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Institute of Energy Saving and Energy Management

Power Supply Department

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__________ **Vladimir POPOV**
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Master’s thesis

under the speciality 141 Electrical Energetics, Electrical Engineering and Electromechanics
specialization Energy Management and Energy Efficient Technologies

on the topic: “**Demand side management sysyem for lokal power grid**”

Completed by: Master student (2d year), group OH-81мн

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

Kyiv, 2020

National Technical University of Ukraine
“Igor Sikorsky Kyiv Polytechnic Institute”

Institute of Energy Saving and Energy Management

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

Speciality: 141 Electrical Energetics, Electrical Engineering and Electromechanics
Specialization: Electric Power Distribution Systems Engineering

“APPROVED”
Head of the Department
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“___” _____________ 2020

TASK
on the Master’s thesis research to student
CHOUAKRIA ABDELDJALIL

1. Topic of the Master’s thesis:

DEMAND SIDE MANAGEMENT SYSYEM FOR LOKAL POWER GRID

research advisor: **Doctor of techn. Science, Prof. Serhii Denysiuk**

approved by the university order dated on «05» _May__ 2020 № 62/20ci

2. Deadline for the Master’s thesis submission by student: ___06.05.2020_______

3. The object of research is the processes of the formation of additional and necessary electricity losses and mechanisms for controlling the demand for electricity in local power supply systems.

4. The subject of the research is the methods and means of optimizing the non-uniformity of electricity consumption processes using the mechanisms of electricity demand control with the use of Frize power modification.

5. List of the tasks that have to be performed: analyze the mechanisms of demand management in modern energy supply systems; evaluate special features of modern decentralized (dispersed) power generation systems; take a look at the methods for assessing the total energy loss in local electrical networks; evaluate the levels of non-optimality of energy consumption taking into account the parameters of local power supply systems, in particular, when active power is consumed at higher harmonics (the presence of voltage and current harmonics of the same name), as well as taking into account the internal resistance of electric power generators and power line resistances; to develop algorithms for measuring the reactive power of Frize in local power systems.

6. List of the graphical (illustrative) material: load graphs of local electric networks, the graph of the dependence of additional losses (reactive power of Frieze) on system parameters, and parameters of system operation modes.

7. Indicative list of publications: Annual scientific-practical international conference "Perspective scientific trends‘2020"; International Scientific and Practical Conference "Actual problems of science and practice".

8. Consultants for different chapters of the Master’s thesis: _____–___________

9. Date, when the task was issued: ____01.10.2019_________________________

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	15.10.2018-01.12.2018	
2.	Identification the preliminary structure of the Master's thesis	01.12.2018-01.03.2019	
3.	Literature review and work on the first chapter of the Master's thesis	01.03.2019-15.05.2019	
4.	Define methodology and methods of research	15.05.2019-01.10.2019	
5.	Analysis of mechanisms of demand management in modern energy supply systems	01.10.2019-15.02.2020	
6.	Modern decentralized (distributed) electricity generation systems	15.02.2020-10.03.2020	
7.	Evaluation of total energy losses in local electric networks	11.03.2020-31.03.2020	
8.	Evaluation of levels of optimality of energy consumption taking into account parameters of local power supply systems	01.04.2020-15.04.2020	
9.	Formatting the text of the Master's thesis	15.04.2020-06.05.2020	
10.	Preparing the Abstract and PowerPoint Presentation of the Master's thesis; receiving an official protocol of plagiarism detection results and peer review	15.04.2020-06.05.2020	
11.	Preliminary Master's thesis defense	18.05.2020	
12.	Master's thesis defense	20.05.2020	

Student _________ **Chouakria Abdeldjalil**

Research Advisor _________ **Serhii Denysiuk**

ABSTRACT

Structure and scope of work. The Master's thesis on the topic "DEMAND SIDE MANAGEMENT SYSYEM FOR LOKAL POWER GRID" consists of an introduction, 4 chapters, conclusions and list of references. The total volume of work is 135 pages, including 29 figures, 11 tables and 52 bibliographic references; 4 annexes on the 18 pages.

