DCF_3 = \frac{3690104,4}{(1+0,1)^3} = 2772430 \text{ UAH}$$

$$DCF_4 = \frac{3690104,4}{(1+0,1)^4} = 2520390,9 \text{ UAH}$$

$$DCF_5 = \frac{3690104,4}{(1+0,1)^5} = 2291264,5 \text{ UAH}$$

$$DCF_6 = \frac{3690104,4}{(1+0,1)^6} = 2082967,7 \text{ UAH}$$

$$DCF_7 = \frac{3690104,4}{(1+0,1)^7} = 1893607 \text{ UAH}$$

$$DCF_8 = \frac{3690104,4}{(1+0,1)^8} = 1721460,9 \text{ UAH}$$

$$DCF_9 = \frac{3690104,4}{(1+0,1)^9} = 1564964,4 \text{ UAH}$$

$$DCF_{10} = \frac{3690104,4}{(1+0,1)^{10}} = 1422694,9 \text{ UAH}$$

$$T_{payback} = 9 + \frac{0,503}{|-1,057|} = 9 \quad year\ 4 \quad months$$

With a payback period of up to 10 years, such complexes are profitable for implementation in the energy industry.

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