NATIONAL TECHNICAL UNIVERSITY OF UKRAINE
“IGOR SIKORSKY KYIV POLYTECHNICAL INSTITUTE”

Institute of Energy Saving and Energy Management

Power Supply Department

“On the rights of the manuscript”
UDC ______________

“Accepted to the defense”
Head of the Department
__________ VLADIMIR POPOV
“___” _____________ 2021

Master’s thesis

under the specialty: 141 Electrical Energetics, Electrical Engineering and Electromechanics
Educational and Professional Program: Engineering of systems for providing consumers with electric energy

on the topic: “Modern technical solutions for controlling the modes of distribution networks with distributed energy sources.”

Completed by: Master student (2d year), group OE-91mn

____________Usatenko Vladyslav___________________________ __________
(Full name) (Signature)

Research Advisor __Professor Popov Vladimir ________________ __________
(Scientific degree, academic title, full name) (Signature)

Reviewer _______Professor Konrad Świrski____________________ __________
(Scientific degree, academic title, full name) (Signature)

I declare that this Master's thesis does not include any borrowings from the works of other authors without corresponding references.
Student _____________
(Signature)

Kyiv, 2021

National Technical University of Ukraine
“Igor Sikorsky Kyiv Polytechnic Institute”
Institute of Energy Saving and Energy Management
Power Supply Department

Level of higher education: second (Master’s), educational and professional program

Specialty: 141 Electrical Energetics, Electrical Engineering and Electromechanics
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“APPROVED”
Head of the Department
__________ VLADIMIR POPOV
“___” _____________ 2021

TASK
on the Master’s thesis research to student
Vladyslav USATENKO

1. Topic of the Master’s thesis: “Modern technical solutions for controlling the modes of distribution networks with distributed energy sources.”
Research advisor: Professor Popov Vladimir _______________
approved by the university order dated on «12» _March_ 2021 № 812-c

2. Deadline for the Master’s thesis submission by student: «20» May 2021

3. Object of research: processes of electricity distribution in electrical networks with local energy sources

4. Input data: parameters of the 10 kV distribution network, loads connected to the network, methodical instructions, the list of tasks from the scientific adviser
5. List of the tasks that have to be performed:
- to study the impact of distributed generation sources on distribution networks;
- to investigate electronic devices that may be useful for use in distribution networks;
- to conduct a study of the SOP its advantages and disadvantages;
- perform calculations that show the feasibility of using the SOP.

6. List of the graphical (illustrative) material: presentation - visual materials on the study results, calculation algorithms and tables with the results obtained.
____

7. Indicative list of publications: ______________________________________

1. V. Popov, O. Yarmolyuk, V. Tkachenko, I. Frolov, V. Usatenko. Features of Technical and Economical Approach to Decision-Making with Perspective Planning of Electric Power Supply Systems. Scientific journal "Power Engineering: Economics, Technology, Ecology". - February 2, 2020.____

2. V. Usatenko. Inspection of power lines using drones. XIV scientific and technical conference «Innovative approaches to the development of modern science» - February 28, 2019.____

8. Consultants for different sections of the Master's thesis: ________________

9. Date, when the task was issued: 1 February 2020

Calendar plan

№ з/п	Name of the stage of the Master's thesis implementation	Terms of implementation	Notes
1.	Identification the purpose of research, object and subject of research	01.10.2019-31.12.2019	
2.	Identification the preliminary structure of the Master's thesis	01.02.2020-31.05.2020	
3.	Literature review and work on the first section of the Master's thesis	01.06.2020-31.08.2020	
4.	Define methodology and methods of research features of SOP	01.09.2020-31.10.2020	
5.	Making practical calculations for SOP	01.11.2020-31.12.2020	
6.	Making research about forecasting	01.01.2021-28.02.2021	
7.	Formatting the text of the Master's thesis	01.03.2021-07.05.2021	
8.	Preparing the Abstract and PowerPoint Presentation of the Master's thesis; receiving an official protocol of plagiarism detection results and peer review	10.05.2021-14.05.2021	
9.	Preliminary Master's thesis defense	18.05.2021	
10.	Master's thesis defense	20.05.2021	

Student _________ Vladyslav USATENKO

Research Advisor _________ Vladimir POPOV

ABSTRACT

The structure and scope of the dissertation. The Master's thesis on the topic "Modern technical solutions for controlling the modes of distribution networks with distributed energy sources" consists of an introduction, 4 sections, conclusions and list of references. The total volume of work is 102 pages, including 20 figures, 14 tables and 59 bibliographic references.

Relevance of the research. The world power industry has traditionally developed through the centralization in the creation of increasingly powerful energy equipment and its integration into energy complexes. As a result, large territorially long energy systems have been formed: European ENTSO-E, UES of Russia, UES of Ukraine and others. In recent years, there has been a stable tendency to change the general concept of energy development. We are talking about the introduction of a new ideology - energy of sustainable development. An important element of such an ideology is the significant use of distributed generation (DG) sources - low-power power plants.

Introduction of DG sources in electrical networks (EN), in particular built on the basis of use renewable energy sources, in addition to reducing the environmental impact and solving many problems related to emissions and waste in production electricity, will, firstly, significantly increase the efficiency of the use of primary re-resources and - in the future - to reduce the cost of electricity, and secondly, to unload distribution network (DN), and finally, "push" the process of modernization of electrical objects and thus increase the reliability of electricity supply.

This, in turn, will allow decrease the risks associated with further increases in energy prices. But there are number of technical issues related to the impact of DG sources on planning, organization of operation and control of electrical networks.

The purpose of the research is to study issues related with the growing spread of use of renewable energy sources in distribution network and how to effectively solve them. To achieve this goal, the following tasks were set and solved:

- the analysis of the current situation with distributed generation in the world;

- investigating the impact of DGs on the operation of the distributed network.

- the possibility of using effective electronic devices to solve problems related to DGs integration in electrical networks;

- to study forecasting techniques for the efficient use of electronic devices and other communication equipment.

The object of research. Processes of electricity distribution in electrical networks with local energy sources.

The subject of research is the optimization electrical networks in the context of increasing use of renewable energy sources.

Practical value of the results. To solve the set tasks in the dissertation the effectiveness and usefulness of the electronic SOP technology and one of the methods of load forecasting for the more effective operation of distribution networks were considered.

Scientific novelty of the obtained results. For the first time, a comprehensive analysis of the feasibility of using complex of devices of power electronics for the purpose of increase of efficiency distribution networks under conditions of wide integration in them of various distributed sources of electric power generation, which will allow to evaluate the effectiveness of their use in power systems of Ukraine.

The method of justification of Soft Open point technology application during the control modes of distribution networks with the distributed power generation sources has been further developed, which allows minimizing electric power losses.

Improved the method of forecasting under conditions of uncertainty of the available input information in order to determine the expected network nodes loads and output power of the distributed power sources, which allows to increase effectiveness of application of remotely controlled switching centers application of remotely controlled switching devices distribution grids.

Publications.

1. V. Popov, O. Yarmolyuk, V. Tkachenko, I. Frolov, V. Usatenko. Features of Technical and Economical Approach to Decision-Making with Perspective Planning of Electric Power Supply Systems. Scientific journal "Power Engineering: Economics, Technology, Ecology". - February 2, 2020.

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Key words: DISTRIBUTION NETWORK, DISTRIBUTED GENERATION SOURCES, POWER ELECTRONICS, SOFT OPEN POINT, FUZZY TIME SERIES, FORECASTING

CONTENTS

LIST OF ABBREVIATIONS

DG - distributed generation.

EN - electrical networks.

DN- distribution network.

RP - relay protection.

SOP - Soft Open Point.

SR - supply restoration.

STATCOM - Static synchronous compensator.

NOP – No operation.

OLTC – On-load tap changer.

UPFC – United power flow controller.

PE- power electronics.

B2B – back to back.

VSC - voltage source converter.

LV – low voltage.

MV – medium voltage.

RES – renewable energy sources.

CHPP - combined heat and power producing.

SOP – soft open point.

TS -time series.

ANN – artificial neural network.

SVM – support vector machine.

MVP - multilayer perceptron.

ARMA – autoregressive moving-average

ARIMA - autoregressive integrated moving-average.

FTS – fuzzy time series.

INTRODUCTION

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1 ANALYSIS OF WORLD EXPERIENCE IN MANAGEMENT AND DEVELOPMENT OF SOURCES OF DISTRIBUTED GENERATION

At present, the global energy industry is gradually transforming from centralized generation to more decentralized generation. Many countries have been rapidly developing distributed generation over the last decade.

A lot of forecasts show a threefold increase in distributed generation capacity by 2026 compared to centralized power supply (Fig. 1.1).

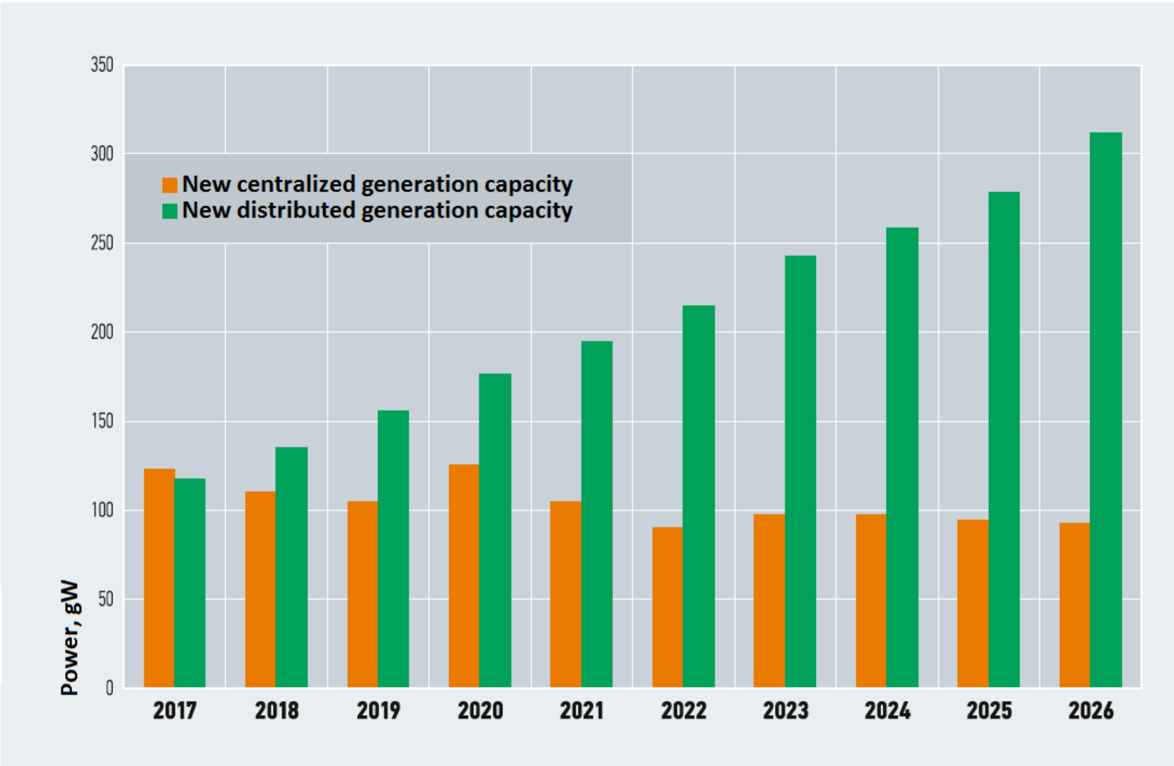


Figure 1.1 – Forecast of the volume of centralized and distributed electricity generation in the world [1]

Distributed generation was developed back in the last century, when new sources of electricity appeared in Europe and the United States - gas turbine and gas piston plants of small capacity. Later, in connection with the aggravation of environmental problems due to global climate change, as well as the desire of many countries to become energy independent, renewable energy sources (RES) appeared. The impetus was also the fact that in 2015, at the Paris COP21 conference dedicated to climate change, the leadership of 196 countries of the world came to an agreement «to take measures to prevent destructive climate change». Among the main points of this agreement was the signing of a document to support the development of renewable energy sources. Currently, renewable energy together with distributed generation are important trends in the development of world energy.

At the fifth international conference Energy Transition Dialogue dedicated to the global transition to renewable energy sources, which took place in Berlin in April 2019, the International Renewable Energy Agency (IRENA) made a presentation titled “Transforming the Global Energy System. Roadmap to 2050». According to them, in 30 years, the share of «green» electricity, produced mainly by the sun and wind, can be increased to 86% [2].

In addition to renewable sources, the most widespread technologies of distributed energy generation in the world practice are:

- technologies on natural gas, low power nuclear power plants;
- micro turbines;
- gas piston units;
- energy storage devices (chemical, inertial, gravitational and others).

Distributed generation includes sources of low power. Navigant Research considers such sources to be wind power plants with a capacity of up to 500 kW, solar power plants up to 1 MW, gas turbines up to 250 kW, as well as gas piston and diesel power plants with a capacity of up to 6 MW.

The boundary limits of the capacities of distributed generation sources, as defined by the European Union Dynamical Exascale Entry Platform (EU-DEEP), are as follows: wind farms - 6 MW; solar stations - 5 MW; thermal power plants (steam, gas turbines, piston engines) - up to 10 MW, micro turbines - up to 500 kW [3].

Currently, in many countries, the development of distributed generation, especially distributed generation based on renewable energy sources, is supported at the state level. The transition of the energy system to a new level leads to sustainable territorial development, energy security, and allows solving global environmental problems.

Among the measures used by states to support the development of distributed generation, it is worth noting tax incentives, concessional lending, the creation of specialized funds through which financing of relevant research and development work is carried out, the approval of the amount of electricity to be generated by renewable energy sources, and so on.

1.1 Situation in EU energy sector

The consumption of traditional energy in Europe, according to the Energy Research Institute of the Academy of Sciences, in the period from 2015 to 2040 will decrease by an average of 0.5-0.8%. At the same time, an increase in the share of electricity in the final energy consumption will be observed.

The European Union is playing a leading role in the energy transition. In 2018, the European Commission developed a long-term strategy for achieving climate neutrality by 2050. This goal is supported by most of the Member States.

In 2019, the EU Council adopted the Clean Energy for All Europeans package of laws, which is an important step towards a decarbonized energy system. The goals it sets for 2030 are quite ambitious. They are mainly associated with the development of energy efficiency (32.5%) and renewable energy sources (32%). Particular attention is paid to solar and wind energy. It is planned by the end of the next decade to increase the total installed capacity for solar photovoltaic cells to almost 500 GW, and for wind turbines to more than 300 GW. This will lead to the fact that the flow of electricity through the networks will significantly increase and become more variable, there will be a need for network development and effective congestion management. With the transition to the decentralization of energy resources, smart meters, storage batteries will become widespread, and innovative business models, such as local energy communities, will be introduced [4].

At present, in European countries, about 30% of all energy produced is produced at distributed generation facilities. This growth is due to the great desire of Europeans to compensate for the lack of traditional energy sources through the development of secondary energy resources. In addition, distributed generation is cost-effective and also solves very important environmental problems for Europe.

Among the objects of distributed generation, the most in demand are facilities that use renewable energy sources. Wood Mackenzie analysts have concluded that the largest amount of electricity produced by 2030 will fall on RES. (Fig 1.2) shows the current growth of the share of RES in the energy sector by years in the period 2010-2018 and promising. Wind energy consumption will increase from 12% in 2018 to 26% by 2030, and solar energy consumption will almost triple from 4 to 11%. Biomass almost doubles its share from 6 to 11%, provided that hydroelectric power generation remains unchanged [5].

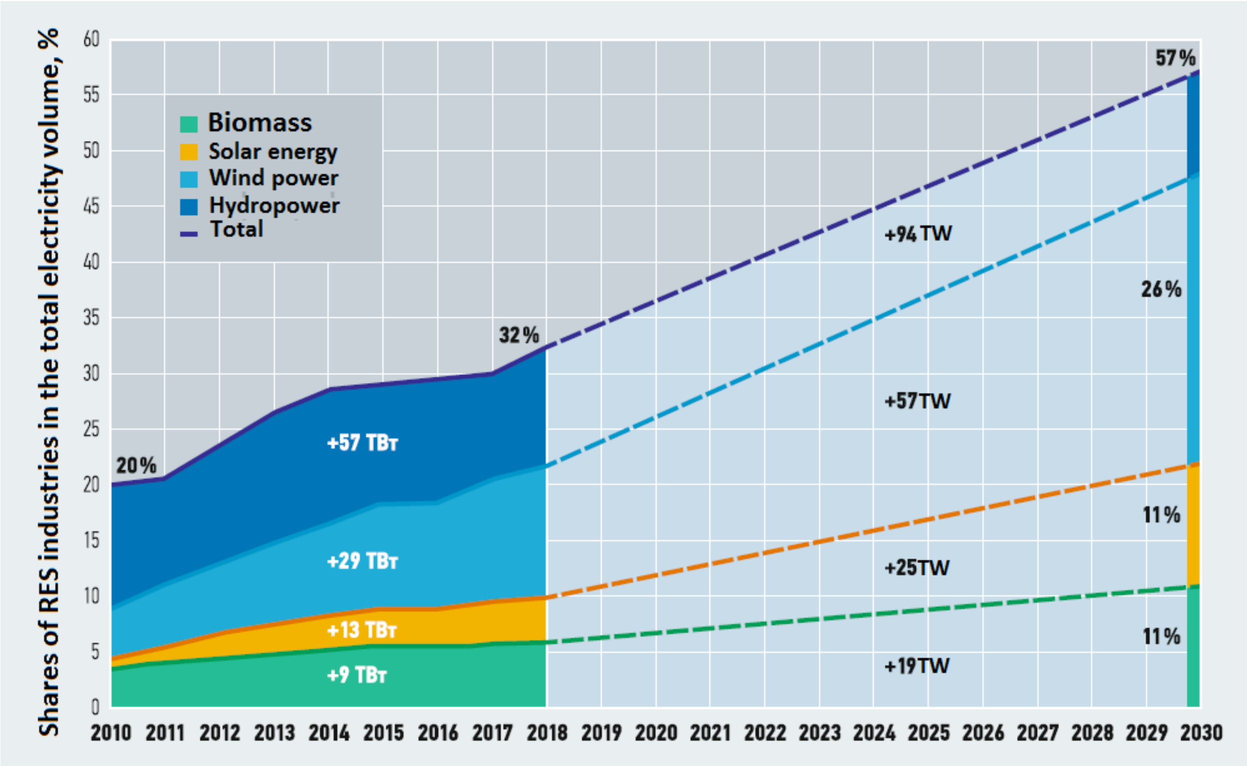


Figure 1.2 – Forecast until 2030 of the share of renewable energy sources in the long-term strategy of the European Commission [1]

More than 20 national research organizations and universities in Europe (Austria, Belgium, Germany, Denmark, Greece, Spain, Finland, France, Italy, Latvia, the Netherlands, Norway, Poland, Portugal and the UK) have joined the Electra integrated research program to strengthen and accelerate the average long-term cooperation in the field of small-scale energy, research of distributed generation and renewable energy sources. Through coordination and collaboration between leading research infrastructures, it is planned to create fundamentally new approaches to energy management that can ensure the coordinated operation of millions of devices with different technical characteristics, with different scales and voltage levels, as well as connection to the grid at all voltage levels.

Situation in Germany energy sector

In 2000, Germany passed a Renewable Energy Law (Erneuerbare-Energien-Gesetz, EEG), which encourages the generation of electricity from renewable sources. This law was the impetus for the introduction of a new energy policy. The source of financing was the «green» tax for all electricity consumers in the country.

In 2010, the state program «Energiewende» was launched, the main goal of which is to phase out hydrocarbons and nuclear energy in favor of renewable energy sources for the period until 2050. According to the program, the share of renewable energy sources should increase to 55%, and carbon dioxide emissions should decrease by 55% compared to 1990 indicators.

In 2016, the reform on the transition of Germany to the «new» energy was launched. As a result of government support, German alternative energy has developed significantly (Fig. 1.3). Thus, the generation of electricity from renewable energy sources increased from 38 TWh in 2000 to 217 TWh in 2017 [6].

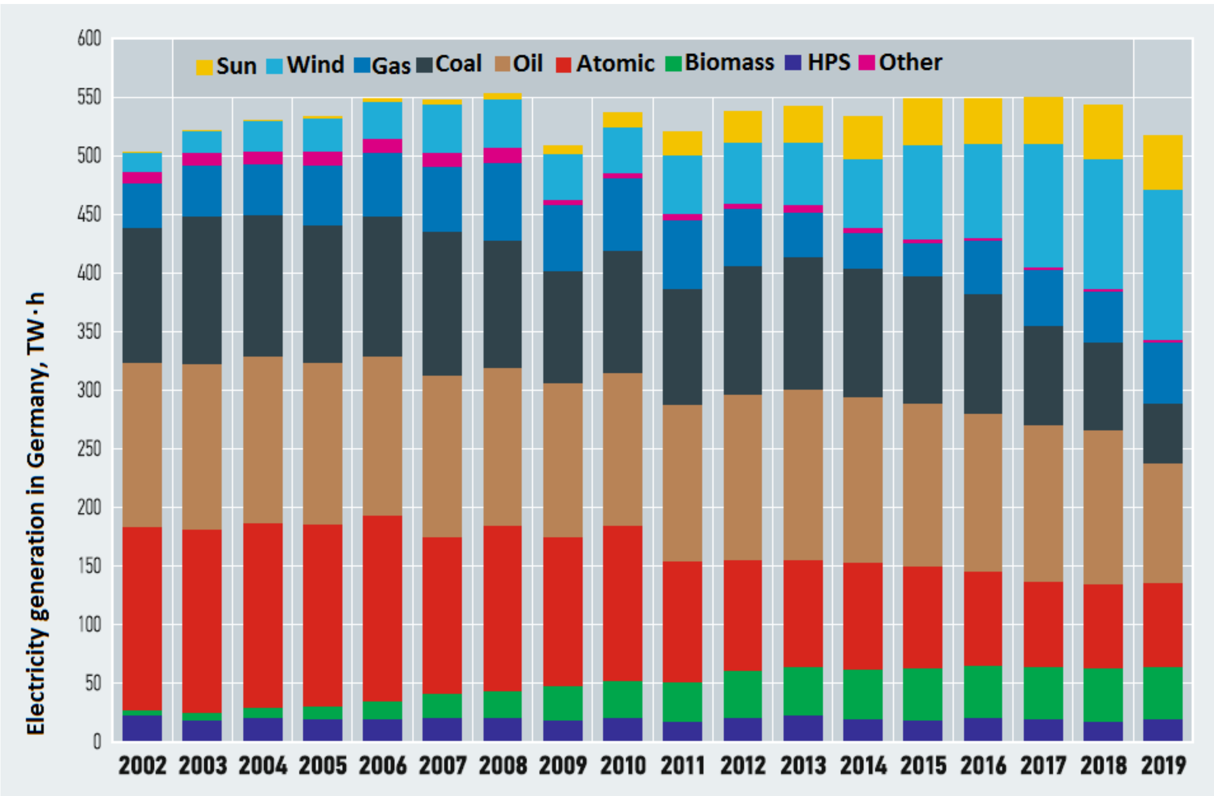


Figure 1.3 – Electricity generation in Germany [7].