Relevance of research. Demand Side Management (DSM) is one of the fundamental up-to-date solutions to manage electricity consumption in the developing world of insufficient electricity capacity, increasing fuel costs and problems of environmental polution. DSM provides measures to reduce consumption and expenses. In most developed countries, DSM programmes are widely used as a means of harmonizing generation and consumption regimes in the electricity supply system. In order to apply various DSM options and strategies, analytical and optimization tools are used. This also requires detailed information about dynamics of electricity consumption, system functioning and planning, understanding on peak loads and their variations due to environmental factors. Energy demand side management includes activities made by end-users to modify their consumption in a best possible way for both utility and the customers, but this does not necessarily lead to decrease in the total energy consumption. Demand Side Management is made through implementation of activities in order to produce the desired daily, monthly or seasonal load curves.

Relationship of work with scientific programs, plans, themes. Today, the Department of Electricity has widely considered and solved the issues of the introduction of dispersed electricity sources into power supply systems and the development of their control systems. This master's thesis corresponds to GDR №2013-n "Development of scientific and methodological bases of aggregation of virtual power plants and active consumers in the conditions of the energy market".

The purpose and objectives of the study. The purpose of the dissertation research is to improve and further develop the mechanisms of electricity demand management in local power supply systems based on the use of Frize power modification.

To reach the delivered mark in the robot, the following tasks were addressed:

- analyze the mechanisms of demand management in modern energy supply systems;
- evaluate special features of modern decentralized (dispersed) power generation systems;
- take a look at the methods for assessing the total energy loss in local electrical networks;
- evaluate the levels of non-optimality of energy consumption taking into account the parameters of local power supply systems, in particular, when active power is consumed at higher harmonics (the presence of voltage and current harmonics of the same name), as well as taking into account the internal resistance of electric power generators and power line resistances;
- to develop algorithms for measuring the reactive power of Frize in local power supply systems.

The object of research is the processes of the formation of additional and necessary electricity losses and mechanisms for controlling the demand for electricity in local power supply systems.

The subject of the research is the methods and means of optimizing the non-uniformity of electricity consumption processes using the mechanisms of electricity demand control with the use of Frize power modification.

The scientific novelty of the results of the master's dissertation is the further development of the methodology of optimization of power consumption graphs using power modification Frize Q_F in the case of power consumption control and implementation of programs to manage electricity demand taking into account the parameters of local power supply systems. consumption of active power at higher harmonics (presence of voltage and current harmonics of the same name), and also the account of internal its resistance of power generators and resistances of power lines.

The practical significance of the obtained results is: (1) in the formation of a number of ratios to assess the levels of suboptimal transmission and consumption of electricity at active power consumption at higher harmonics (presence of the same voltage and current harmonics) and taking into account the internal resistance of power generators and transmission lines; (2) in the development of software-oriented algorithms for measuring the reactive power of Frieze in local power supply systems, allowing to upgrade the DSM program.

Software modeling, in particular Microsoft Excel spreadsheets, was used to verify the obtained data and original relationships.

Approbation of master's thesis and publications. The results of the study were published at two international scientific and technical conferences and included in the collections of works:

1) Denysiuk S.P., Chouakria Abdeldjalil "Mechanisms for managing the demand for electricity of industrial enterprises" (7 pages) – Annual scientific-practical international conference "PERSPECTIVE SCIENTIFIC TRENDS‘2020"; April 21–22, 2020, Beltsu, Moldova;

2) Denysiuk S.P., Chouakria Abdeldjalil "Demand-side management mechanisms for industrial enterprises" (6 pages) – XIV International Scientific and Practical Conference "ACTUAL PROBLEMS OF SCIENCE AND PRACTICE"; April 27–28, 2020, Stockholm, Sweden.

Keywords: demand side management, lokal power grid energy efficiency, optimization, load balancing mechanisms, power consumption.