Nuclear power plants in Germany have almost halved their output, and stations that run on coal - by one and a half times. The seven currently operating nuclear power plants are planned to be sequentially closed by the end of 2022.

After the closure of the Prosper-Haniel and Ibbenbüren mines, coal mining in the country ceased. Only lignite still practically retains its power in the power industry. According to the EU Reference Scenario 2016, Energy, transport & GHG emissions trends to 2050 (July 2016), coal capacity in Germany will decrease from 45 GW in 2016 to 36.8 GW in 2030 by 2030.

Gas generation, despite its growing environmental friendliness, is in the lowest demand. The reason for this is the fact that the cost of gas generation exceeds that of coal.

Despite the fact that the generation of electricity from renewable energy is constantly growing, the German energy sector faces a number of challenges. These problems are often related to energy costs. So, in sunny and windy weather, the cost of energy obtained from wind generators and solar panels sharply decreases, and sometimes even goes into negative value. At the same time, in cloudy calm weather, prices for energy from traditional sources increase dramatically. And this is a justified measure, since at the peaks of renewable energy generation, the owners of supporting capacities are forced to sell their energy at a minus or stop facilities.

Coal and gas plants have to work in the background after green power plants, as a result, they very often do not operate at full capacity, which increases their payback period.

This situation in Germany leads to the fact that instead of jointly coordinated work of energy sources, they constantly compete with each other.

As a solution to such problems, the country sees the use of «Virtual Power Plants» (VVP) as a digital community of decentralized generators and consumers. An example is the project of the German energy company RWE, as a result of which renewable generation in the Rhine-Ruhr region was united in the VVP. Thanks to

Siemens developments used in the project, free capacities appeared in the region, which RWE sells on the European Energy Exchange.

An important feature is the fact that generation based on renewable energy sources located at household consumers is involved in the electricity trade [8].

Another positive example is the village of Wildpoldsried, which won a tender to participate in the Siemens experiment in 2011. As a result of research carried out in this village, it turned out that wind turbines are the most powerful energy producers, in second place were biogas plants, in third - solar panels. During the experiment, a system was created, thanks to which it became possible to balance voltage fluctuations in the power grid from alternative sources and reduce the idle time of generators. The received and accumulated energy was supplied either to the needs of the population, or, if necessary, to the general energy network of Germany.

It should be noted that in Germany the distributed renewable energy regime prevails. At the same time, distributed photovoltaic power generation accounts for more than 95%, and distributed wind energy reaches more than 85% of the total power generation from corresponding sources.

The highest concentration of renewable energy sources is observed in the northern federal states, as well as in the North and Baltic Seas, that is, far from the main load centers, which are mainly located in the south of the country. Taking into account the wind resources existing in Germany, the centralized development of wind energy is preferable for the northern states. The southern regions of the country, where the main load centers are located, are characterized by high capacities of solar energy. Solar power plants here are mainly distributed generation facilities.

Situation in Spain energy sector

The National Comprehensive Plan for Energy and Climate 2021-2030, approved by the Spanish government in early 2019, notes that by 2030 it is necessary to increase the share of renewable energy sources in the country's energy balance to 74%. In the spring of 2019, the Regulation on Own Consumption was issued, the main idea is to revitalize the market for photovoltaic systems. Currently, owners of small solar installations (up to 100 kW) are entitled to receive remuneration for surplus electricity and share the “surplus” energy within the housing community.

The growth rate of distributed generation in Spain increased significantly at the end of 2018 after the decrease in tariffs for own consumption.

Solar energy is also being staked on in the energy transformation scenario presented by the Spanish government in the report of the “Committee of Experts”. In one of the macro development scenarios, called the Distributed Generation Scenario (DG), a significant increase in distributed generation based on renewable energy sources in combination with energy storage systems is predicted. At the same time, an increase in the volume of solar generation is expected by 2030 to 31–77 GW [9].

The five currently operating nuclear power plants are planned to be decommissioned between 2023 and 2028. Seven of the fifteen operating coal-fired power plants are due to close in 2020 in accordance with the EU's recommendations. In their place in the energy sector, it is planned to introduce renewable energy facilities.

However, Spain is in no hurry to give up coal. Currently, 15–20% of all electricity is generated at coal-fired power plants in the country. The state supports the domestic coal industry because it employs nearly 4,000 people. For the preservation of capacities, the owners of coal-fired CHPPs receive payments as support from the state.

Royal Decree-Law No. 244/2019 regulates the administrative, technical and economic conditions for the supply of electricity in relation to energy production and own consumption.

According to this decree, two types of self-consumption model are established:

1. Methods of supply with self-consumption without surplus. When installed physical devices prevent excess energy from entering the transportation or distribution network.

2. Supply conditions with self-consumption with surplus. When generating plants can, in addition to supplying energy for their own consumption, inject surplus energy into transport and distribution networks.

In 2018, approximately 2% of electricity in Spain was generated from own consumption. The approval of Royal Decree No. 244/2019 was a strong impetus for the growth of installed capacity for own consumption.

Situation in Italy energy sector

In 2019, the Italian Ministry of Economic Development developed a draft National Energy and Climate Plan for 2030. Among the goals of this project is to more than double the share of solar energy in the country's energy balance by 2030 compared to 2018.[10]

The capacity of coal-fired thermal power plants in the country is about 15%. This value has remained almost constant over the past few years. There are currently 11 coal-fired power plants in Italy, but many of them are nearing the end of their service life. Italy has developed integrated systems that optimize local energy production and consumption. Energy efficient types of consumption are possible only by uniting several people (for example, households) into a community of developed consumers.

For this purpose, Regalgrid platforms have been created in Italy. Regalgrid makes it possible to digitally connect various system elements to maximize the energy consumption of the user community. This can be achieved with cloud software integrated into a device called Smart Node Control Unit (SNOCU), which can be connected to inverters, batteries and smart meters already available on the market.

Interestingly, although effective and profitable, this solution is not fully applicable in the country where it was developed. This is mainly due to the fact that in Italy there is practically no legislation regulating the distribution of energy to users.

Situation in Denmark energy sector

In this European country, one of the main priorities for energy development, according to the Danish state program, is the construction of small energy facilities. The implementation of the program has led to the fact that distributed generation accounts for more than 50% of the total electricity generated in the country. This year it is planned to receive 33% from renewable energy sources.

By 2040, Denmark plans to reach 85% of renewable energy sources, and by 2050, completely abandon fossil fuels [11]. Denmark's largest energy company, DONG Energy, is looking for ways to use excess energy to create greater benefits for its customers.

Denmark is considered the world leader in wind energy (Fig. 1.4). It is not in vain called the «Land of the Winds». Everyone knows that the length of the Danish coastline is more than 7,300 km.

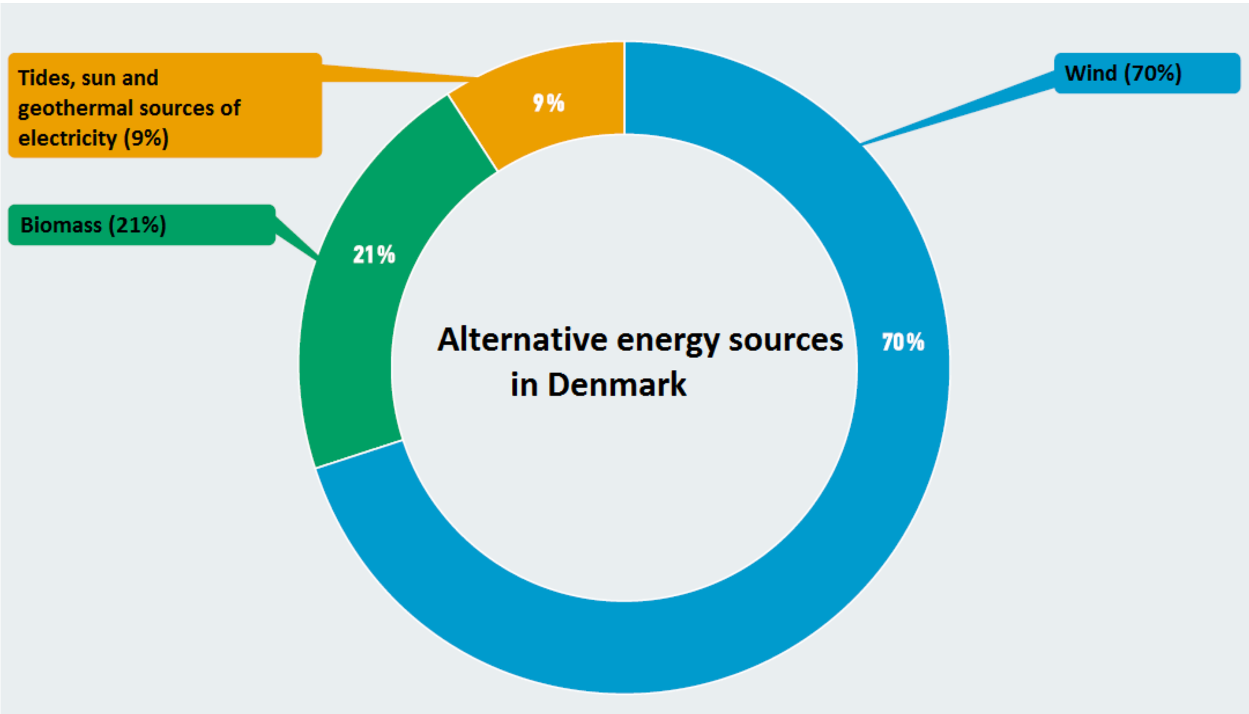


Figure 1.4 – Using of alternative energy sources in Denmark [12]

Recently, there has been a tendency to switch from mainland wind power to offshore. This is due to the fact that Denmark, being a small country in terms of territory, has a high population density and a large number of land-based wind turbines interfere with residents and «litter» useful areas.

It is known that offshore wind farms, in comparison with mainland ones, provide a higher output for the same installed capacity. It is planned to reduce the number of onshore wind turbines by 2030 from 4,300 units (in 2019) to 1,850.

The Scandinavian state also supports the development of bioenergy. The Danish government is allocating $ 537 million for the production of biogas and other «green gases» [12].

The share of solar energy in Denmark in 2018 accounted for only 2.8%. However, according to the Danish Energy Companies Organization Dansk Energi, the 25% increase in the amount of electricity generated by solar power plants in 2018 compared to 2017 is commendable. Photovoltaic solar power generation has grown from 768 GWh in 2017 to 961 GWh in 2018.

The system of measures to support mini-CHPs practiced in Denmark has greatly contributed to the fact that over the past decades, several hundred small energy centers on natural gas and biomass have appeared in the country (Fig. 1.5) [3]. It should be noted that the “energy transition” in Denmark began with the oil shocks of the 1970s. This transition required coordination between government, network operator and utilities. In Denmark, a pilot management project has been developed to demonstrate the ability of a local system to interconnect and manage distributed generation over the transmission network.

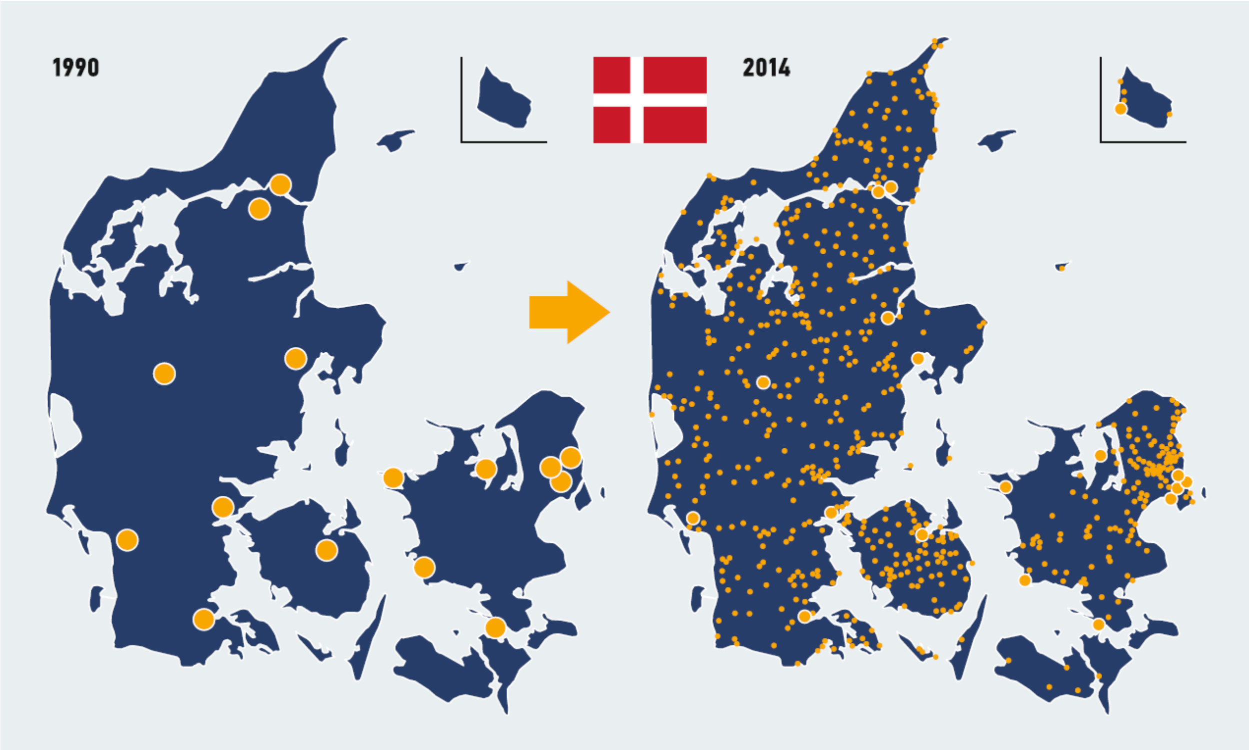


Figure 1.5 – Decentralization of energy in Denmark based on distributed cogeneration [12]

Situation in Great Britain energy sector

The total installed generating capacity in the UK in 2017 was 81 GW. The structure of installed generating capacity in 2017 is shown in (Fig. 1.6)

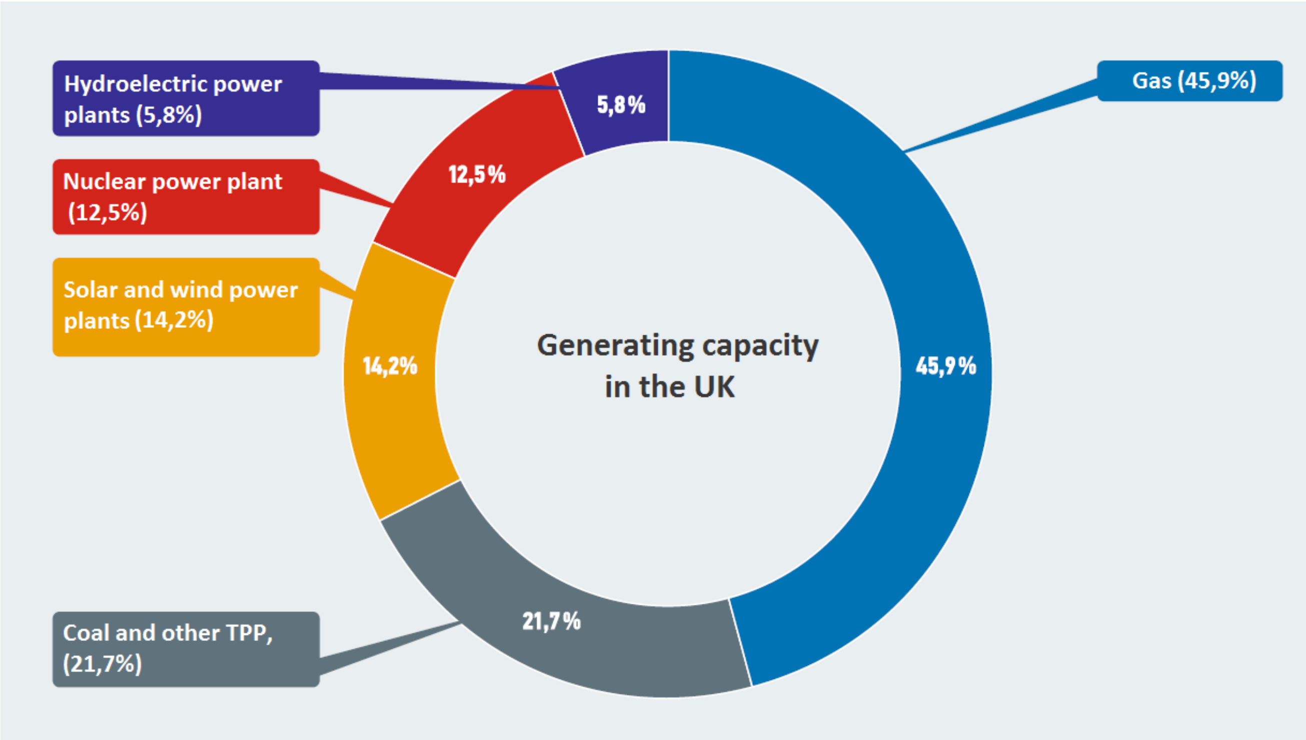


Figure 1.6 – Structure of installed generating capacity in 2018 in the UK [1]

The energy policy of the UK government is aimed at a transition to low carbon energy. In accordance with this, it is planned to completely abandon coal generation by 2025. To this end, a systematic reduction in the share of coal in the total volume of electricity production is being carried out - from 30% in 2014 to 6.7% in 2017. The reduction is carried out by completely decommissioning coal-fired power plants or transferring their biofuels.

National Grid Electricity System Operator is partnering with SP Energy Networks (SPEN) and TNEI to develop the Distributed ReStart project. The aim of this project is to investigate the role of Distributed Energy Resources (DER) in the UK in energy recovery in the event of a complete or partial outage of the National Electricity Transmission System.

According to participants, the advantage of DER is that it provides a cleaner and greener alternative to power generation. The Distributed ReStart project is expected to demonstrate, for the first time, bottom-up coordination from distribution networks to the transmission layer to provide a secure and efficient Black Start service. Black Start is the process of restoring power to consumers after a power outage. The problem being addressed in the project is how to combine coordination, commercial and regulatory frameworks and energy solutions to achieve the DER Black Start [10].

1.2 Situation in the USA energy sector

The main source of electricity in the United States is coal-fired power plants. However, the share of the energy they generate in the total generation is decreasing. In 17 states, renewable energy sources outstripped coal-fired power plants in terms of productivity. Between 2011 and 2016, more than 61 GW of coal-fired generation was cut in the United States. One of the main reasons for this decline was the tightening of environmental regulations. The decommissioning of coal-fired power facilities will continue. So, by 2030 it is planned to reduce another 65 GW of capacity.

According to statistics from the Energy Information Administration (EIA) of the US Department of Energy, in half of the states, more energy is generated from renewable energy sources, rather than nuclear power plants, in 30% of states, renewables are ahead of coal-fired power plants.

The United States has a leading position in the world in terms of installed renewable energy capacity (second after China in 2018):

- bioenergy (16.2 GW);
- wind energy (96 GW);
- hydro (80 GW);
- solar energy (62 GW).

In 2019, it is planned to put into operation 23.7 GW, of which 66% will come from renewable energy sources (Fig. 1.7) [14]. In 2018, the United States accounted for more than 60% of all global corporate purchases of green energy. During that period, contracts were signed for 8.5 GW of energy. This figure turned out to be three times higher than the figure for 2017.

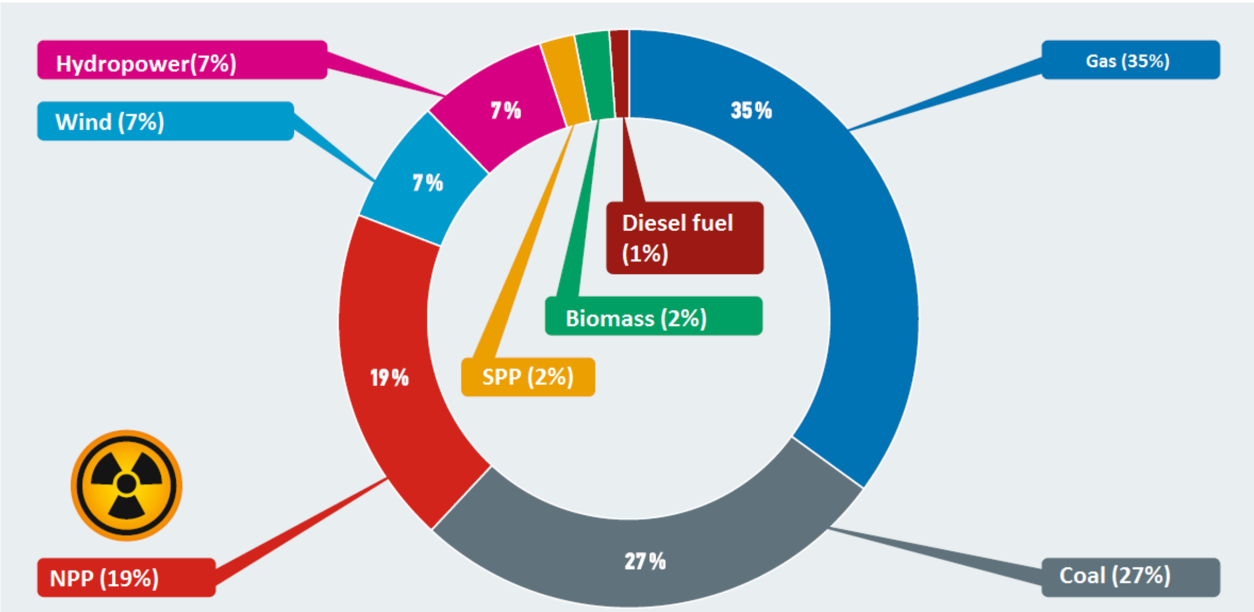


Figure 1.7 – Installed generating capacity structure in the USA [1]

In the field of renewable communal energy, the first were associations called «energy cooperatives». The activities of such associations are aimed at joint ownership and joint exploitation of renewable energy resources. Despite the fact that the bulk of the capacity in the United States remains with large energy enterprises, more than 70% of the total number of solar communal energy projects are occupied by energy systems that are owned by cooperatives. The Touchstone Energy Cooperatives Association had 750 members for 2017 [15].

According to this association, energy cooperatives are common in 46 states. According to the US Department of Energy, in 2007, the country operated about 12 million small distributed generation units (unit capacity up to 60 MW) with a total installed capacity of over 220 GW. According to various sources, this capacity is constantly growing, gaining about 5 GW per year.

It should be noted that representative offices of large companies (Apple, Google, BMW, Walmart) meet their electricity needs with the help of their own generating capacities. It uses gas, biogas, fuel cells and solar energy. However, according to the EIA, the total share of self-generated generation in the United States does not exceed 5% of the industry indicators [16].

Also, the EIA in 2019 in its energy development forecast noted that the most preferred generation technologies in the United States would be photovoltaic solar energy and combined gas generation. According to the US Department of Energy Administration, wind energy is competitive only in certain regions, while coal and nuclear energy is economically unattractive. The State of California is a leader in the implementation of distributed generation technologies. This state is the largest market for solar panels, smart meters and electric vehicles. California is aiming for a full carbon-free energy transition by 2045. At the same time, it is planned that the growth of distributed generation will be supported at the state level.

1.3 Situation in the China energy sector

Currently, the PRC is the most energy-consuming state. According to 2017 data, 69,6% of the total electricity generation falls on coal-fired energy. However, at the same time, there are a number of problems in the country, such as a shortage of raw materials in the domestic market, low efficiency of coal generation, high levels of CO2 emissions and an insufficiently effective management system. These problems contributed to the Chinese government's decision to change the coal-fired power supply system.

Therefore, recently, special attention in the country has been paid to the development of renewable energy sources to change the energy balance and introduce a distributed generation system. In general, since 1990, there has been an increase in the share of renewable sources in the production of electrical energy (Fig. 1.8) [17].

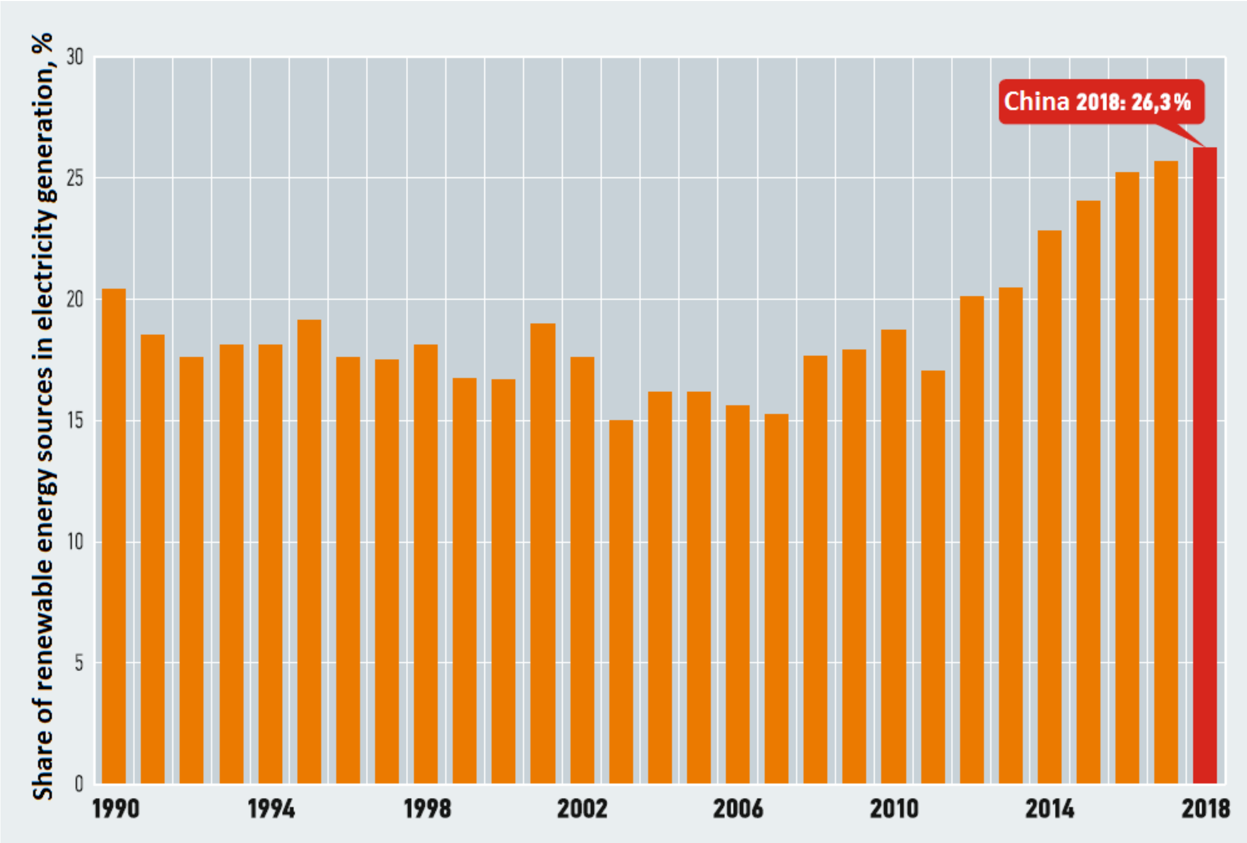


Figure 1.8 – Share of renewable energy sources in electricity generation in China [1]

In 1912, the first hydroelectric power station was built on the Thanglang Chuang River. In the period 1949-1960, hydroelectric power plants were built on small and medium-sized reservoirs. With the opening of the country to the outside world in 1978 and the advent of foreign technology in China, larger and more technologically sophisticated hydroelectric power plants began to be designed and built.

In 2011, the station accounted for about 2% of the total generation of the PRC, or about 98.1 GWh of electricity (14% of the total generation of Chinese hydroelectric power plants). In 2013, the increase in the capacity of hydroelectric power plants amounted to 30,5 GW. Ultimately, in practical terms, the productivity of hydropower in the Chinese state increased from 0,5 MW in 1912 to 77 GW in 2000 [18].

Thus, hydropower currently dominates the renewable energy sector in China. Hydroelectric power plants account for 18% of all electricity generation in the PRC.

In addition to the development of water energy, the use of wind energy has become widespread in China. In 1986, the PRC State Aviation Department built the first wind turbine in Shandong Province. This gave a powerful impetus to the development of wind energy, and the capacity of the installed wind generators is increasing every year.

At the beginning of the 21st century, the National Development and Reform Commission issued a plan to stimulate the domestic production of equipment for wind energy, as a result of which, by 2012, China became a leader in this area, reaching a productive capacity of 63 million kW.

Solar energy has been actively developed in the fuel and energy complex (FEC) of China in recent years. In 2009, the Golden Sun program was adopted, which provides for the introduction of desert lands in the west, north and center of China into the economic circulation. In a short period of time, China has shown outstanding growth in the development of solar energy, which made it possible in 2012 to take the leading position in the production of solar panels in the world.

In general, over the period 1990–2018, the use of wind and solar installations made it possible to increase the share of electricity production from zero to 7,8%. And in the plans of the PRC government to bring this figure to the level of 15% or more [19].

China is characterized by two key factors in the development of renewable energy and distributed generation:

- climate change;
- the desire to ensure the country's energy security.

The country has been experiencing serious problems with air pollution for quite a long time. This factor, as a consequence, leads to the fact that private investors are beginning to actively invest in the development of renewable energy.

In early 2006, the «Renewable Energy Law» was passed, which required grid utilities to include all possible renewable energy sources, except in cases involving grid security concerns. Moreover, the acquisition of renewable energy was given a high priority in the preparation of the annual electricity generation plan. All this led to the fact that by 2018 the XIII five-year plan, according to which in 2020 the country was to achieve 105 GW of solar energy, was exceeded (by the end of 2017, more than 130 GW were generated in the PRC).

As a result, the National Development and Reform Commission, together with the Ministry of Finance and the National Energy Administration, decided in 2018 to end the issuance of quotas for the construction of industrial solar power plants, and even banned the issuance of building permits for the provinces. It should be noted that this year it is also envisaged to reduce the volume of newly commissioned distributed generation capacities to 10 GW.

China's leadership in the production of wind turbines and solar panels leads to an oversupply due to lack of demand. With a shortage of power grids for transportation and an unreliable supply of energy from renewable energy sources, China is failing to realize its potential in wind and solar energy.

With the current low cost of coal, it is unlikely that this type of fuel will be abandoned in the short term. Nevertheless, the trend towards an increase in the use of less harmful renewable energy sources is strengthening its position, taking into account the state policy and various state programs for the development of «non-fuel» types of energy resources.

A systematic approach to the diversification of energy sources and the desire to reduce the negative impact on the environment seems to be important, namely, the consideration of the entire energy system in a complex, starting from the construction of additional capacities and ending with the transportation of generated energy to the final consumer.

1.4 Situation in the Ukraine energy sector

Widespread use of DG power supplies in the EN of Ukraine there will be some technical problems. And they will be different at different stages.

At the first stage, which characterizes by the presence of single sources of DG in the EN, as a rule, will occur mainly problems associated with EN re-equipment.

It is necessary not only to modify existing RP systems, but also to replace them with new ones. Maximum current protections, which are most common in DS, should be replaced by directional and/or differential RP systems:

- Replacement of switching equipment (due to increased short-circuit currents);
- Installation of appropriate technical means of "allocation" of DG sources to work autonomously load (energy islands mode);
- Definition of operational schemes and development of technical support (devices of synchronize the DG energy islands with the main network, the corresponding automation of frequency and voltage regulation etc.) for the operation of DG sources in the power supply mode of certain fragments of the EN in the event of an accident in the main EN.

When the relative share of the power of the installed DG sources reaches 5-10% or more from generation at centralized power plants, then comes the second stage of development of EM with new problems.

Inconsistency of traditional approaches to planning and management of established and after-accident mode regimes for those tasks that arise with a high degree of implementation of DG sources.

Ensuring the stability of the modes of operation of distribution networks, especially with significant implementation renewable energy sources.

Optimization of steady-state modes of DN with a high degree of implementation sources of DG.

In addition to the identified technical problems, there is another problem that precedes them - the definition optimal installation locations and capacity of relevant

DG sources. This problem is solved by provided that a systematic approach is applied, which will avoid irrational use of resources and potential of DG sources.

Conclusion to chapter 1

Based on the analysis of world experience in the management and development of sources of distributed generation, the following conclusions can be mentioned:

1) World experience points to the fact that to use distributed generation to increase the reliability of distribution networks is important a comprehensive approach to the analysis of all components that affect their functioning, namely: the introduction of "smart grid"; development and use of universal international standards, active implementation of monitoring by regulator etc.

2) It was concluded that the share of DES tends to increase. However, it was also noted that a significant share of DES is occupied by RES, which may create additional challenges in the dispatching of distribution networks. This phenomenon requires additional analysis and forecasting to create a strategy for future management of distribution networks in order to avoid the negative consequences that may be created, while continuing the trend of significant growth in the share of RES in the segment of electricity generation.

According to the results, all current issues related to the world experience in the management and development of sources of dispersed generation and the possibility of using SOP in distribution networks, which is presented in the practical part of the master's thesis, were taken into account.

2 CHALLENGES WITH RENEWABLE ENERGY SOURCES IN REAL DISTRIBUTION SYSTEMS

The introduction of DG affects the distribution of EN and converts them into active elements of power systems. This leads to the need to make changes (or revision and modernization) in the adoption of management strategy, operation and planning of EN.

2.1 Influence of DG use on modes of operation of distribution networks

Influence of DG on electricity losses in EN

Installation of DG power supplies in a DN near the load can change the direction of power flows. There are three situations regarding the nodal load and DG [20]:

The actual load of each node in the EN is greater than or equal to the output power of DG sources connected to this node.

In the EN there is at least one node, where the output power of the DG sources is greater than the actual load of this node, but the total power of the DG sources of this EN is generally less than its total load.

In EN there is at least one node, where the output power of the DG is greater than the actual load-of this node and the total power of the DG sources of this EN is generally greater than its total load.

In the first case, the installed DG sources in the EN will reduce power losses in the DN.

In the second case, DG sources can permanently increase the power loss in some transmission lines of the DN, but, in general, the total power loss in the EN are reduced.

In the third case, the total power loss of the entire DN will be greater than before installation of DG sources. At the same time, the situation when transportation takes place is quite unfortunate electrical energy in the opposite direction, i.e. from the end of the EN to its main section. This is due to the fact that the cross section of transmission line wires in distribution networks usually decreases from the main section of the transmission line to it send end and the resistance of the transmission line and its losses depend on the cross section of the wires.

Also, various DG sources work with different *cosφ* and their output reactive power may vary from insignificant generation (gas turbine installations, etc.) to significant, on the scale of DN, consumption (wind farms, etc.), which is also negative affects the magnitude of power losses in EN [21].

Thus, the installation of DG sources can both increase and decrease power losses in EN, which mainly depends on the location, capacity, level of implementation DG sources in EN, their *cosφ* , as well as from the topology of EN, etc.

Influence of DG on voltage in EN

There are two types of influence.

First, it has an impact on voltage levels in steady-state mode of operation of the EN [22]. In traditional DN, i.e. in radial type EN, voltage reduction occurs along the direction of power supply to the consumer from the main section of the transmission line to its end. After establishing the sources of DG in such EN occurs reducing the load of the feeder, and the voltage along the transmission line may increase. Important there is a *cosφ* of the DG sources and the type of generator (synchronous or asynchronous). In some cases, when using relatively powerful synchronous generators, the permissible by voltage level (> 1.1 U_{base}). Thus, the magnitude of the voltage change depends on the places of installation DG sources, their capacity and cosφ (generation or consumption).

Second, the influence of DG on voltage fluctuations in EN [22]. In traditional DN, active and the reactive load of the nodes changes over time, which causes certain fluctuations in the voltage level EN. In the direction from the main section to the end of the transmission line voltage fluctuations usually increase. If the load is concentrated mainly at the end of the transmission line, the voltage level will fluctuate more intensely. Once the DG sources are connected to the DN, the latter will affect the voltage levels in the nodes, increasing or decreasing them.

In the case where DG sources work matched to the local load, i.e., their power increases (decreases) with increasing (reducing) the load in the nodes, they will dampen voltage fluctuations. But when the sources of the DG work inconsistently with the local load, as the power of DG sources depends on the primary resources and output characteristics which are difficult to control (such as wind speed, intensity radiation of sunlight, etc.), then in such a situation DG can significantly increase the fluctuations voltage in EN. In addition, some sources of DG (e.g., wind farms, photovoltaic cells) are inherent strong fluctuations of the output power, which significantly affects the fluctuations of voltage levels in the EN nodes, the effect stronger, then greater the installed capacity of the DG sources.

Influence of DG on the quality of electricity

Installation of DG sources in DN has quite significant impact on the quality of electricity [23, 24].

First, DG sources lead to increasing the dose of flicker, which can occur during the introduction or decommissioning of powerful sources DG in DN, sudden change of output power of DG sources, interaction between DG sources and regulating devices.

Second, DG sources can generate high-order harmonics in EN, in this case, the sources of the DG or themselves may be sources of harmonics of higher orders or to connect to the DN through the inverter, which generates a harmonic network of higher orders, which is typical for fuel and photovoltaic cells, wind turbines, etc.

Third, DG sources affect voltage dips, which is mostly related to the type of generator. For example, in DG with synchronous generators after a voltage failure the latter is restored to approximately the original level, and in the case of asynchronous generators the voltage is not restored to the initial level due to reduction of reactive power support [25]. It should also be noted that the total impact DG sources for voltage dips, although it depends on the power of the DG, but not strongly enough.

2.2 Influence of DG on level of protection, automation and reliability of distribution network

Influence of DG on relay protection and automation

Since traditional DN are radial type, the power flow is unidirectional from the main section to the end consumers, and in most emergencies instantaneous current protection is used [26]. As a rule, the relay protection (RP) of DN is designed with the installation of the maximum relay current and reclosers on the main feeder of feeders substations and fuses in the branches of EN. To ensure the protection of DN in practice disconnection of the transmission line where the accident occurred, isolation of the damaged element (sections of transmission line) and reconnect the line. But this approach to RP DN is not designed for the existence of additional power sources, such as DG sources, which raises a number of issues.

First, this is a problem associated with the use of fairly common in DN reclosers devices together with DG sources [20]. The current-free pause during recloser operation, as a rule, lasts fraction of a second, which does not cause great harm to consumers. In the case where the protection of DG sources is not worked during the current less pause of the recloser, such a source remains connected to the EN and will be on-try to maintain mains voltage. So, the electric arc will not attenuate and the damage will not be self-liquidated, which will lead to a significant interruption in the power supply [27]. At the same time, it is necessary to means that even if the DG source is switched off throughout the recloser no-current pause, the time due to the elimination of the arc, decreases during the operation of RP DG sources. Another reason for disabling DG sources from the mains during the current-free pause of the reclosers is to support the safe operation of the DG source itself. If the DG source remains connected to the network, the speed of its rotation the generator may change (for rotating type DG) due to power imbalance.

Therefore, to avoid these undesirable situations during operation, the EN must to solve the problem of coordinating the work of reclosers with the work of RP sources of DG. Use longer current-free pauses are one possible solution to this problem, although it may reduce the quality of electricity.

Secondly, it is a significant complication of the construction of RP network systems with installed DG devices. For example, in the event of a short circuit outside the feeder, which includes sources of DG, but in within one substation, the DG source participates in the power supply of the short circuit. In this situation, the relay, which is located at the beginning of the transmission line with the DG, which is possible if you do not take into account the direction of flow current. The use of directional or even differential RP systems in DN allows solve this problem.

Some authors [28] draw attention to another possible problem related to the work of RP in DN, which in the literature is called "blindness" RP. It can manifest when sources DG are located between the short circuit point and the feeder. The DG source is involved in the power supply of short circuits and thereby increases the levels of short-circuit currents. But the short-circuit current passing through the feeder actually changes due to the participation of DG sources, which can occur when the total short-circuit current is distributed between various sources.

Thus, RP in DN under certain conditions does not always work properly in emergency situations for which it was designed to establish the sources of the DG [29, 30]. It should also be noted that the connection of DG sources can lead to a delay in the operation of RP life feeder - this is due to the time of protection of the sources of the DG.

Influence of DG on reliability and operation of EN

If DG sources are used only as a backup power supply, it can be argued that the reliability of the power supply rises. But when the DG sources work in parallel with the system, the reliability of power supply consumers in some cases may decline. For example, in EN, where there are enough sources DGs and their work are not coordinated with each other, there will be a decrease in system reliability. Also, as noted in [31], a decrease in the level of reliability of power supply can occur at high concentrations of DG sources of the same type (for example, at the concentration of photovoltaic cells the sadness of which depends on the intensity of solar radiation).

At the same time, the problem of autonomous operation of DG sources, the so-called problem, is quite acute energy islands [32]. DG sources, as a rule, are not intended for feeding of fragments of EN independently, because they are unable to maintain an adequate level of electricity quality and can be harmful operational personnel in danger [33]. Therefore, cases of EN de-energization must be detected by devices protection of DG sources and the latter must be disconnected from the EN [34]. In this case, given the existing in power systems of developed countries requirements of standards, DG sources should switch to 100-300 ms autonomous load [35]. This has led to the development of research to develop various detection tools energy island regimes involving both passive and active methods. Passive methods involve voltage or frequency measurements, methods have also been developed that take into account the rate of change of these parameters. The latter are more reliable than the use of simple voltage or frequency relays, but they have “Dead zones" [36]. Active methods for detecting energy islands generate test signals on the network frequency, which usually exceeds the industrial, and the measured values determine the presence of voltage on nutrient feeder. Similar devices in Ukraine are being developed at the Institute of Electrodynamics of the National Academy of Sciences of Ukraine [36]. Thus, it can be noted that the establishment of DG sources leads to a significant increase reliability of electricity supply only to certain consumers.

A more effective way to increase the reliability of electricity supply in the event in the power system is the formation of energy islands, which are not limited to the source of DG and auto-load, and cover certain fragments of EN with balanced generation and standalone load. This solution allows more efficient use of the installed capacity of the DG, significantly increase the reliability of DN and expand the coverage area of electricity inhabitants. Application of the specified variant of increase of reliability of power supply allows on qualitatively new level to solve many known problems, such as the restoration of power supplied-energized consumers [37]. But this option requires a serious technical re-equipment of EN installation of modern expensive enough technical equipment, and also development of the corresponding management instructions for operational staff.

Influence of DG on EN design and development

In the event that a large number appears additional relationships, which is typical for the DG, it seriously affects the design and operation of DN, as well as the reliability and security of the system as a whole [37]. This requires input appropriate changes in traditional methods of planning DN.

First, the emergence of DG sources in DN introduces much more uncertainty into the loading, planning and operation of EN. In addition, the sources of the DG with the "correct" placement reduce power losses in the EN and this can to some extent delay or reduce the amount of necessary investment in the modernization and development of DN. But if the place and capacity of DG sources are not optimally defined, this will inevitably lead to an increase loss of electric energy, inadmissible deviations of tension in certain nodes of a network, and also can change the value, duration and direction of short-circuit currents. Thus, in order to accept the opt-In order to plan the development of DN, it is necessary to make an accurate assessment of the DG sources for the distribution network, i.e., appropriate software and hardware should be developed tools that are able to accurately assess the impact of the DG on the network, determine optimal locations and power of DG sources, making a gradual increase in the volume of DG sources in DN is safe and effective.