CONTENTS

LIST OF ACRONYMS

CR – consumer regulators

DEES – distributed electric power systems

DER – distributed energy resources

DG – distributed generation

DS – distributed storage

DSM – Demand Side Management

EMC – electromagnetic compatibility

GD – grid-dependent (mode)

GI – grid-independent (mode)

ICE – indicators of the quality of electricity

IEA – International Energy Agency

NPPs – nuclear power plants

PCC – point of common connection

PSP – pumped storage power plant

PV – photovoltaic

TPPs – near thermal power plants

INTRODUCTION

Demand Side Management (DSM) is one of the fundamental up-to-date solutions to manage electricity consumption in the developing world of insufficient electricity capacity, increasing fuel costs and problems of environmental polution. DSM provides measures to reduce consumption and expenses. In order to apply various DSM options and strategies, analytical and optimization tools are used. This also requires detailed information about dynamics of electricity consumption, system functioning and planning, understanding on peak loads and their variations due to environmental factors. Energy demand side management includes activities made by end-users to modify their consumption in a best possible way for both utility and the customers, but this does not necessarily lead to decrease in the total energy consumption. DSM is made through implementation of activities in order to produce the desired daily, monthly or seasonal load curves [1, 2]. Basic definitions Basic definitions for DSM are given in Annexes A.

For utilities, DSM means avoiding or delaying the need to invest in new capacities, improving the power quality, ensuring efficient generation, transmission and distribution of energy [3, 4]. For the residential customer, it means reduced bills and taking advantage of the financial incentive provided by utility company. For commercial and industrial customers, it means lower costs included in their products price, making them more competitive on the market. DSM gives the customer a new role and freedom in shifting the demands to off-peak periods to reduce the electricity bill, whereas providing lower costs per kWh to the utility.

The scope of the DSM programs is the planning, development and implementing of programs whose objective is to shape actively the daily and seasonal electric load profiles of customers to realize or achieve better overall system utilization [5]. DSM activity has grown and matured over the past decades. Many utilities have implemented DSM programs on a routine basis and more utilities are considering DSM as a part of their resource planning process. The benefits from applying DSM programs are mutual for both the customer and the utility, utilities will have better utilization of the available system capacity. For customers, the amount of monthly electric bill will be decreased besides the improvement in the electrical service quality.

At the heart of the DSM programs, there is a series of measures intended to encourage specific groups of customers to modify their energy usage patterns in a manner consistent with the utility's DSM objectives while maintaining or enhancing customer satisfaction [1–5]. Different utilities have different programs to be applied on their customers. These programs are different according to the number of participated customers in the program, nature of the targeted load type (commercial, industrial or residential), the revenue from each program and the level of customer’s satisfaction or reaction towards similar applied programs. These programs can be augmented in five steps: DSM targets, financial and feasibility study, designing of effective programs, program implementation & monitoring and program evaluation.

In general, consumers participating in demand management programs do not reduce the integral consumption values, but simply redistribute the load during the day, shifting consumption from peak periods to off-peak periods. Changes in consumption should not lead to a deterioration in the core business of the consumer of electricity as an economic entity - that is, a decrease in the supply of its marketable products, a decrease in the quantity or quality of the services provided. Objective: find the opportunity to participate in the demand management program without reducing the efficiency of the process.

In the traditional structure of the energy market, consumers simply consume electricity depending on their tasks, and the energy system should provide for their need for electricity, loading generating and network capacities, and also investing in the construction of new and modernizing old generating and network capacities in a timely manner. One of the fundamental limitations of traditional electricity markets is the inelasticity of demand - electricity consumption is virtually independent of market prices. With this construction of market mechanisms, the active side that forms the price is electricity producers.

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CHAPTER 1. ANALYSIS OF MECHANISMS OF DEMAND MANAGEMENT IN MODERN ENERGY SUPPLY SYSTEMS

1.1. Electricity Demand Management Mechanisms

One of the effective methods for increasing energy efficiency, successfully applied in the practice of developed countries of the world and demonstrating a significant positive effect, is such a tool as demand management for electricity.