Second, the planning of the development of traditional DN, for the most part, covers the period from 5 to 20 years. As a rule, the load on the grid is growing steadily every year. Constantly arising new load nodes as a result of construction of new substations. Due to computational problems, related to the dimension of the problem of calculating modes (usually thousands of nodes are considered), in case, when the number of new generator nodes will grow rapidly, there will be difficulties in determining optimal EN development plan (optimal programs that take into account the cost of capital construction, for maintenance and minimal power loss).

Third, consumers or independent electricity producers who would like to install DG sources in DS, there will be contradictions with energy supply companies that want to maintain the existing level of control and security of EN. Therefore, the establishment of a large number sources of DG in DN will significantly affect the structure of the EN itself, as a result of which it will reduce dependence on the transit network and centralized power plants. For the purpose of ensuring the required level of EN safety and the required quality of electricity of the DG source must be able to operate flexibly. Thus, the characteristics of EN with traditional living feeders with unidirectional flows undergo significant changes. This will result in a number problems related to voltage regulation and maintaining the balance of reactive power. For solving them, it is necessary to install additional equipment for control and regulation DG sources that will be integrated into the existing DN. This is not just a matter of necessity modernization of existing automated systems of distribution and metering of electricity, as well as changes ideology of EN control and the transition from passive to active control systems.

2.3 Use of electronic devices in distributed networks to improve the quality of electricity supply

On-Load Tap-Changing Transformer.

The transformer which is not disconnected from the main supply when the tap setting is to be changed such type of transformer in known as on-load tap changing transformer. The tap setting arrangement is mainly used for changing the turn ratio of the transformer to regulate the system voltage while the transformer is delivering the load. The main feature of an on-load tap changer is that during its operation the main circuit of the switch should not be opened. Thus, no part of the switch should get the short circuit.

In tap changing transformer different types of an impedance circuit are used for limiting the current during the operation of a tap changing. The impedance circuit may be resistor or reactor type, and by the impedance circuit, the tap changer can be classified as the resistor and reactor type. Nowadays the current limiting is carried out by using a pair of resistors [38].

Shunt Capacitor.

A capacitor bank is very essential equipment of an electrical power system. The power required to run all the electrical appliances is the load as useful power is active power. The active power is expressed in kW or MW. The maximum load connected to the electrical power system is mainly inductive in nature such as electrical transformer, induction motors, synchronous motor, electric furnaces, fluorescent lighting are all inductive in nature.

In addition to these, inductance of different lines also contributes inductance to the system.

Because of these inductances, the system current lags behind system voltage. As the lagging angle between voltage and current increases, the power factor of the system decreases. As the electrical power factor decreases, for same active power demand the system draws more current from source. More current causes, more line losses.

Poor electrical power factor causes poor voltage regulation. So to avoid these difficulties, the electrical power factor of the system to be improved. As a capacitor causes current to lead the voltage, capacitive reactance can be used to cancel the inductive reactance of the system.

The capacitor reactance can be used to cancel the inductive reactance of the system.

The capacitor reactance is generally applied to the system by using static capacitor in shut or series with system. Instead of using a single unit of capacitor per phase of the system, it is quite effective to use a bank of capacitor units, in the view of maintenance and erection. This group or bank of capacitor units is known as capacitor bank.

There are mainly two categories of capacitor bank according to their connection arrangements [39]:

- Shunt capacitor.
- Series capacitor.

The Shunt capacitor is very commonly used.

Unified Power Flow Controller.

A unified power flow controller (UPFC) is an electrical device for providing fast-acting reactive power compensation on high-voltage electricity transmission networks. It uses a pair of three-phase controllable bridges to produce current that is injected into a transmission line using a series transformer. The controller can control active and reactive power flows in a transmission line.

Unified Power Flow Controller (UPFC), as a representative of the third generation of FACTS devices, is by far the most comprehensive FACTS device, in power system steady-state it can implement power flow regulation, reasonably controlling line active power and reactive power, improving the transmission capacity of power system, and in power system transient state it can realize fast-acting reactive power compensation, dynamically supporting the voltage at the access point and improving system voltage stability, moreover, it can improve the damping of the system and power angle stability [40].

Smart transformer

ST is also known as «Solid-State Transformer (SST)» and introduction of SST was in 1968. Smart transformer (ST) has the ability to control the bidirectional power flow and works as a communication hub between grid and microgrid. As a result, ST is known as `Energy Router' as it resembles the duties of router in an internet network and works as a communication hub to regulate data within the local grid and data center.

The potentiality to use the SST in electric distribution as the enabling technology for smart grid functionalities is much higher: the SST is supposed to replace the standard low-frequency transformer, connecting the MV grid to the LV grid and offer dc-connectivity, and services to Low-voltage and Medium Voltage grids. In this case the advantages in terms of weight and volume have a limited impact while the efficiency and reliability are primary requirements since high losses as well as interruption of services cannot be tolerated [41].

Dynamic Voltage Conditioner (DVC) and Dynamic Voltage Regulator (DVR).

A device that can perfectly satisfy modern power system requirement. Indeed, its mission is regulation and not only restoration, so it can operate to deal with short- and fast-term voltage disturbances, as a typical DVR, and it can operate to deal with long-term voltage disturbances in the range ±10% of the nominal value.

Hardware configuration of the DVC is equally the same as a DVR, only its control logic is updated to add several new important functionalities and enable its continuous operating, in particular to compensate long duration voltage drifts, within smart grid system.

Dynamic voltage regulator (DVR) provides the most effective solution for these voltage quality problems. DVR is a power electronics-based power quality compensation system that is connected in series with the grid. DVR provides effective protection by preventing the voltage quality events occurring in the grid from being seen on the load side with its high-performance voltage compensation ability.

The main purpose of DVR is to provide voltage quality on the load side by detecting and compensating power quality events occurring in the grid voltage in less than a half-cycle period. DVR basically consists of a control system and a power circuit. The control system of DVR continuously monitors the grid voltage, detects the power quality events occurring in the voltage less than a half cycle period with the help of the control and detection methods, and generates the control signals required for the compensation. The power circuit of the DVR generates the compensation voltage and inject it into the grid in series to prevent voltage quality problems on the load side. Therefore, it ensures that the loads are protected from voltage quality problems occurring in the grid [42].

STATic synchronous COMpensator

A STATic synchronous COMpensator (STATCOM) is nowadays a fast-acting device capable of providing or absorbing reactive current and by that regulating the voltage at the point of connection to a power grid. It is categorized under Flexible AC transmission system (FACTS) devices. The technology is based on voltage source converter (VSC) with semiconductor valves in a modular multi-level configuration. The dynamic reactive current output range is symmetrical (during normal disturbed network conditions), however non-symmetrical designs are possible by introducing mechanically or thyristor switched shunt elements with unified control systems to cover most conventional applications. The STATCOM design and fast response makes the technology very convenient for maintaining voltage during network faults (as STATCOMs are capable to provide fast fault current injection limited to the rated current), enhancing short term voltage stability. In addition, STATCOMs could provide power factor correction, reactive power control, damping of low-frequency power oscillations (usually by means of reactive power modulation), active harmonic filtering, flicker mitigation and power quality improvements. Typical applications are in the electric power transmission, electric power distribution, electrical networks of heavy industrial plants, arc furnaces, high-speed railway systems and other electric systems, where voltage stability and power quality are of utmost importance [43].

Unified Power Quality Conditioner

The UPQC is a relatively new device and not much work has been reported on it yet. A unified power quality conditioner (UPQC) is a device that is similar in construction to a unified power flow conditioner (UPFC) [44]. The UPQC, like a UPFC, employs two voltage source inverters (VSIs) that are connected to a common dc energy storage capacitor. One of these two VSls is connected in series with the ac line while the other is connected in shunt with the same line. A UPFC is employed in a power transmission system to perform shunt and series compensation at the same time. Similarly, a UPQC can also perform both the tasks in a power distribution system.

However, at this point the similarities in the operating principles of these two devices end. Since a power transmission line generally operates in a balanced, distortion (harmonic) free environment, a UPFC must only provide balanced shunt or series compensation. A power distribution system, on the other hand, may contain unbalance, distortion and even de components. Therefore a UPQC must operate under this environment while providing shunt or series compensation.

Conclusion to chapter 2

Distribution generation sources have a diverse impact on electrical networks. This applies to not only electrical equipment, relay protection systems and automation, but also ensuring the reliability, efficiency of electricity supply and quality of electricity.

So, DG implementation requires a review of management, operational and planning strategies development of electrical networks. In this case, only the application of a systematic approach to the solution problems of introduction of sources of distributive generation in electric networks will allow to avoid inefficient use of their capabilities and reduced reliability of electrical networks, which is characteristic of the reform process.

One of the effective methods to solve some of the above problems, is the use of power electronics in distribution networks.

3 FEATURES OF THE STRUCTURE AND OPERATION OF SOP IN DISTRIBUTION NETWORKS

3.1 Basic principles and construction of SOP

There are various proposals to ensure reliable and efficient operation of power distribution systems with sources of distributed generation and its accumulation, among which the possibility of operating these networks in a closed mode is considered. This automatically makes it possible to optimally redistribute power flows, minimize electricity losses, but at the same time this solution leads to increased short-circuit currents, which may require replacement of switching equipment, increases the risk of large-scale outages, to avoid which the network is quite complex and cost relay protection devices [45].

Distributed generation and new demands such as electric vehicles make it very challenging to manage power flows and to keep system voltage profiles within their statutory limits or other predefined targets. It’s often necessary to go for costly and sometimes bulky and time-consuming upgrades. Soft open points (SOP) could be the answer. Picture of SOP presented at Figure 3.1.

Figure 3.1. Soft open point [46].

A “soft open point” (also named “soft normally open point” or SNOP) sounds like a programming trick. But in fact it is an intelligent counter-inverse (AC/DC/AC) converter based on power electronics, which harmonizes the conflicting requirements of many aspects of power grids: for example, the impact of network topology protection requirements compared to reliability, where radial and porous (normally closed) have their advantages and disadvantages. Radial systems have no connections between adjacent feeders and allow the use of a simple and consistent protection scheme. But they are not as reliable as mesh systems, which, however, require a more complex protection scheme. An example of SOP in a typical single-line circuit is shown in Figure 3.2 [46].

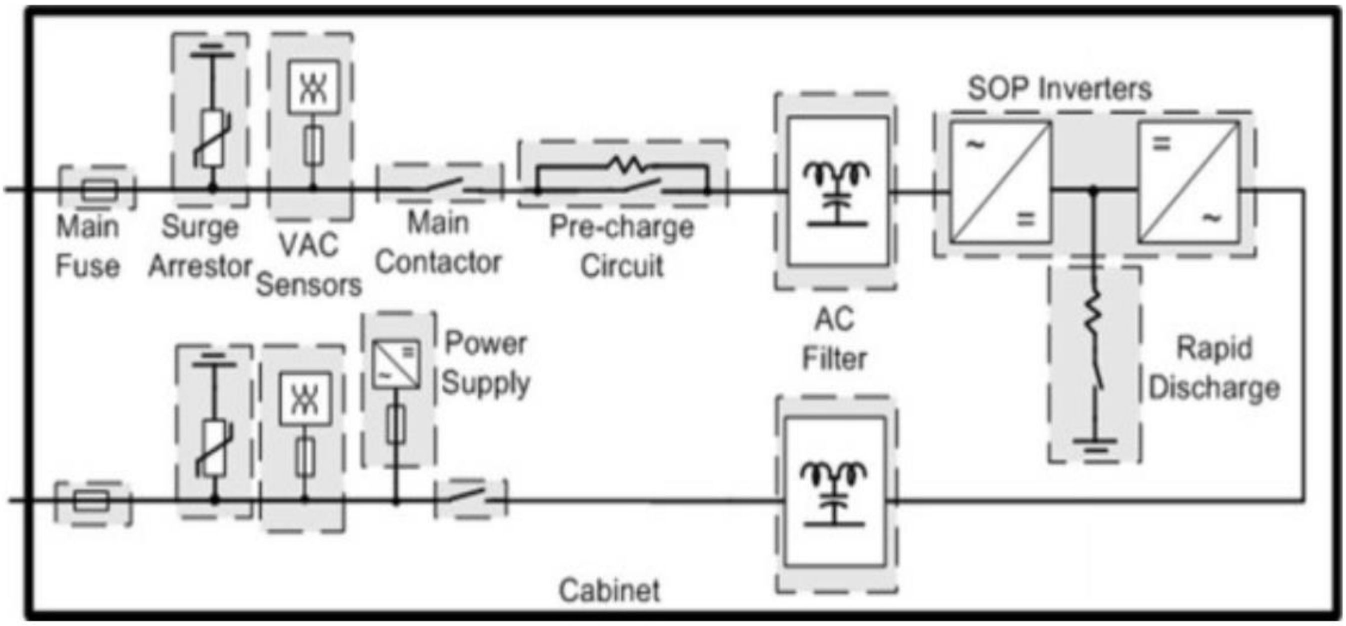


Figure 3.2. SOP Typical One-Line Circuit Diagram [46].

The installation of the appropriate power electronics device in the network node presented in Figure 3.3 makes it possible to combine the advantages that occur during the operation of distribution networks in open and closed modes, and at the same time eliminate the disadvantages of each of them.

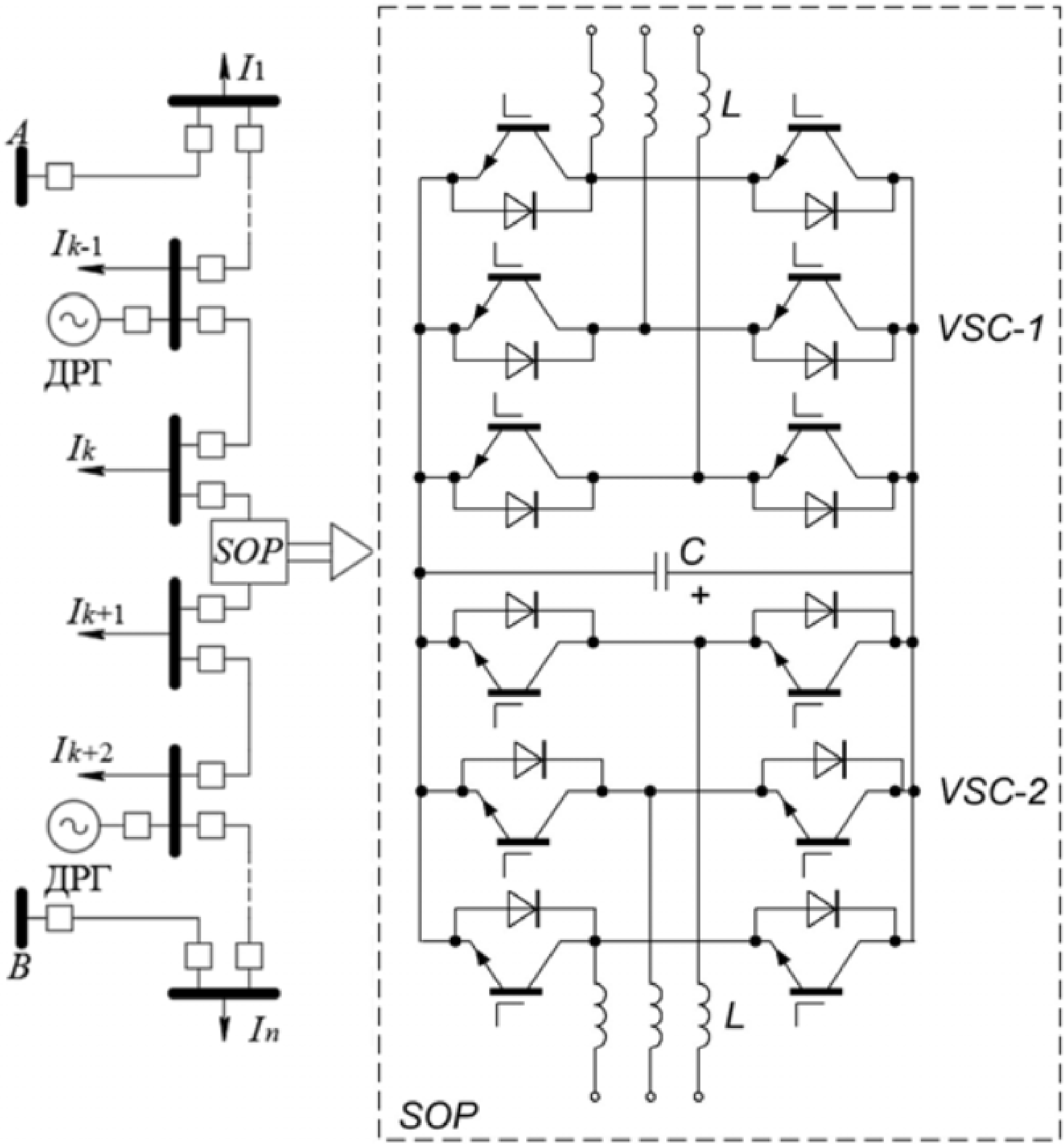


Figure 3.3. Structure of SOP [45].

Instead of simply switching on/off switching devices in certain nodes of the distribution line, SOP allows you to smoothly control the flow of active power between parts of the distribution line, consume or generate reactive power, regulate voltage in normal mode, and isolate damage and disaster recovery. time of planned works [47].

In addition, in distribution networks, if they have both consumers with sharply changing power consumption and dispersed energy sources, in which the output power is characterized by frequent fluctuations, the use of appropriate means of power electronics is certainly appropriate, based primarily on the lack of control inertia. and switching restrictions [45].

Studies show that the most acceptable solution is to use voltage converters "VoltageSourceConvertor" (VSC) type "Back-toback" with a DC link. Connected in series via a capacitor on the DC side, both VSC converters (Figure 2.2) allow you to generate a voltage with the desired amplitude and phase angle, which allows you to control the active power flows through the DC insert and reactive power generation on both buses, as well as reduce voltage ripple due to the appropriate connection of IGBT modules in the VSC. The presence of filter reactors with inductance L provides attenuation of higher harmonics, limitation of short-circuit currents and facilitates the control of power flows. Although the principles of operation of such converters are known from experience in power systems [48].

However, the strategy for their use in distribution networks will be fundamentally different.

The technical limitations for VSCs used in SOPs are the allowable power (currents) and voltage on their buses, as well as the requirement to maintain a balance of active power [1].

$$\sqrt{P_{VSC}^2 + Q_{VSC}^2} \le S_{VSC\text{н}}, \quad U_{VSC} \le U_{VSC\text{н}}, \quad P_{inj}^A + P_{inj}^B + \Delta P_{SOP} = 0,$$

where P_{inj}^A, P_{inj}^B - receipt of active power in the right and left parts of the circuit (Fig. 3.2);

ΔP_{SOP} – active power loss in VSC.

In the general case, losses in SOP components include: losses in semiconductor devices and passive elements (capacitor bank and filter reactors) VSC1 and VSC2, transformers and cooling system of converters that depend nonlinearly (square) on the values of the current flowing through them. in particular, from the exchange of active and reactive power in the AC network. The question of their definition is considered in [49].

The main interest is the justification of the optimal conditions for the use of SOP. In particular, two formulations of this problem are considered, related, respectively, to the minimization of active power losses:

$$\Delta P = \sum R_k \frac{P_k^2 + Q_k^2}{U_k^2} + \Delta P_{SOP} \rightarrow \min ,$$

where k – line section number.

As well as minimizing the imbalance of line loads:

$$LBI = \sum_k \left(\frac{I_k}{I_{k\text{н}}} \right)^2 \rightarrow \min ,$$

Where $I_k, I_{k\text{н}}$ actual and rated currents of the k-th section of the line, respectively.

Then the optimal parameters of SOP operation are determined in the process of minimizing the objective function $Z[P^I_{s\_inj}, Q^I_{s\_inj}, Q^J_{s\_inj}]^T$, which includes restrictions on voltage at the nodes and current at the sites in the form of appropriate penalty functions.

However, the solution obtained cannot be considered truly optimal, because in this case the greatest interest is to minimize the loss of electricity, rather than improving certain characteristics of the regime. Therefore, in contrast to existing research, a new SOP control strategy is proposed here, according to which at each point in time the value of the flow distribution is provided as close as possible to that which would occur in the presence of its two-way power supply (i.e. when closed) [45].

In this case, the control is carried out on the load of one of the sections of the network that is adjacent to the SOP. The imbalance between the actual load on the site and its desired value (that which should have been when operating in closed mode) is compensated by additional generation (positive or negative) by the SOP.

In addition, the mode of operation of the distribution network circuit obtained in this way will automatically provide the most favorable voltage mode. It is important to note that in the presence of distributed generation sources in the network, the latter in many cases generate only active power into the network. Then the modes are possible when the flow distribution points for active and reactive capacities do not coincide [45].

SOP technology makes it possible to take this situation into account due to the independence of active and reactive power generation control. However, it is impossible to ensure optimal power flows simultaneously on both sections adjacent to the SOP tires. If the solution obtained in the case when the optimal load is provided only on one of the adjacent SOP sections of the network does not satisfy the user, the problem is formed in such a way as to allow to determine the flow distributions on both sections of the network adjacent to SOP and sequential modes work by the specified VSC in the process of solving the corresponding optimization problem [45].

The implementation of this strategy avoids a number of technical problems during the broad integration of alternative energy sources with variable and difficult to predict the value of output power in the distribution network, while ensuring the most efficient mode of their operation.

3.2. Advantages and Disadvantages of SOP

Hybrid benefits

The placement of "soft" open points (SOP) in the distribution system creates a hybrid structure that combines the advantages offered by radial and cellular systems, and that removes any disadvantages. For example, support for an isolated load on a feeder can be provided immediately by transmitting power from an adjacent feeder, as in a cellular system, while perturbations and faults on one feeder are isolated from another feeder, as in a radial system [46].

SOPs are attracting increasing attention in response to the growing integration of distributed generation (DG) and the need to address issues related to voltage outages, grid losses, power quality, protection and reliability. Large-scale integration of distributed generation must deal with the possible negative impact of voltage surges on network buses.

The main task of the operator is to minimize the overall impact on the voltage, so they want to connect the DG with a voltage high enough that their impact was negligible. Technically, this is not bad, but the connection costs are much higher at higher voltages, so the developers prefer to choose smaller values. In addition, SOPs offer additional control and controllability during commissioning in lower voltage networks, which usually create the biggest problems, such as voltage control [46].

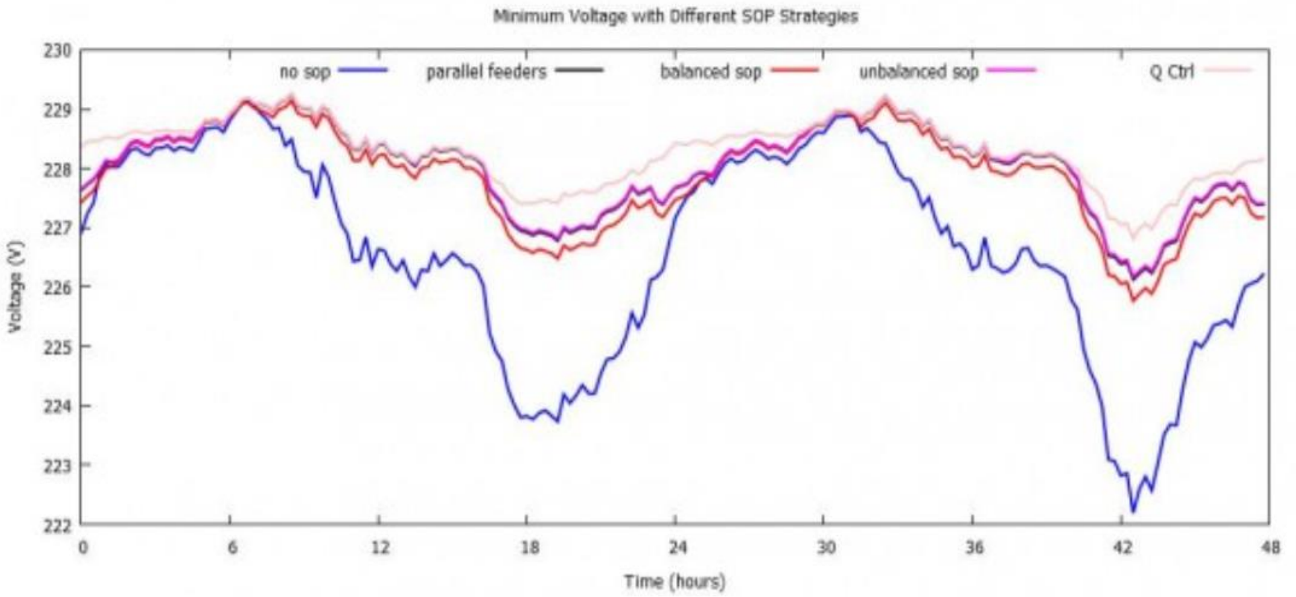


Figure 3.4 Minimum voltage with different SOP strategies [46].

The traditional solution to prevent the WG from violating the upper voltage limits is to install devices to regulate the voltage levels depending on the load. But this leads to a violation of the lower limit for other feeders on which DG is not installed. One of the great advantages of implementing low-voltage SOP in a distribution system is that its back-to-back configuration provides precise and dynamic control of bidirectional real power flows between two networks that cannot be connected naturally due to fault levels. and the voltage/phase angle difference.

This is especially useful in emergency situations where a fault in this feeder often results in a loss of power downstream because the faulty component must be isolated. SOP "acts as a firewall", limiting short-circuit currents and quickly restoring power without affecting neighboring feeders [46].

An economical solution

The SOP solution is not only elegantly technical, but also economically attractive. Alstom Grid researchers working in Stafford, UK, were shortlisted for the Grid Sector for the 2014 Alstom Innovation Award. Among other things, the researchers pointed to the results of a study conducted by the Faculty of Electrical Engineering of Imperial College London, which assessed the cost savings through the use of SOP to optimize distribution systems. They studied real systems in which load balancing was taken into account as a major component of distribution planning. Even in this case, the SOP approach has reduced losses by at least 10% and sometimes by more than 20%. In systems that are not as well designed as the test cases, the use of SOP to accurately balance the main feeder currents can lead to a sharp reduction in network losses.

If network constraints, low- and medium-voltage asset management, and cost are an issue, SOPs may well be the solution. In addition to the added benefits of additional network observation and manageability, SOP can offer much more efficient, stable, and optimal network performance [46].

SOP's goal is to significantly increase the flexibility of current distribution networks with minor equipment or infrastructure upgrades. Distribution systems are generally classified as radial or grid systems, each with its own inherent advantages and disadvantages.

Due to the placement of SOP in the distribution system, a hybrid type of system is formed, it has the advantages of both radial and grid systems (simplified protection scheme and high reliability) with the elimination of the main disadvantages (no isolation between the feeders). Other key features and properties of the distribution system containing SOP is [50]:

• support for loads isolated due to a feeder fault can be provided immediately by transferring power from another feeder connected via SOP;

• the voltage at the terminals of the SOP interface can be adjusted to a certain level or, if necessary, set points for reactive power can be assigned;

• real power flow between feed lines can be controlled to improve applicant load balancing and reduce losses;

• disturbances and faults on one feeder can be separated from other feeders connected to the network via SOP;

• with a voltage converter with current limitation, the contributions to the fault currents are small (and adjustable if necessary for the correct operation of the protection system);

• system voltages can be controlled by varying the real and reactive power flux through the SOP, which allows for increased DG integration levels.

With the ability to influence the voltage profile of the entire distribution system, SNOPs can work for purposes such as minimizing losses by limiting voltage to specified limits. Thus, the ability to adjust the voltage is the main feature of this document [50].

In many cases, a dynamic OLTC combined with an SOP gives better results, but the performance gains are greater than a passive network compensated for by SOP alone. A cost-benefit analysis on a case-by-case basis would be necessary to determine whether it is reasonable to have both devices. There are also a few cases where strong coupling with reactive power compensation devices provides better results, but the disadvantages of large grid networks should be considered when evaluating this option [50].

3.3 Advantages of using SOP in distribution networks in comparison with other switching devices.

The practical use of SOP is currently not widespread, but there are a large number of works in which the mathematical modulation of SOP in the distribution network.

For example, in [51], the following issues were considered:

- The benefits of using SOPs for medium voltage distribution networks with an emphasis on reducing power losses, balancing the feeder load and improving the voltage profile were investigated.

- A typical power injection model was developed and used to determine the optimal SOP operation using the improved Powell direct dialing method. The model took into account the physical limitations and power losses of the SOP device (based on back-to-voltage converters).
- Distribution network reconfiguration algorithms, with and without SOPs, have been developed and used to identify the benefits of using SOPs.

Based on the results of the work, the following conclusions were made regarding the advantages of using SOP in the distribution network [51]:

- The results showed that using only one SOP achieves a similar improvement in network performance compared to the use of network reconfiguration with all branches equipped with remotely controlled switches. The combination of SOP management and network reconfiguration ensured optimal network performance.
- Optimal SOP performance is achieved using an improved Powell direction set method, and a combined method that takes into account both SOP and network reconfiguration has been proposed to demonstrate the benefits of using SOP. Different amounts of SOPs were considered, and it was shown that SOPs significantly reduced power losses, equalized feeder load, and improved voltage profile. Compared with network reconfiguration, the use of only one SOP has made it possible to achieve a similar improvement in reducing power losses in the network and balancing the load of the feeder. The greatest improvements were obtained by combining SOP and network reconfiguration, where smaller SOP sizes were required. The high degree of penetration of DG into the distribution network increases the need to minimize losses and balance the load of the feeder. Using only one SOP allowed for greater performance than using network reconfiguration.
- The combination of SOP and network reconfiguration has contributed to the greatest improvements. In addition, SOPs can significantly reduce peak currents in feeders and reduce unwanted voltage spikes caused by DG connection

and consumption. Thus, SOPs can be used as an alternative to modernizing infrastructure to accommodate distributed energy resources.

- The impact of SOP device losses has been illustrated, which shows that the economic benefits of SOP derived from the reduction of total network power losses decreased with decreasing device efficiency. However, a greater positive effect was obtained with increasing system load. The efficiency requirements of the SOP device for the overall reduction of network losses were reduced with increasing system load.

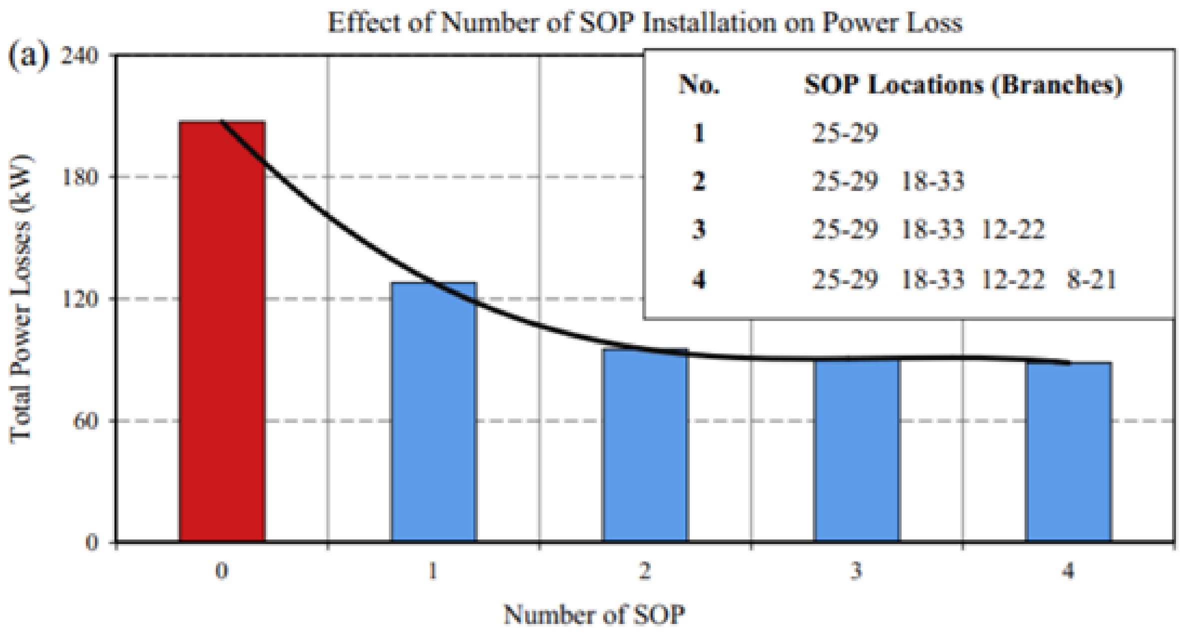
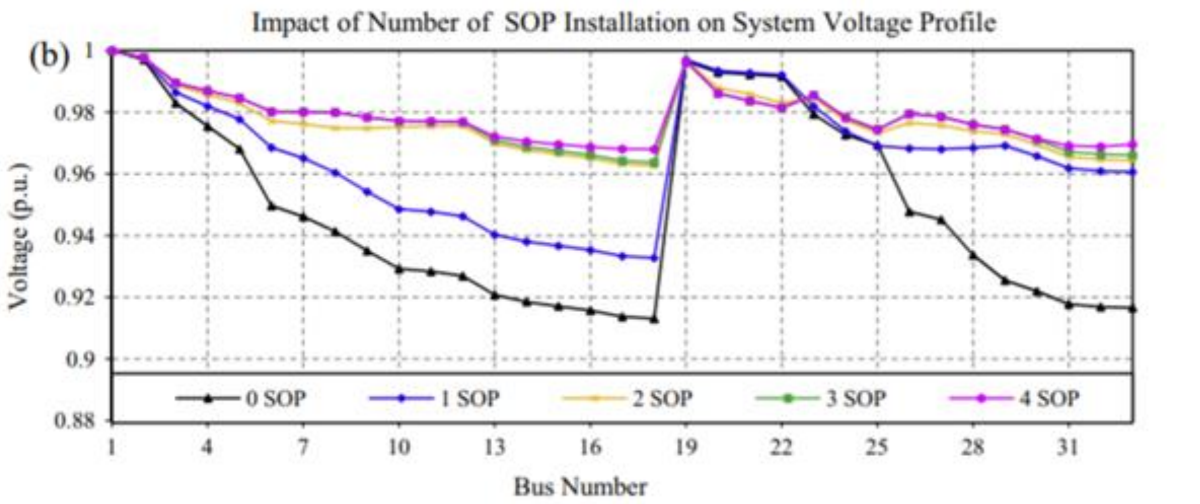


Figure 3.5 Research results.



Impact of different number of SOP installation on power loss minimization and voltage profile improvement.

Figure 3.6 Research results.

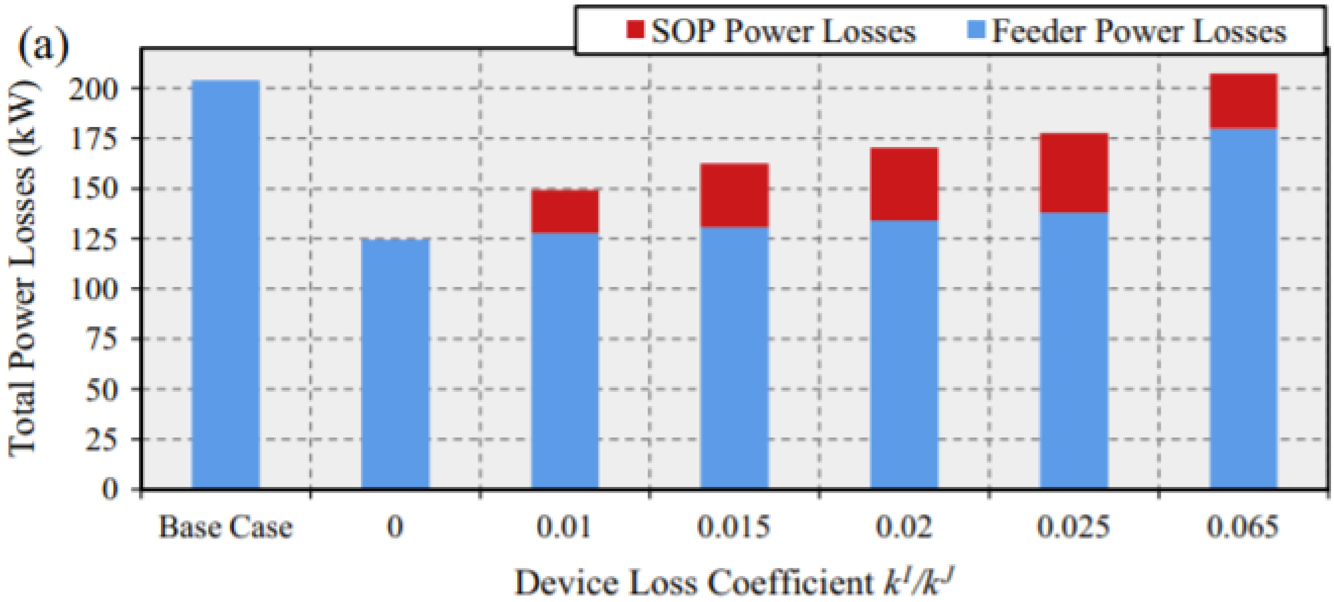


Figure 3.7 Research results.

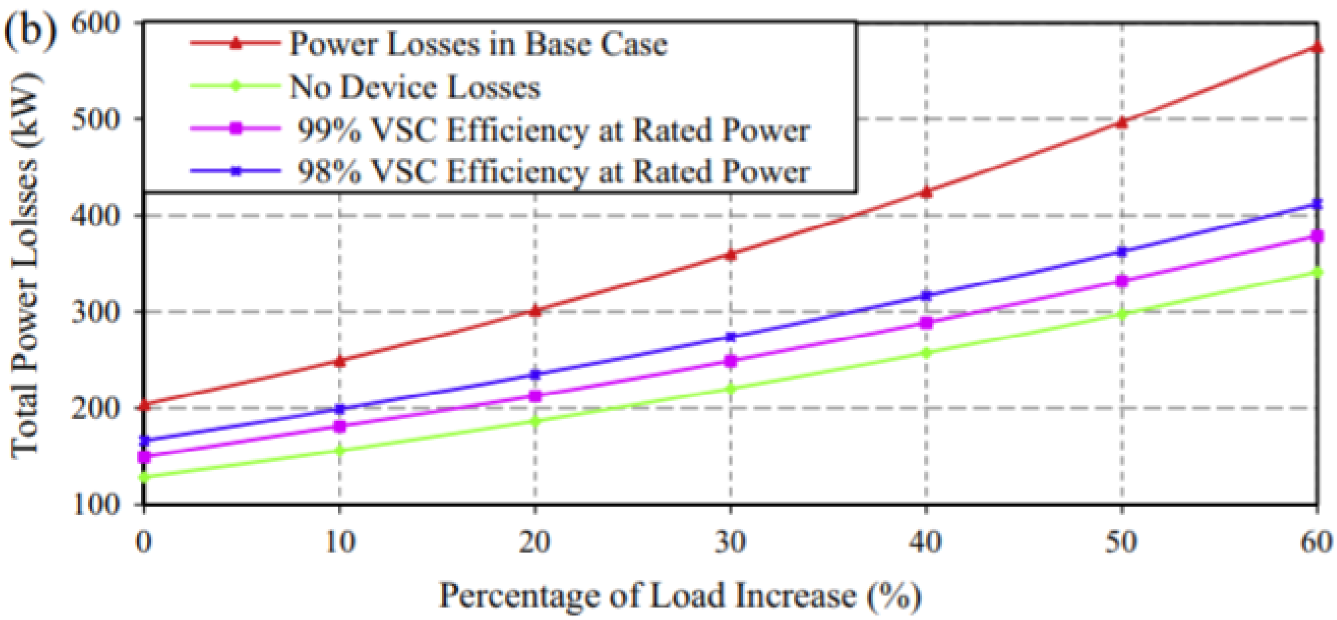


Figure 3.8 Research results.

Although this paper focuses on quantifying the technical benefits of SOPs, the proposed algorithm can also be used for further economic analysis and planning of SOP application studies when life cycle costs should be quantified in optimal quantities. the location and size of the SOP should be determined taking into account the capital costs of the SOP.

Also, the analysis of the benefits of using SOP is presented in [52], the main task that was set by the researchers is as follows:

- The problem of asymmetric integration of distributed generation exacerbates the three-phase unbalanced state in distribution systems. Such unbalanced operation causes inefficient use of network resources and security risks in the system.
- The SOP can provide precise control of the active and reactive power flow to balance the power flow between phases, so an SOP-based operational strategy for unbalanced active distribution networks can be considered. By regulating the operation of the SOP, this strategy can reduce power losses while mitigating three-phase imbalances in the upper tier network.
- An option of using semi-definite programming (SDP) relaxation can be considered, which is recommended for converting the original non-convex nonlinear optimization model into SDP formulation, which can be effectively solved to meet the requirements of rapid tuning.
- To test the effectiveness and efficiency of the proposed strategy, case studies of the modified distribution system of 33 IEEE nodes and 123 IEEE nodes are conducted.

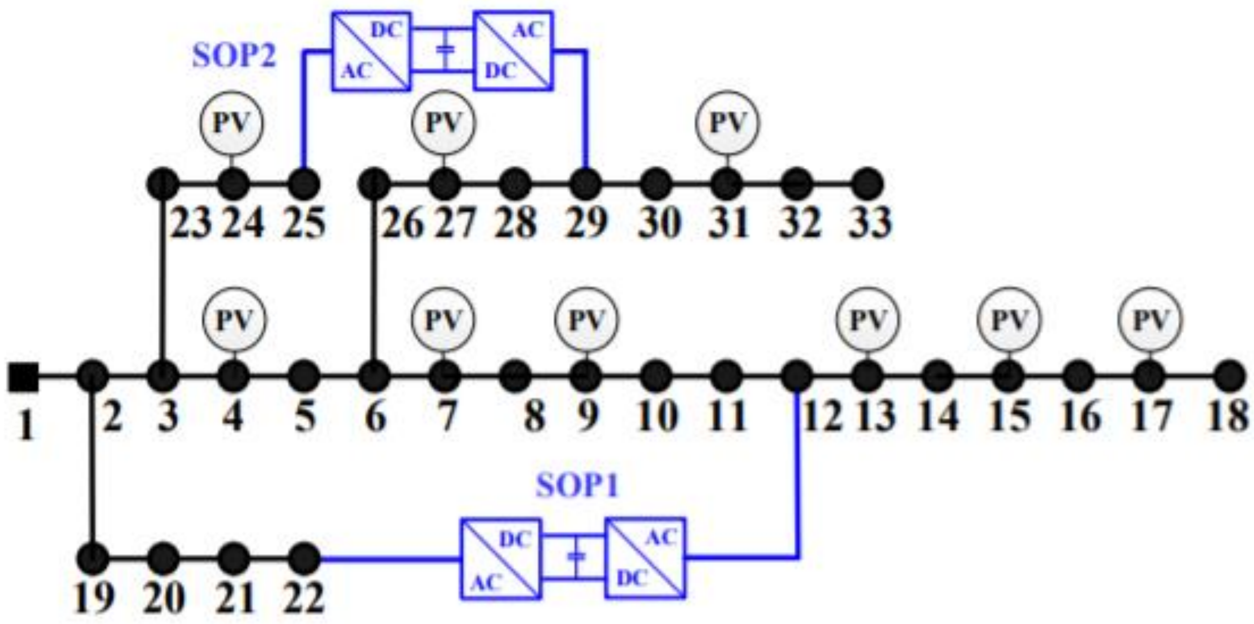


Figure 3.9 Structure of the modified IEEE 33-node system, that been tested.

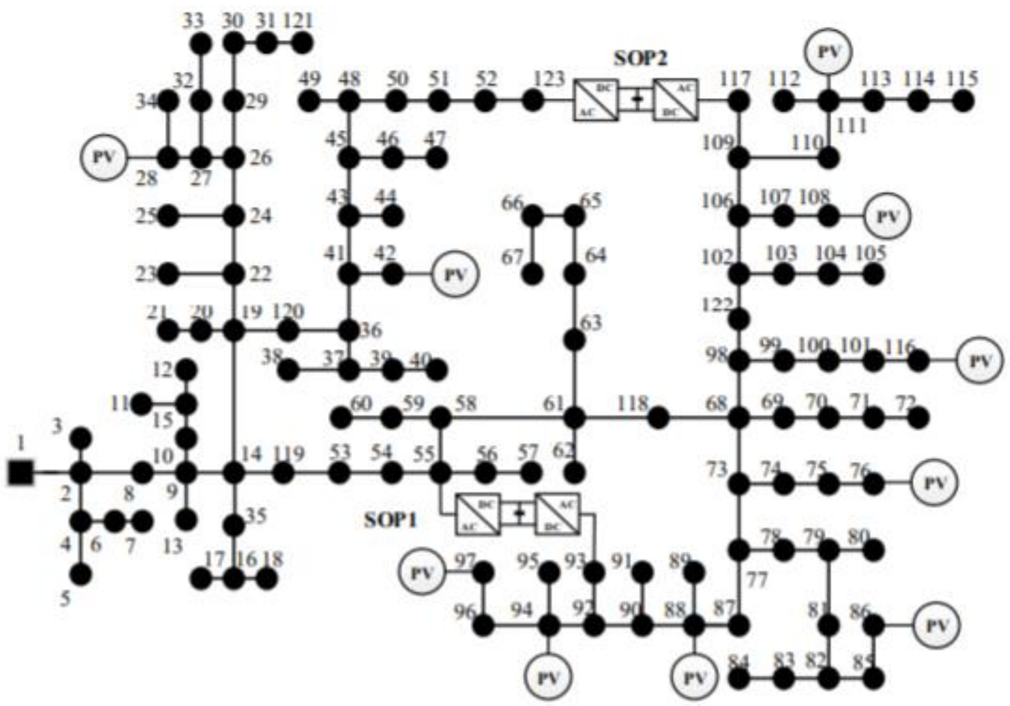


Figure 3.10 Structure of the modified IEEE 123-node system, that been tested.

The following conclusions are made regarding the advantages of SOP based on the results of the analysis of work [52]:

- Based on the results of the analysis, the paper presented an operational strategy based on SOP to minimize operating losses and mitigate the three-phase imbalance in ADN.
- Given the asymmetric access with a high level of DG penetration, an SOP-based performance optimization model for unbalanced ADNs has been developed.
- The optimization results show that the SOP-based strategy significantly mitigates the unbalanced state and reduces power losses in the ADN. The original NLP model is transformed into an SDP model by convex relaxation.
- Numerical tests empirically show that the proposed SDP relaxation model is numerically accurate with increased computational efficiency for the studied cases, which makes it suitable for solving unbalanced optimization of large-scale ADNs with high levels of DG penetration.

- Given the relatively high cost of SOP and coordination with traditional control devices such as on-load tap-changers and communication switches, expanding the coordinated strategy will be more practical for realistic ADN operation and needs to be fully considered.

For three-phase tuning of devices with discrete variables, a more efficient operation strategy based on mixed integer SDP for unbalanced ADNs also requires further research.

Additionally, the works [53 - 54] were considered, in these works, the conclusions about the advantages of using SOP in distribution networks partially intersect with the previously considered works [51 - 52]. The main conclusion of the considered works is that due to the use of SOP, advantages can be obtained (which were previously listed in the conclusions [51 - 52]), which cannot be achieved when using in the network switching devices such as reclosers or sectionalizers.

Conclusion to chapter 3

The spread of the use of dispersed sources of generation and means of energy storage in the structure of distribution networks makes ineffective the existing approaches to solving the problems of planning and managing their modes, in particular, the choice of optimal openings.

The basic conditions of expediency of power electronics means are substantiated and the new approach to management of their work during formation of so-called "soft" points of opening of distribution lines is developed that gives the chance to provide independent rational management of streams of active and reactive capacities. in real time, promptly responding to changes in power consumption and local generation of electricity to minimize its losses.

In order to introduce new technical means to implement even certain components of the well-known concept Smart Grid developed an appropriate method of economic justification of such decisions, which allows to objectively take into account the positive consequences of their implementation, at least from the standpoint of improving reliability and efficiency quality of electric energy by voltage, etc.

4 PRACTICAL SOLUTIONS OF USING MODERN TECHNICAL EQUIPMENTS FOR CONTROLLING MODES OF DISTRIBUTION NETWORKS WITH DISTRIBUTED ENERGY SOURCES.

4.1 The feasibility of using the SOP in practice

Let's consider a practical calculation associated with the use of SOP technology on the example of a 10 kV distribution network circuit with DG sources connected to the second and eighth load nodes (Fig. 4.1).

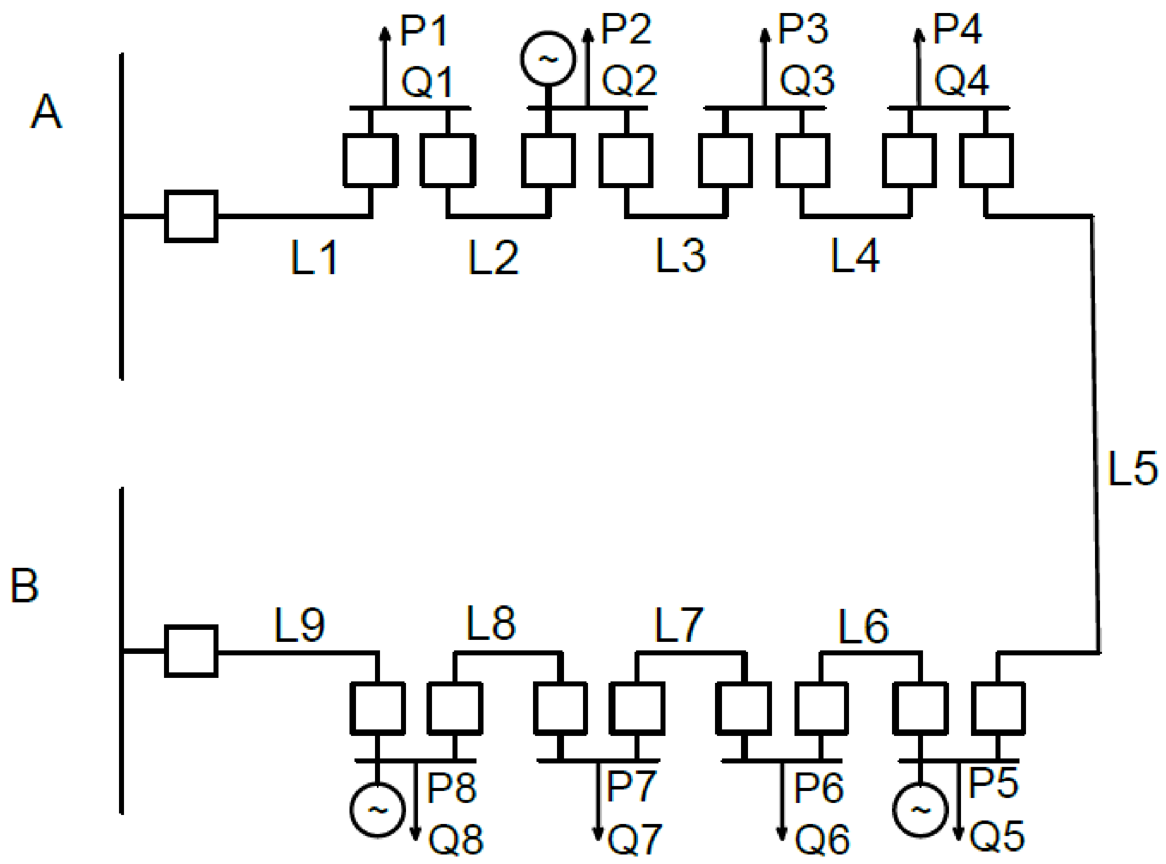


Figure 4.1 – Considered distribution network

Naturally, during the day, both the load at the grid nodes and the output power of the generating sources (especially, if the latter are solar panels or wind farms) may change significantly at different periods of time. To assess the degree of influence of these changes on the mode parameters of the network operation, we first find the flux distribution without taking into account DG sources, for a certain period of time (Tab. 4.1) in order to determine the optimal breaking point of the considered circuit. For this purpose, let's conventionally assume that the given network circuit operates in the closed mode.

Table 4.1 Load values (t=1)

n	1	2	3	4	5	6	7	8
P_n	152,3	274,6	420,9	282,8	633,2	423,1	128,25	301,4
Q_n	163,11	182,5	207,1	153,5	505,4	274,1	96,3	134,7

The method for determining the flow distribution in a circuit with two-way power supply is well known. In general, the existing approach allows for the determination of the flow distribution to take into account the heterogeneity of the network, the difference in voltage levels in the supply nodes, and power losses in individual sections.

For the network circuit (Fig. 4.1), the power flows at its head sections are defined as follows.

$$S_{0-1} = \frac{\sum_{k=2}^{n-1} S_k Z_{k,n}}{Z_{1,n}} + \frac{U_1 - U_n}{Z_{1,n}} U_N$$

$$S_{(n-1)-n} = \frac{\sum_{k=2}^{n-1} S_k Z_{1,k}}{Z_{1,n}} - \frac{U_1 - U_n}{Z_{1,n}} U_N \qquad (1)$$

In the above expressions, the second terms are equalizing powers due to unequal voltages in the power nodes.

As a result of these calculations, the network section with the minimum load is determined, where it seems appropriate to place a normally disconnected switching device.

However, in the example under consideration, the peculiarity is the presence in the circuit of both load nodes and sources of generation, –as well as the fact that in many modes, due to the variability of the output power there may be a situation where the points of the reactive and active power flow partition may not coincide.

If there are generation sources in the network circuit, they can be taken into account as a load taken with a negative value. The result obtained in accordance with (1) allows, on the basis of the first Kirchhoff law, to determine the flow distribution in the loop without regard to power losses.

In addition, given that in this case we are analyzing a 10 kV distribution network, often made up of cable lines with virtually the same cross-section, when performing these calculations, we can accept assumptions about the uniformity of the network (const $\frac{X}{R} = const$) and the admissibility of not taking into account power losses when determining the flow distribution.

These factors make it possible, on the one hand, to calculate the current distribution independently for active and reactive power, and, on the other hand, to simplify the calculation procedure itself.

In particular, for a homogeneous network (Fig. 4.1) we have:

$$S_1 = \frac{\sum_{k=2}^{n-1} S_k (R_{k,n} - jX_{k,n})}{R_{1,n} - jX_{1,n}} = \frac{\sum_{k=2}^{n-1} S_k \left(1 - j\frac{X_{k,n}}{R_{k,n}}\right) R_{k,n}}{\left(1 - j\frac{X_{1,n}}{R_{1,n}}\right) R_{1,n}} = \frac{\sum_{k=2}^{n-1} S_k R_{k,n}}{R_{1,n}} = \frac{\sum_{k=2}^{n-1} P_k R_{k,n}}{R_{1,n}} + j\frac{\sum_{k=2}^{n-1} Q_k R_{k,n}}{R_{1,n}} \quad (2)$$

According to (2), let's calculate the flow distribution without taking into account the DG sources and find out the point of the flow distribution. Let's present the calculation results in tabular form (Tab. 4.2).

Table 4.2 Calculation of flow separation on network sections (t=1)

	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9
S_n	1500,5	1282,3	952,6	483,5	161,7	-648,4	-1152,2	-1313	1643,1
Q_n	840,62	677,5	495	287,9	134,4	-370	-645,1	-741,4	876,1
P_n	1236,2	1084	809,3	388,4	105,6	-527,6	-950,7	-1078,9	1380,3

According to the results of the calculations, we can see that the fifth node is a point of flow separation, with both active and reactive power at the same time.

Now let's take into account the presence of the DGs (which are connected to 2 and 5 nodes), which, of course, will change the total load in these nodes; we will assume that node 8 is connected by storage batteries, which in this case will act as an additional load (Tab. 4.3).

Table 4.3 Load values (t=2)

n	1	2	3	4	5	6	7	8
P_n	152,3	274,6-101	420,9	282,8	633,2-333,2	423,1	128,25	301,4+50
Q_n	43,11	62,5	87,1	33,5	5,4	211,1	134,3	173,7

The results of the calculation for determining the flow distribution for the network mode under consideration are presented in Tab. 4.4.

Table 4.4 Calculation of flow separation on network sections (t=2)

	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9
S_n	1082.3	924.1	739.5	309.6	24.9	-275.2	-748.0	-933.7	1325.7
Q_n	286.3	243.2	180.7	93.6	60.1	54.7	-156.4	-290.7	464.4
P_n	1026.5	874.2	700.6	279.6	-3.2	-303.2	-726.3	-854.5	1205.9

In the presence of the influence of DGs and taking into account the daily variations of the load the results change significantly, which can be clearly seen from the data presented in Tab. 4.4. Moreover, in this case, the points of the flow distribution for active and reactive power do not coincide, which complicates the choice of the optimal point of disconnection.

Let us consider a calculation with a higher level of saturation of the distribution grid with distributed generation and energy storage resources, which reflects the trends in the development of the modern electric power industry.

In this case we will consider that in each node of the network there are DGs (1-5 - generating, 6-8 - accumulating). Let's assume that in the considered period of time all DGs work practically with maximum capacity, which significantly reduces the active load in nodes 1-5 (Tab. 4.5).

Table 4.5 Load values(t=3)

n	1	2	3	4	5	6	7	8
P_n	32,3	23,6	121	82,8	50	400	99,75	300
Q_n	240	350	400	273,5	500,4	211,1	134,3	173,7

The calculation results of the presented mode are presented in Tab. 4.6.

Table 4.6 Calculation of flow separation on network sections (t=3)

	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9
S_n	1344.1	1101.9	751.1	333.2	47.5	-455.4	-907.7	-1075.0	1421.7
Q_n	1210.6	970.6	620.6	220.6	-52.9	-553.3	-764.4	-898.7	1072.4
P_n	385.6	353.3	329.7	208.7	125.9	75.9	-324.1	-423.8	723.8

From the presented results we can see that the points of the flow distribution on both active and reactive power have once again changed.

Let's consider another no less interesting variant with the use of the DGs in each node of the network, but already in the assumption that the output power of the generating sources has significantly decreased (for example, which may be characteristic for the night time), but all the storage devices (5-8) work at full power (Tab. 4.7).

Table 4.7 Load values (t=4)

n	1	2	3	4	5	6	7	8
P_n	30.5	54.9	84.2	56.6	950.0	580.0	30.5	54.9
Q_n	30.0	16.0	25.0	15.0	120.0	150.0	30.0	16.0

The results of the calculation of this mode are presented in Tab. 4.8.

Table 4.8 Calculation of flow separation on network sections (t=4)

	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9
S_n	883.2	840.4	783.2	695.4	636.9	-320.7	-919.7	-1166.7	1560.3
Q_n	208.7	178.7	162.7	137.7	122.7	2.7	-147.3	-237.3	417.3
P_n	847.7	817.3	762.4	678.2	621.6	-328.4	-908.4	-1138.4	1488.4

From the presented results, we can see that the points of the flow distribution have changed once again.

Based on the calculations performed, it can be fundamentally concluded that under conditions of frequent changes in loads and/or output parameters of distributed energy resources, it is possible to ensure the optimal (in terms of minimum power and energy losses) mode of operation of the distribution network, which will take place in the case of opening the circuit at the point of flow distribution, can only be provided by using SOP technology.

However, in many cases, changes in loads and/or parameters of generating and/or storage devices, which lead to a change in the point of flow distribution, are cyclic in nature and occur relatively rarely (no more than 1-2) times a day. In such modes, the use of SOP technology, given its high cost, will be economically inexpedient. In such situations, a more reasonable solution to maintain the points of disconnection as close as possible to the points of flow distribution, is the use of remotely controlled switching devices, allowing to quickly manage the flow distribution in the network (Fig. 4.2).

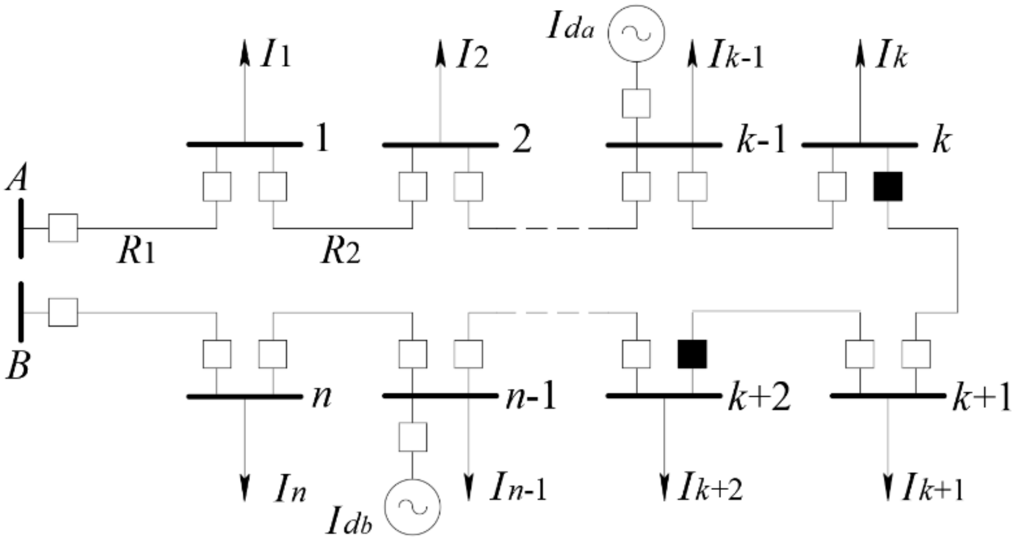


Fig 4.2

In this case, the algorithm for solving the problem of optimal placement of remotely controlled switching devices and controlling their work can be presented as follows.

1. A number of distribution network circuits are defined in which it would be advisable to install remote-controlled switching devices.
2. For the selected distribution network circuits by individual time sections, using the characteristic load schedules of nodes and generation from distributed energy sources, the optimal places of their disconnection are determined, based on minimization of power losses.
3. A decision is made on the rational locations of remotely controlled circuit breakers.
4. Determination of the economically feasible frequency of operation of remotely controlled switchgear within a day.
5. Forecasting of distribution network parameters with distributed power generation and accumulation sources with a specified preemptive interval is made.
6. Forecast values of indicators are calculated, on the basis of analysis of which a decision is made about the expediency of changing the state of remotely controlled switchgear.

7. A decision is made on the expediency of changing the position of the break point of the distribution network circuit.

When deciding on the expediency of equipping the network with remote-controlled switching devices, an important factor that needs to be taken into account is the switching life of circuit breakers, which even for modern equipment does not usually exceed 20,000 operations during their life cycle, which affects the rationale for the frequency of their operation.

In the simplest case, knowing the switching life of the circuit breakers and the design period of the project, you can determine the limit number of their switching within a day. This allows you to make decisions about the advisability of reconfiguration of the distribution line to take into account not only the fact that the relevant conditions are met, but also the duration of the expected mode changes to avoid exceeding the daily limit of switching.

A more time-consuming approach is associated with assessing the cost-effectiveness of both equipping a distribution line with remote-controlled switchgear and determining a reasonable frequency of their operation. It is obvious that such an analysis gives a more convincing answer regarding both the expediency of equipping this or that distribution line with remote-controlled switches and the strategy of their further use, up to the justification of their replacement during the calculation period due to the exhaustion of the switching resource, if it is justified by the expected value of the reduction of losses of electric energy.

In any case, there is a question of estimating the duration of the distribution network loop mode, which determines the expediency of changing the place of its opening.

Thus, the forecasting procedure will play an important role in the decision-making process regarding the implementation of re-switching in the analyzed distribution line. The quality of forecasting largely determines the validity of the decision and, consequently, the efficiency of the distribution network mode control.

4.2 Theoretical basis of forecasting

With scientific and technological progress and improvement of the energy system of the country, forecasting is becoming one of the decisive scientific factors in shaping the strategy and tactics of energy development.

Thus, modern conditions require a maximum expansion of the forecasting front, further improving the methodology and methodology of energy forecasts development. The higher the level of forecasting of energy development processes, the more effective planning and management of these processes in society.

There are several basic definitions of concepts in the field of forecasting.

Forecast is a scientifically sound, probable judgment about the possible state of an object in the future, about alternative ways and timing of its implementation. The process of developing forecasts is called forecasting. One of the important areas of forecasting social development is energy forecasting, since the strategy of development of this industry largely determines the direction of development of other sectors of national economies and the world as a whole.

Energy forecasting is the process of developing energy forecasts based on scientific methods of cognition of phenomena in the energy sector and the use of the totality of methods, means and ways of forecasting.

Forecasting, including energy forecasting, correlates with a broader concept - foresight as a leading reflection of reality, based on knowledge of the laws of nature, society and thinking.

The forecasting process consists of several stages, each of which solves a specific problem:

- problem statement - the object of the forecast is specified, goals and objectives are formed, accuracy and lead time of the forecast are determined;
- formation of the forecast object according to the set task - the structure of the object is determined, significant factors are highlighted, their co-subordination, hierarchy and interrelation are established;

- collection of retrospective information about the object - sources of information are determined, methods of processing and presentation of information are developed, its required volume is established;
- formalization of the task - a methodology for the formalized representation of information is developed, and a class of models is selected to describe the object of the forecast;
- choice of methods and algorithm - the most appropriate forecasting method is selected from the known ones, an appropriate algorithm is developed, and the accuracy of the forecast is evaluated;
- modeling on the basis of retrospective data evaluation of the model quality;
- issuance of forecast results.

The probability of a prediction, that is, its feasibility, is achieved:

- The provision of specific baseline information;
- Conformity (adequacy) of the adopted methods of selection of information, its analysis and transformation, as well as the forecasting itself;
- Competence of forecasters and their giftedness, first of all their ability and skills of heuristic approach and talent of intuition.

Forecasts can differ in purpose, nature, validity (calculation basis), duration of the period for which the forecast is developed, dependence and impact of the object of forecasting on related objects and areas. Based on a number of existing proposals for solving practical problems, the following classification of forecasts can be used:

1. By the degree of probability are distinguished:

- *Hypothetical predictions*, which are based on the study of general trends in the development of science and technology and in the making of which the expert estimates of specialists, obtained largely through intuition, that is, a feeling, a hunch, a penetrating prediction, based, however, on knowledge of the subject, play a major role

- *Analytical-calculative forecasts*, which in contrast to the hypothetical are based on the analysis of the dynamics of available statistical indicators and various calculations carried out by: extrapolation, interpolation, processing the dynamics of statistical series of indicators, correlation dependencies, comparing the indicators of the predicted object with other observations;
- *Planned-calculated forecasts*, the most typical type of which are plan fulfillment forecasts. The basis of plan-calculated forecasts, as a rule, are various variants of initial events.

2. By the duration of the forecasting cycle, it is reasonable to distribute the forecasts as follows:

- Forecasts for the very distant future, for example, in the power engineering industry for a period of more than 20 years;
- Long-term forecasts in the energy industry, preferably for more than 15 years;
- Medium-term forecasts preferably for a period of 1 day to 5 years;
- Short-term forecasts up to 1 day or one day in advance.

3. According to the scale of forecasting, the forecasts are divided into

- *Sublocal forecasts*, limited to the development of a single energy enterprise;
- *Local*, involving forecasts for the entire energy sector;
- *Global*, encompassing all levels of forecasting in the electric power industry, taking into account its mutual influence and the entire national economy;

4. Based on the methodological peculiarities of development and different source information, all types of forecasts form three main groups:

- Forecasting with the help of statistical methods. It is based, as a rule, on reliable initial data, available dynamics of development of a certain sphere of research, material level of production, resources, etc., revealing quantitative tendencies of further development of predicted object by using statistical methods:

extrapolation with its various modifications, interpolation, exponential analysis and others;

- Forecasts made mainly on the basis of expert evaluations of specialists, including through various types of questionnaires and their further processing, mainly with the help of mathematical statistics;
- Forecasts, the development of which is conducted simultaneously by statistical and expert methods (combined) using the design of models and the use of feedback to eliminate possible errors in the judgments of experts.

The use of different types of forecasts, their combination to create adequate judgments on the development of the energy industry in the future depends on the tasks that are set in the development of a particular forecast, and to some extent determines the methods used to develop forecasts.

At the present stage, according to experts, there are more than 150 different forecasting methods. However, in practice, the main 15-20.

4.3 The most common forecasting methods

Artificial Neural network

The conventional models are limited and can lead to unpleasant decisions. This is the result of an unnecessarily large number of computational capabilities, which leads to large terms of problem solving and the complexity of some nonlinear data models. For this type of challenges, artificial neural networks and machine learning technologies provide a rich and accessible alternative. Growing computing power has made it easier to predict a wide range of changes in energy system management from load forecasting to safety assessment or fault diagnostics. However, due to a number of problems, the use of conventional models leads to unsuccessful solutions due to the high complexity of interrelations between the variables and the volume of requirements to the computing capacity.

These are the cases when artificial neural networks (ANN) are used. ANN is an intellectual method of machine learning based on human brain structures. Like the human brain, ANN is composed of neurons and interactions within several spheres. A neuron is the basic element of the ANN, it can receive or send a normalized signal from some to other neurons of the network. The connections between neurons are called "weight", one for each connection coming to the neuron from the other one. In general, there are three main features that define the ANN: the architecture of the network (direct or repeated), the training rule that is used to identify the weight during the training of the network, and the activation function between the input and output of the neuron. One of the most frequently used methods is multilayer perceptron (MLP). This MLP measure runs on the rule of inverse propagation, which evaluates the output error and reduces it, regulating the weight by inverse propagation the error from the output to the inflow node. ANN are particularly suitable for predicting energy consumption. They provide a good estimation in cases of lack of data and can solve complex nonlinear problems, demonstrating reliability and flexibility.

Time series analysis

Some of the most widely used methods of time series analysis and forecasting are the autoregressive integrated moving-average (ARIMA) and autoregressive moving-average (ARMA). ARMA and ARIMA were introduced in 1970 by two statisticians, Box and Jenkins [55]. The basic ARMA model consists of the autoregressive model (AR) and the moving average model (MA). The autoregressive model is a linear regression of the current value based on one or more previous values. As for AR, the moving average model is a linear regression, with the difference that it regresses stream values against the white noise of one or more previous values. Let us assume that an essential condition for processing the ARMA model is that the time series is stationary. If not, the stationarity is achieved by differentiating the non-stationary series at the first place. The introduction of this condition leads to a new model, which is called ARIMA, and "I" is for "Integrated". In order to deal with seasonality, Box and Jenkins introduced a new model, the seasonal ARIMA or SARIMA

Support Vector Machine

The Support Vector Method (SVM) was first presented by Volodymyr Vapnik with a paper at the COLT 1992 conference [56]. Initially, SVMs were created to solve the problems of image classification, such as character recognition, face identification, and text classification. In 1995, Volodymyr Vapnik extended SVM to the regression algorithm in his book "The Nature of Statistical Learning Theory" [57]. For many years, different applications have been found in the literature; for example, the problem of time series prediction. The goal of SVM is to create an optimal partitioned hyper plot in a larger space of objects, so that the following observations can be classified into separate sets. In practice, the real data are not so self-reliant. In order to ensure hyper plot, it is necessary to ask for the requirement that the disintegrating hyper plot will ideally disintegrate each training observation. For this purpose, the soft vector classification (SVC) was created. In the case of nonlinear interfaces, SVM is handy. Indeed, SVM allows nonlinear interfaces to be resolved using the appropriate rearrangement.

Unfortunately, calculating on a large space of objects with high dimensions can be very expensive. To improve the efficiency of calculations, a solution also called the "kernel trick" is used [58]. Kernels are functions that are used to represent intrinsic products between the observations and not the observations themselves. Thus, it modifies the "subordination" between two observations in a more flexible way, allowing to modify and solve a nonlinear problem by means of a linear problem on a higher dimensional space.

Specificity of using time series for forecasting of electricity consumption

Forecasting of electric loads and levels of electric power supply plays an important role in planning the development of electric power supply systems. This procedure is traditionally carried out on the basis of statistical data analysis. In this case, one of the most widespread mathematical tools, which are used to solve this problem, is the time series.

Time series (TS) is a sequence of discrete series of measurements (indicators, observations) $y(t_1)$, $y(t_2)$, ..., $y(t_N)$, characterizing the status of the investigated process, arranged at non-standard evenly distant moments of time.

Analysis of time series is a self-contained field of applied mathematics. The aim of time series analysis is to identify the causal mechanisms that caused the behavior of the studied process, the creation of models that not only explain the behavior of the process, but can also be used to assess its predictive values.

Deterministic processes are characterized by sufficient information for determining the functional dependence $y = f(t)$. In that case, if the process proceeds in conditions of statistical uncertainty, stochastic time series models are traditionally used and numerical time series, which contain both systematic and accidental components, are studied. This approach is based on theoretical assumptions of probability theory and applied statistics. Processes that function in conditions of "non-statistical" ambiguity can be modeled by non-exact time series, the theoretical basis of which is the theory of non-exact multiples.

The task of modelling the time series in general can be formulated as follows. Let the values of the time series $Y = \{y(1), y(2),..., y(N)\}$, where $y(t)$ is the value of the indicator of the investigated process recorded in the t-step of the time (t = 1 , 2, ..., N). It is necessary to generate estimates of future values of the series $Y = \{y(N+1), y(N+2), ..., y(N+\tau)\}$, $1 \leq \tau \leq N$ where τ being the forecasting horizon.

The basic idea that unites the approaches to modeling of time series is based on the determination of systematic (regular) dependencies and analysis of obtained reserves by fixed criteria. Regardless of the method used, it is assumed that the pattern of changes detected for a certain period of time series in the past will be preserved for a limited period of time in the future.

Statistical approach of TS modeling is based on the updating of the approximate model by a particular numerical time series y_t, which reflects statistical dependence, to describe and numerically forecast the behavior of the surveyed process.

The model can be represented as follows

$y_t = f(x_t, a) + \varepsilon_t$.

In this model, the sporadic series y_t is considered as a sum of some systematic component $f(x_t, a)$, where a is a parameter and the random component ε_t, which are regarded as independent realizations of the random process of "white noise" type with a constant mathematical estimation, constant and small dispersion.

The systematic structure $f(x_t, a)$, of the time series can be represented in the form of a linear combination of components and decomposed into trend, periodic, seasonal components, are clearly dependent on the time (when $x_t = t$), and on the autoregressive component (when $x_t = t - r$), which describes the dependence between the current value of the time series level and the past value discounted by the lag p.

Time series which model clearly expresses the dependence on the time t and is represented in the form $y_t = f(t, a)$ are included in the class of deterministic time series. Time series which model describes the behavior of stationary and non-stationary processes represented as $y_t = f(y_{t-p}, a) + \varepsilon_t$, are included in the class of stochastic ones.

Stochastic time series differ from non-stochastic ones in the following properties: its mathematical approximation, dispersion and covariance do not depend on the moment of time in which they are calculated. The fundamental assumption of the statistical approach is that any stationary random process is represented as a superposition of a certain regular process $f(y_{t-p}, a)$ and white noise ε_t.

The methodology of time series modeling within the framework of statistical approach is reduced to the iterative solution of the following tasks: defining a general class of models, identifying a test model, estimating parameters of the test model, diagnostic testing, using the model

Talking about predicting the levels of electric power consumption, it is necessary to point out the following. With the enormous growth of distributed generation in the world and especially in Ukraine in recent years (mostly solar and wind electricity), we must take into account the information support in this sector. Unfortunately, in Ukraine, information support for renewable energy (especially solar energy) is a weak point. Therefore, it is necessary to focus on the possibilities and peculiarities of forecasting in conditions of lack of operational information.

4.4 Application of Fuzzy Time Series approach in Electric Load Forecasting

Fuzzy Time Series represents a new scientific field.

The indicated approach allows using applied knowledge for non-exact interpretation of time series levels, constructing fuzzy time series and revealing dependencies in the form of non-exact production rules.

The principle of creating time series (TS) is based on the assumption that linguistic interpretation of the values of the time series is possible, based on the notion of imprecise sets. This semantically meaningful interpretation of TS values, which refers both to its levels and to certain moments of time, is expressed in fuzzy linguistic evaluations, depends on the essence and context of properties of the object, which is observed, as well as on the perception of the expert, who performs the interpretation.

The applied aspect of the problematic of the analysis of nonnumerical time series is defined by the possibility of expanding the set of applied problems of TS processing, low technologies of their solution and the field of results due to the operation of not only numerical, but also qualitative information, expressed by linguistic terms. In general, widening of the field of results of solving the problem of time series analysis through partial modelling of TS will allow to take more well-grounded decisions on the basis of processing of qualitative information.

Unlike the traditional time series, the values of the fuzzy TS are imprecise multipliers, not the real values of the TS levels. In 1993, Song and Chissom [59] proposed fuzzy models of time-variant and time-invariant time series of the first order and used the developed fist-order clock series. used the developed models to predict the number of students at the University of Alabama (USA) to be enrolled by phasing a clear time series. This was the first use fuzzy models when modeling TS and the first identification of models of nonwhite time series.

In the case of an imprecise time series, the following imprecise equation is used as a model of autoregression:

$$y_t^j = y_{t-1}^j \circ R_{ij}(t,t-1),\quad y_t^j \in Y_t,\quad y_{t-1}^j \in Y_{t-1},\quad i \in I,\quad j \in J\ .$$

where ○ – indicates the composition operation from the theory of fuzzy sets; $R(t,t-1) \bigcup_{i,j} R_{ij}(t,t-1)$ – a system of fuzzy relations, which can be symbolically recorded in the form of $Y_t \to Y_{t-1}$.

The system of relations *R* in the expression $y_t^j = y_{t-1}^j \circ R_{ij}(t,t-1)$ is called the model of the first order fuzzy time series and this model is considered as an important single case of the general model of the order *p*:

$$Y_t = (Y_{t-1} \times Y_{t-2} \times \ldots \times Y_{t-p}) \circ R(t,t-p),$$

$$R(t,t-p) = \max_p \left\{ \min_{j,i_1,i_2,\ldots i_p} \left[y_t^j, y_{t-1}^{i_1}, \ldots, y_{t-p}^{i_p} \right] \right\}.$$

Modeling of fuzzy time series according to the fuzzy model proposed in the work [59] is based on the implementation of the following steps, which will be described in detail in next section:

1. Determination of fuzzy variables - dividing data into low intervals (fuzzy sets), determining linguistic values of fussy sets and their adjacency functions.

2. Formation of logical relations $Y_t \to Y_{t-1}$.

3. Input data fuzzification is a measure of the degree of relevance of the input data to the input fuzzy variables.

4. Calculation of the result of applying the fuzzy rule *R* (*t*,*t* -1) for each implication.

5. Calculation of the resultant ratio *R*

$$\bigcup_{i,j} R_{ij}(t,t-1)$$

6. Applying the obtained model to the input data and obtaining the output fuzzy results.

7. Defuzzification fuzzy results.

Use of Fuzzy Time Series for forecasting the levels of electricity consumption

The basic prediction algorithm for solving the applied problem of forecasting the levels of electric power supply on the basis of fuzzy time series can be represented as follows.

1. On the basis of the available statistical data we determine the universum of possible values of the predicted parameter, on which the corresponding fuzzy (linguistic) estimates (sets) are formed. In this case the boundary values of the universum (U) are found as follows:

$$U : \left[D_{\min} - \Delta D_1, \, D_{\max} + \Delta D_2 \right]$$

where $D_{\min}$, $D_{\max}$ - minimum and maximum values of the studied parameter, which were observed in the sample (available statistical data); $\Delta D_1, \Delta D_2$ - the corresponding positive numbers.

For example, if we rely on the statistical data given in Table 4. 9, we can assume $\Delta D_1 = 8, \Delta D_2 = 7$ and, therefore, the universum U is defined like that U: [120, 210].

Table 4.9 Statistical data (results of observations)

N (results of observations)	Statistical data (predictive parameter)
1	128
2	136
3	137
4	147
5	155
6	153
7	156
8	159
9	168
10	164
11	164
12	154
13	155
14	151
15	151
16	160
17	169
18	181
19	190
20	203
21	198

2. Split the universum U into several intervals of the same width, e.g. into 9.

$$u_1:[120,130],\ u_2:[130,140],\ u_3:[140,150],$$
$$u_4:[150,160],\ u_5:[160,170],\ u_6:[170,180],$$
$$u_7:[180,190],\ u_8:[190,200],\ u_9:[200,210].$$

3. We define fuzzy sets on the U (universum), which correspond to certain linguistic variables that, in this case, characterize the level of electricity consumption.

$$A_1 = \text{(extremely low)},$$
$$A_2 = \text{(very low)},$$
$$A_3 = \text{(low)},$$
$$A_4 = \text{(less than average)},$$
$$A_5 = \text{(average)},$$
$$A_6 = \text{(higher than average)},$$
$$A_7 = \text{(high)},$$
$$A_8 = \text{(very high)},$$
$$A_9 = \text{(extremely high)}.$$

Thus obtained, the intervals *u1, ... u9* are selected as elements of each fuzzy set. To set values of the adjacency function on *u1, ... u9* for all fuzzy sets A_i *(i = 1, ..., 9*) we determine the degree to which each u_k *(k = 1, ..., 9)* belongs to a fuzzy set (linguistic variable) *Ai*. If u_k fully belongs to A_i the adjacency function is 1; if u_k does not belong to A_i then the adjacency function is 0; in other cases we choose values from 0 to 1 depending on the degree to which u_k belongs to A_i.

For example, the presented fuzzy sets A_i (*i = 1, ..., 9*) can be described in this way intuitively.

$$A_1 = \left\{ {u_1}/{1}, {u_2}/{0{,}5}, {u_3}/{0{,}1}, {u_4}/{0}, {u_5}/{0}, {u_6}/{0}, {u_7}/{0}, {u_8}/{0}, {u_9}/{0} \right\}$$
$$A_2 = \left\{ {u_1}/{0{,}5}, {u_2}/{1}, {u_3}/{0{,}5}, {u_4}/{0{,}1}, {u_5}/{0}, {u_6}/{0}, {u_7}/{0}, {u_8}/{0}, {u_9}/{0} \right\}$$
$$A_3 = \left\{ {u_1}/{0{,}1}, {u_2}/{0{,}5}, {u_3}/{1}, {u_4}/{0{,}5}, {u_5}/{0{,}1}, {u_6}/{0}, {u_7}/{0}, {u_8}/{0}, {u_9}/{0} \right\}$$

$$A_4 = \left\{ \frac{u_1}{0}, \frac{u_2}{0{,}1}, \frac{u_3}{0{,}5}, \frac{u_4}{1}, \frac{u_5}{0{,}5}, \frac{u_6}{0{,}1}, \frac{u_7}{0}, \frac{u_8}{0}, \frac{u_9}{0} \right\}$$

$$A_5 = \left\{ \frac{u_1}{0}, \frac{u_2}{0}, \frac{u_3}{0{,}1}, \frac{u_4}{0{,}5}, \frac{u_5}{1}, \frac{u_6}{0{,}5}, \frac{u_7}{0{,}1}, \frac{u_8}{0}, \frac{u_9}{0} \right\}$$

$$A_6 = \left\{ \frac{u_1}{0}, \frac{u_2}{0}, \frac{u_3}{0}, \frac{u_4}{0{,}1}, \frac{u_5}{0{,}5}, \frac{u_6}{1}, \frac{u_7}{0{,}5}, \frac{u_8}{0{,}1}, \frac{u_9}{0} \right\}$$

$$A_7 = \left\{ \frac{u_1}{0}, \frac{u_2}{0}, \frac{u_3}{0}, \frac{u_4}{0}, \frac{u_5}{0{,}1}, \frac{u_6}{0{,}5}, \frac{u_7}{1}, \frac{u_8}{0{,}5}, \frac{u_9}{0{,}1} \right\}$$

$$A_8 = \left\{ \frac{u_1}{0}, \frac{u_2}{0}, \frac{u_3}{0}, \frac{u_4}{0}, \frac{u_5}{0}, \frac{u_6}{0{,}1}, \frac{u_7}{0{,}5}, \frac{u_8}{1}, \frac{u_9}{0{,}5} \right\}$$

$$A_9 = \left\{ \frac{u_1}{0}, \frac{u_2}{0}, \frac{u_3}{0}, \frac{u_4}{0}, \frac{u_5}{0}, \frac{u_6}{0}, \frac{u_7}{0{,}1}, \frac{u_8}{0{,}5}, \frac{u_9}{1} \right\}$$

4. We perform statistical data fuzzification base on Tab. 4.10. For this purpose, we determine the appropriate set, which corresponds to each result of observations (table 4.9).

Table 4.10 Functions of linguistic variables that are used for fuzzification statistical data

	120-130 u_1	130-140 u_2	140-150 u_3	150-160 u_4	160-170 u_5	170-180 u_6	180-190 u_7	190-200 u_8	200-210 u_9
A_1	1	0,5	0,1						
A_2	0,5	1	0,5	0,1					
A_3	0,1	0,5	1	0,5	0,1				
A_4		0,1	0,5	1	0,5	0,1			
A_5			0,1	0,5	1	0,5	0,1		
A_6				0,1	0,5	1	0,5	0,1	
A_7					0,1	0,5	1	0,5	0,1
A_8						0,1	0,5	1	0,5
A_9							0,1	0,5	1

This evaluates the level at which each observation belongs to one or another fuzzy set A_i (i=1,..,9). Values of the dependence functions of corresponding fuzzy sets (each of them contains 9 elements) are presented in Table 4.11.

Table 4.11 – Fuzzy evaluations of statistical data

T	A_1 120 -130	A_2 130 -140	A_3 140 -150	A_4 150 -160	A_5 160 -170	A_6 170 -180	A_7 180 -190	A_8 190 -200	A_9 200 -210	Results of the observations (stat. data)
1	1	0,5	0,1							128 (A1)
2	0,5	1	0,5	0,1						136 (A2)
3	0,5	1	0,5	0,1						137 (A2)
4	0,1	0,5	1	0,5	0,1					147(A3)
5		0,1	0,5	1	0,5	0,1				155 (A4)
6		0,1	0,5	1	0,5	0,1				153 (A4)
7		0,1	0,5	1	0,5	0,1				156 (A4)
8		0,1	0,5	1	0,5	0,1				159 (A4)
9			0,1	0,5	1	0,5	0,1			168 (A5)
10			0,1	0,5	1	0,5	0,1			169(A5)
11			0,1	0,5	1	0,5	0,1			164 (A5)
12		0,1	0,5	1	0,5	0,1				154 (A4)
13		0,1	0,5	1	0,5	0,1				155 (A4)
14		0,1	0,5	1	0,5	0,1				151 (A4)
15		0,1	0,5	1	0,5	0,1				151 (A4)
16		0,1	0,5	1	0,5	0,1				160 (A4)
17			0,1	0,5	1	0,5	0,1			169 (A5)
18				0,1	0,5	1	0,5	0,1		180 (A7)
19					0,1	0,5	1	0,5	0,1	190 (A7)
20							0,1	0,5	1	203 (A9)
21						0,1	0,5	1	0,5	198 (A8)

Based on the analysis of the data in Table 4.11 all logical relations can be formed. In this case the repeated fuzzy relations are not taken into account.

Thus, in this case we have:

$$A_1 \to A_2 \quad A_2 \to A_2 \quad A_2 \to A_3$$
$$A_3 \to A_4 \quad A_4 \to A_4 \quad A_4 \to A_5$$
$$A_5 \to A_5 \quad A_5 \to A_4 \quad A_5 \to A_7$$
$$A_7 \to A_7 \quad A_7 \to A_9 \quad A_9 \to A_8$$

Forecast value determination is carried out according to the phrase $F(t) = F(t-1) \circ R(t,t-1)$,

where fuzzy relation $R(t,t-1)$ find under the condition that:

$$R(t,t-1) = \dots f_{i1}(t-1) \times f_{j0}(t) \bigcup f_{i2}(t-2) \times f_{j1}(t-1) \bigcup \dots f_{im}(t-m) \times f_{jm-1}(t-m+1) \dots$$

or

$$R(t,t-1) = \bigcup_{i,j} R_{i,j}(t,t-1), \quad i = 1,\dots,I; \quad j = 1,\dots,J.$$

Define the operation «×» for two vectors as follows.

If C and B are two vector-rows of size m and $D=(d_{ij})=C^T\times B$. Then the elements of matrix D in i –th row and j – th column d_{ij} will be determined according to the condition $d_{ij}=\min(C_i,B_j)\quad(i,j=1,...,m)$, where C_i and B_j are respectively the i-th and j-th elements of matrices C and B.

Let

$$\begin{array}{lll} R_1=A_1^T\cdot A_2\ ; & R_2=A_2^T\cdot A_2\ ; & R_3=A_2^T\cdot A_3\ ; \\ R_4=A_3^T\cdot A_4\ ; & R_5=A_4^T\cdot A_4\ ; & R_6=A_4^T\cdot A_5\ ; \\ R_7=A_5^T\cdot A_5\ ; & R_8=A_5^T\cdot A_4\ ; & R_9=A_5^T\cdot A_7\ ; \\ R_{10}=A_7^T\cdot A_7\ ; & R_{11}=A_7^T\cdot A_9\ ; & R_{12}=A_9^T\cdot A_8\ ; \end{array} \qquad (1)$$

Then, if

$$R=\begin{vmatrix} x_1 \\ . \\ . \\ . \\ x_n \end{vmatrix}\begin{vmatrix} y_1,\ldots,y_n \end{vmatrix}=\begin{vmatrix} \min(x_1,y_1) & \min(x_1,y_2) & ... & ... \\ \min(x_2,y_1) & ... & ... & \min(x_2,y_n) \\ ... & ... & ... & ... \\ ... & ... & ... & ... \\ \min(x_n,y_1) & ... & ... & \min(x_n,y_n) \end{vmatrix},$$

In this case we have:

$$R_1=\begin{vmatrix} 1 \\ 0,5 \\ 0,1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{vmatrix}\begin{vmatrix} 0,5 & 1 & 0,5 & 0,1 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}=\begin{vmatrix} 0,5 & 1 & 0,5 & 0,1 & 0 & 0 & 0 & 0 & 0 \\ 0,5 & 0,5 & 0,5 & 0,1 & 0 & 0 & 0 & 0 & 0 \\ 0,1 & 0,1 & 0,1 & 0,1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}$$

$$R_2 = \begin{vmatrix} 0,5 \\ 1 \\ 0,5 \\ 0,1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{vmatrix} \begin{vmatrix} 0,5 & 1 & 0,5 & 0,1 & 0 & 0 & 0 & 0 & 0 \end{vmatrix} = \begin{vmatrix} 0,5 & 0,5 & 0,5 & 0,1 & 0 & 0 & 0 & 0 & 0 \\ 0,5 & 1 & 0,5 & 0,1 & 0 & 0 & 0 & 0 & 0 \\ 0,5 & 0,5 & 0,5 & 0,1 & 0 & 0 & 0 & 0 & 0 \\ 0,1 & 0,1 & 0,1 & 0,1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}$$

$$R_3 = \begin{vmatrix} 0,5 \\ 1 \\ 0,5 \\ 0,1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{vmatrix} \begin{vmatrix} 0,1 & 0,5 & 1 & 0,5 & 0,1 & 0 & 0 & 0 & 0 \end{vmatrix} = \begin{vmatrix} 0,1 & 0,5 & 0,5 & 0,5 & 0,1 & 0 & 0 & 0 & 0 \\ 0,1 & 0,5 & 1 & 0,5 & 0,1 & 0 & 0 & 0 & 0 \\ 0,1 & 0,5 & 0,5 & 0,5 & 0,1 & 0 & 0 & 0 & 0 \\ 0,1 & 0,1 & 0,1 & 0,1 & 0,1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}$$

$$R_4 = \begin{vmatrix} 0,1 \\ 0,5 \\ 1 \\ 0,5 \\ 0,1 \\ 0 \\ 0 \\ 0 \\ 0 \end{vmatrix} \begin{vmatrix} 0 & 0,1 & 0,5 & 1 & 0,5 & 0,1 & 0 & 0 & 0 \end{vmatrix} = \begin{vmatrix} 0 & 0,1 & 0,1 & 0,1 & 0,1 & 0,1 & 0 & 0 & 0 \\ 0 & 0,1 & 0,5 & 0,5 & 0,5 & 0,1 & 0 & 0 & 0 \\ 0 & 0,1 & 0,5 & 1 & 0,5 & 0,1 & 0 & 0 & 0 \\ 0 & 0,1 & 0,5 & 0,5 & 0,5 & 0,1 & 0 & 0 & 0 \\ 0 & 0,1 & 0,1 & 0,1 & 0,1 & 0,1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}$$

$$R_5 = \begin{vmatrix} 0 \\ 0{,}1 \\ 0{,}5 \\ 1 \\ 0{,}5 \\ 0{,}1 \\ 0 \\ 0 \\ 0 \end{vmatrix} \begin{vmatrix} 0 & 0{,}1 & 0{,}5 & 1 & 0{,}5 & 0{,}1 & 0 & 0 & 0 \end{vmatrix} = \begin{vmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 & 0 & 0 & 0 \\ 0 & 0{,}1 & 0{,}5 & 0{,}5 & 0{,}5 & 0{,}1 & 0 & 0 & 0 \\ 0 & 0{,}1 & 0{,}5 & 1 & 0{,}5 & 0{,}1 & 0 & 0 & 0 \\ 0 & 0{,}1 & 0{,}5 & 0{,}5 & 0{,}5 & 0{,}1 & 0 & 0 & 0 \\ 0 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}$$

$$R_6 = \begin{vmatrix} 0 \\ 0{,}1 \\ 0{,}5 \\ 1 \\ 0{,}5 \\ 0{,}1 \\ 0 \\ 0 \\ 0 \end{vmatrix} \begin{vmatrix} 0 & 0 & 0{,}1 & 0{,}5 & 1 & 0{,}5 & 0{,}1 & 0 & 0 \end{vmatrix} = \begin{vmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 & 0 & 0 \\ 0 & 0 & 0{,}1 & 0{,}5 & 0{,}5 & 0{,}5 & 0{,}1 & 0 & 0 \\ 0 & 0 & 0{,}1 & 0{,}5 & 1 & 0{,}5 & 0{,}1 & 0 & 0 \\ 0 & 0 & 0{,}1 & 0{,}5 & 0{,}5 & 0{,}5 & 0{,}1 & 0 & 0 \\ 0 & 0 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}$$

$$R_7 = \begin{vmatrix} 0 \\ 0 \\ 0{,}1 \\ 0{,}5 \\ 1 \\ 0{,}5 \\ 0{,}1 \\ 0 \\ 0 \end{vmatrix} \begin{vmatrix} 0 & 0 & 0{,}1 & 0{,}5 & 1 & 0{,}5 & 0{,}1 & 0 & 0 \end{vmatrix} = \begin{vmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 & 0 & 0 \\ 0 & 0 & 0{,}1 & 0{,}5 & 0{,}5 & 0{,}5 & 0{,}1 & 0 & 0 \\ 0 & 0 & 0{,}1 & 0{,}5 & 1 & 0{,}5 & 0{,}1 & 0 & 0 \\ 0 & 0 & 0{,}1 & 0{,}5 & 0{,}5 & 0{,}5 & 0{,}1 & 0 & 0 \\ 0 & 0 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}$$

$$R_8 = \begin{vmatrix} 0 \\ 0 \\ 0{,}1 \\ 0{,}5 \\ 1 \\ 0{,}5 \\ 0{,}1 \\ 0 \\ 0 \end{vmatrix} \begin{vmatrix} 0 & 0{,}1 & 0{,}5 & 1 & 0{,}5 & 0{,}1 & 0 & 0 & 0 \end{vmatrix} = \begin{vmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 & 0 & 0 & 0 \\ 0 & 0{,}1 & 0{,}5 & 0{,}5 & 0{,}5 & 0{,}1 & 0 & 0 & 0 \\ 0 & 0{,}1 & 0{,}5 & 1 & 0{,}5 & 0{,}1 & 0 & 0 & 0 \\ 0 & 0{,}1 & 0{,}5 & 0{,}5 & 0{,}5 & 0{,}1 & 0 & 0 & 0 \\ 0 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}$$

$$R_9 = \begin{vmatrix} 0 \\ 0 \\ 0{,}1 \\ 0{,}5 \\ 1 \\ 0{,}5 \\ 0{,}1 \\ 0 \\ 0 \end{vmatrix} \begin{vmatrix} 0 & 0 & 0 & 0 & 0{,}1 & 0{,}5 & 1 & 0{,}5 & 0{,}1 \end{vmatrix} = \begin{vmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 \\ 0 & 0 & 0 & 0 & 0{,}1 & 0{,}5 & 0{,}5 & 0{,}5 & 0{,}1 \\ 0 & 0 & 0 & 0 & 0{,}1 & 0{,}5 & 1 & 0{,}5 & 0{,}1 \\ 0 & 0 & 0 & 0 & 0{,}1 & 0{,}5 & 0{,}5 & 0{,}5 & 0{,}1 \\ 0 & 0 & 0 & 0 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}$$

$$R_{10} = \begin{vmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0{,}1 \\ 0{,}5 \\ 1 \\ 0{,}5 \\ 0{,}1 \end{vmatrix} \begin{vmatrix} 0 & 0 & 0 & 0 & 0{,}1 & 0{,}5 & 1 & 0{,}5 & 0{,}1 \end{vmatrix} = \begin{vmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 \\ 0 & 0 & 0 & 0 & 0{,}1 & 0{,}5 & 0{,}5 & 0{,}5 & 0{,}1 \\ 0 & 0 & 0 & 0 & 0{,}1 & 0{,}5 & 1 & 0{,}5 & 0{,}1 \\ 0 & 0 & 0 & 0 & 0{,}1 & 0{,}5 & 0{,}5 & 0{,}5 & 0{,}1 \\ 0 & 0 & 0 & 0 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 \end{vmatrix}$$

$$R_{11} = \begin{vmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0,1 \\ 0,5 \\ 1 \\ 0,5 \\ 0,1 \end{vmatrix} \begin{vmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0,1 & 0,5 & 1 \end{vmatrix} = \begin{vmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0,1 & 0,1 & 0,1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0,1 & 0,5 & 0,5 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0,1 & 0,5 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0,1 & 0,5 & 0,5 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0,1 & 0,1 & 0,1 \end{vmatrix}$$

$$R_{12} = \begin{vmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0,1 \\ 0,5 \\ 1 \end{vmatrix} \begin{vmatrix} 0 & 0 & 0 & 0 & 0 & 0,1 & 0,5 & 1 & 0,5 \end{vmatrix} = \begin{vmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0,1 & 0,1 & 0,1 & 0,1 \\ 0 & 0 & 0 & 0 & 0 & 0,1 & 0,5 & 0,5 & 0,5 \\ 0 & 0 & 0 & 0 & 0 & 0,1 & 0,5 & 1 & 0,5 \end{vmatrix}$$

According to the received data, we find a fuzzy ratio

$$R = R(t, t-1) = \bigcup_{i=1}^{12} R_i.,$$

where the operation of the association of fuzzy relations is represented by the max operator

$$R = \begin{vmatrix} 0{,}5 & 1 & 0{,}5 & 0{,}5 & 0{,}1 & 0{,}1 & 0 & 0 & 0 \\ 0{,}5 & 1 & 0{,}5 & 0{,}5 & 0{,}5 & 0{,}1 & 0{,}1 & 0 & 0 \\ 0{,}5 & 0{,}5 & 0{,}5 & 1 & 0{,}5 & 0{,}5 & 0{,}1 & 0{,}1 & 0{,}1 \\ 0{,}1 & 0{,}1 & 0{,}5 & 1 & 1 & 0{,}5 & 0{,}5 & 0{,}5 & 0{,}1 \\ 0 & 0{,}1 & 0{,}5 & 1 & 1 & 0{,}5 & 1 & 0{,}5 & 0{,}1 \\ 0 & 0{,}1 & 0{,}5 & 0{,}5 & 0{,}5 & 0{,}5 & 0{,}5 & 0{,}5 & 0{,}5 \\ 0 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}1 & 0{,}5 & 1 & 0{,}5 & 1 \\ 0 & 0 & 0 & 0 & 0{,}1 & 0{,}5 & 0{,}5 & 0{,}5 & 0{,}5 \\ 0 & 0 & 0 & 0 & 0{,}1 & 0{,}1 & 0{,}5 & 1 & 0{,}5 \end{vmatrix}$$

Using the obtained fuzzy ratio R, the predicted values can be calculated in this way

$$A_t = A_{t-1} \circ R,,$$

where «$\circ$» - min – max operator.

Define the elements of the matrix R

$$\begin{aligned} a_{11} = \max\{ & \min(1;0{,}5);\ \min(0{,}5;0{,}5);\ \min(0{,}1;0{,}5); \\ & \min(0;0{,}1);\ \min(0;0);\ \min(0;0); \\ & \min(0;0);\ \min(0;0);\ \min(0;0)\} = 0{,}5 \end{aligned}$$

$$\begin{aligned} a_{12} = \max\{ & \min(1;1);\ \min(0{,}5;1);\ \min(0{,}1;0{,}5); \\ & \min(0;0{,}1);\ \min(0;0{,}1);\ \min(0;0{,}1); \\ & \min(0;0{,}1);\ \min(0;0);\ \min(0;0)\} = 1 \end{aligned}$$

$$\begin{aligned} a_{13} = \max\{ & \min(1;0{,}5);\ \min(0{,}5;0{,}5);\ \min(0{,}1;0{,}5); \\ & \min(0;0{,}5);\ \min(0;0{,}5);\ \min(0;0{,}5); \\ & \min(0;0{,}1);\ \min(0;0);\ \min(0;0)\} = 0{,}5 \end{aligned}$$

$$a_{14} = \max\{0{,}5;\ 0{,}5;\ 0{,}1;\ 0;\ 0;\ 0;\ 0;\ 0;\ 0\} = 0{,}5;$$

$$a_{15} = \max\{0{,}1;\ 0{,}5;\ 0{,}1;\ 0;\ 0;\ 0;\ 0;\ 0;\ 0\} = 0{,}5;$$

$$a_{16} = \max\{0{,}1;\ 0{,}1;\ 0{,}1;\ 0;\ 0;\ 0;\ 0;\ 0;\ 0\} = 0{,}1;$$

$$a_{17} = \max\{0;\ 0{,}1;\ 0{,}1;\ 0;\ 0;\ 0;\ 0;\ 0;\ 0\} = 0{,}1;$$

$$a_{18} = \max\{0;\ 0;\ 0;\ 0;\ 0;\ 0;\ 0;\ 0;\ 0\} = 0{,}1;$$

$$a_{19} = \max\{0;\ 0;\ 0{,}1;\ 0;\ 0;\ 0;\ 0;\ 0;\ 0\} = 0{,}1.$$

6. Calculation of predicted values

As an illustration, we make a prediction of the level of electricity consumption for the period of time t = 2.

$$A_2 = \{0,5;\ 1,0;\ 0,5;\ 0,5;\ 0,5;\ 0,1;\ 0,1;\ 0,1;\ 0,1\} = 145 \text{ (the exact value is 136)}$$

7. We interpret the obtained results. Sometimes, for practical use, the results of calculations (received in the form of fuzzy sets) require defuzzification. Here different methods can be used. In particular, it can be a combination of different approaches, based on such considerations:

- if the adjacency function of the predicted value has only one maximum, then the midpoint of the corresponding intervals is considered as the final result;

- if the adjacency function of the predicted value has two or more consequent maximums, then the point in the middle of the combined intervals is considered as the deterministic equivalent;

- In other cases, the centroid method is used for determining the deterministic equivalent of the predicted value

Justification of the rational number of intervals of the statistical values universum

Although in recent years in the technical literature a lot of models of fuzzy time series have been proposed, the analysis of their practical use has shown, that special attention should be paid to selecting the optimal number of sets (intervals) for which the universum of statistical values are divided.

Therefore, the important task will be to investigate how the prediction accuracy depends on the number of the specified intervals.

There are several methods of dividing the input data into sets. The main of them are: Sturges method, Scott method, Fridman and Diakonis method and fuzzy clustering method.

Calculate the number of intervals based on the above data

According to the Sturges method:

$$h = \frac{R}{1+\log_2 n} \approx \frac{R}{1+3,222\lg n},$$

where $R = D_{\max} - D_{\min}$.

By placing the corresponding values obtain:

$$h = \frac{203-128}{1+3,222\lg 21} = 14,26$$

By the Scott Method:

$$h \approx \frac{3,5\sigma}{\sqrt{n}}$$

where $\sigma = \sqrt{\frac{1}{n}\sum_i \left(D_i - \frac{\sum_i D_i}{n} \right)^2}$.

$$h \approx \frac{3,5 \cdot 18,8}{\sqrt{21}} = 14,34$$

According to the Fridman and Diakonis Method:

$$h \approx \frac{2,6IQR}{\sqrt[3]{n}}$$

$$h \approx \frac{2,6 \cdot (168-151)}{\sqrt[3]{21}} = 16$$

According to the method of fuzzy clustering there is a method for calculating the number of intervals:

$$n = \frac{R-S}{2S}$$

where -

$$S = \Delta D_m = \frac{1}{n-1}\sum_{i=1}^{n-1}\left| D_{(i)} - D_{(i+1)} \right|,$$

$$R = \left(D_{\max} + \Delta D_m \right) - \left(D_{\min} - \Delta D_m \right).$$

$$n = \frac{75-6}{2 \cdot 6} = 5,75$$

For further analysis, we compare the prediction errors. They occur at a sufficiently specified number of intervals (in our case - 9) and the number of intervals calculated with the help of the above formulas (namely: 6 and 15).

As an indicator of the quality of the forecast, we will use the rate (δ), which is calculated by the formula:

$$\delta = \frac{|D_{\text{пі}} - D_i|}{D_i} \cdot 100\%$$

Predicting the level of electricity consumption for 6 intervals, obviously that the average rate is $\delta_{cep}^{6} = 6,4\ \%$. All further calculations are shown in Table 4.12.

Table 4.12 The results of the calculation of predictive values with the number of intevalues - 6

Data	Forecasted data	Rate
128	149.03	16.43
136	153.75	13.05
137	153.75	12.2
147	153.75	4.59
155	157.5	1.61
153	157.5	2.94
156	157.5	0.96
159	157.5	0.94
168	159.37	5.13
164	157.5	3.96
164	157.5	3.96
154	157.5	2.27
155	157.5	1.61
151	157.5	4.3
151	157.5	4.3
160	157.5	1.56
169	159.37	5.7
181	170	6.08
189	170	10.05
203	168.38	17.05
198	168.38	14.96

For 9 intervals the average rate is $\delta_{cep}^{9} = 4{,}16\ \%$.

Table 4.13 The results of the calculation of predictive values with the number of intevalues - 9

Data	Forecasted data	Rate
128	143.82	12.36
136	145.81	7.22
137	145.81	6.43
147	155.44	5.74
155	155.88	0.57
153	155.88	1.88
156	155.88	0.08
159	155.88	1.96
168	166.35	0.98
164	166.35	1.43
164	166.35	1.43
154	155.88	1.22
155	155.88	0.57
151	155.88	3.23
151	155.88	3.23
160	166.34	3.97
169	166.34	1.57
181	173.48	4.16
189	173.48	8.21
203	180.34	11.16
198	178.33	9.93

For 15 intervals the average rate is $\delta_{cep}^{15} = 2,5\ \%$.

Table 4.14 The results of the calculation of predictive values with the number of intevalues - 15

Data	Forecasted data	Rate
128	138.71	8.36
136	142.53	4.80
137	142.53	4.04
147	151.44	3.02
155	156.89	1.22
153	156.89	2.54
156	162.96	4.46

159	162.96	2.49
168	169.14	0.68
164	164.67	0.41
164	164.67	0.41
154	156.89	1.88
155	156.89	1.22
151	156.89	3.90
151	156.89	3.90
160	162.96	1.85
169	169.14	0.08
181	178.53	1.37
189	186.00	1.59
203	195.65	3.62
198	195.65	1.19

Analyzing the results of the performed calculations, we can say that the accuracy of prediction depends on the number of intervals of the distribution of the initial statistical values of the parameter under consideration. At the same time the research is not sufficient to conclude that a certain number of intervals, into which the initial value universum is divided, provides the minimum average prediction error.

Conclusion to chapter 4

According to the results of the chapter, based on the calculations presented in the paper, it can be noted that one of the most important aspects of choosing the location of the SOP in the distribution network is the value of the load. Therefore, in order to optimize the operation of the SOP in the distribution network, the correct forecasting of the load in the network should be carried out taking into account the possible development of the distribution network in the next 15 - 20 (ideally 25 -30) years. To create such a forecast, the section provided appropriate practical calculations.

The section also noted the possibility of using different approaches to forecasting the probable load that may be available in the distribution network due to variable consumer demand for electricity.

As the use of SOPs in distribution networks is currently not a common phenomenon, in order to assess their future operation, in chapter 4, a calculation (forecast) was made regarding their use and the optimal location in the distribution network, which showed significant advantages of using SOP in comparison with other types of protective equipment, including due to the properties of SOP, which were previously described in the conclusions to the third chapter.

CONCLUSION

It was concluded that the share of DES tends to increase. However, it was also noted that a significant share of DES is occupied by RES, which may create additional challenges in the dispatching of distribution networks. This phenomenon requires additional analysis and forecasting to create a strategy for future management of distribution networks in order to avoid the negative consequences that may be created, while continuing the trend of significant growth in the share of RES in the segment of electricity generation.

It has been shown that a wide and complex use of modern power electronics will not only make it possible to exclude possible negative consequences associated with the widespread use of distributed generation, but also significantly improve the efficiency of electric networks due to reduction of electric energy losses, quality and a high level of reliability of power supply.

By the example of SOP technology application the possibility of real-time control modes of distribution networks in the presence of distributed sources of energy accumulation and generation with a varying output power is demonstrated.

A methodology for forecasting different modes of electric networks with sources of distributed generation in conditions of uncertainty and lack of basic information, which is typical situation for many energy companies in Ukraine, has been proposed.

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