New trends in the electric power industry, the emergence of digital interval electricity meters, the development of telecommunications and “smart grids”, in particular, have determined the possibility of increasing the elasticity of consumption. One of the evidences of these changes is DSM, which provide for the active participation of electricity consumers in the management of the energy system, and the most recent trend is the involvement of retail consumers in this process [1–3].

Currently, researchers pay great attention to the implementation of integrated smart grid technologies (Smartgrid) in the electric power industry, the transformation of the existing control system in the electric power industry, taking into account new technological capabilities [6]. Intelligent energy technology uses the mechanism of demand management for electricity consumption, as a form of economic interaction of electric power entities with end users of electric energy, which provides mutually beneficial, cost-effective regulation of volumes and modes of energy consumption.

Programs that encourage consumers to participate in economic and emergency demand management are widespread in the world and are actively used in the USA, the European Union, Australia, New Zealand, China and other countries [7–9].

Foreign experience shows that demand management of existing consumers allows energy companies to serve new customers with relatively lower tariffs. But this requires strong motivation to fight for each client and the desire to improve the quality of service. An emphasis should also be placed on institutional issues. Undoubtedly, the restructuring of the electric power industry and the liquidation of regional vertically integrated companies have seriously worsened the conditions for demand management and shifted the emphasis in this regard to regional electric grid companies, which usually have insufficient capacity for this activity.

According to foreign experts, the maximum potential to reduce peak load in the power system through the use of control programs Demand is 10–15% of the peak load. And these estimates are based on the current technological level of the electric power industry. The ongoing electrification process, when an increasing number of end-user equipment uses precisely electric energy, for example, the development of electric vehicles, the development of the latest technologies such as the Internet of Things, increase the potential for demand management.

The special properties of electricity as a commodity (simultaneous production and consumption, the impossibility of creating stocks or replacing it with another commodity) led to the fact that historically consumers did not have the practical ability to influence the balance of supply and demand, and, consequently, the market prices. On the other hand, the characteristics of electricity as a commodity, due to its physical properties, determine the need for continuous maintenance of the balance of production and consumption. Electricity markets are designed to encourage participants to maintain such a balance. Traditionally, the main role in maintaining balance is played by power plants. In the absence of special incentive measures for consumers (for example, such as demand response), demand for electricity does not depend or depends little on market prices; consumers do not reduce consumption when prices rise. In conditions of inelastic demand, producers are the active party determining the price of electricity. As the load grows, less efficient generators are used to meet this growth. In recent years, with the advent of digital interval electricity meters, the development of telecommunications and “smart grids”, it has become possible to increase the elasticity of consumption by deliberately influencing consumer equipment when necessary. Demand management is an effective tool to reduce prices in the electricity market during peak hours when less efficient generating facilities are used to cover electricity demand. Moreover, a relatively small decrease in consumption can lead to a significant reduction in the price of electricity.

The use of demand management mechanism is beneficial for all energy market actors [4, 5, 10, 11]:

1) benefits for consumers: demand management involves improving energy-efficient production parameters based on improved energy efficiency, rationalization of power consumption modes and reduced energy costs (elimination of sub-optimal energy demand and capacity per unit of output);

2) benefits for energy companies: eliminates the threat of loss of revenue for generating and network companies due to the increase of own generation in industry; due to the reduction of demand uncertainty, the quality of energy development planning in regions (industrial units) is improved.

According to the results of the analysis, we will outline the main factors that determine the social value of managing electricity demand as an organizational and economic innovation, in terms of supply and demand:

1) demand side (consumers): rising electricity prices; significant energy-saving potential not realized by consumers; low level of electrification of the national economy; the tendency to flatten electric load schedules; increased demand for jet power (industry); unsatisfactory organization of instrument accounting (low-power consumers); the need to maintain preferential prices for the population.

2) supply side (manufacturers and suppliers): combination of poor investment climate, high investment risks and energy shortages; lack of peak generators; critical deterioration of fixed assets of energy companies; the need for high costs to

improve system reliability and reliability of power supply; high losses in electricity transmission (especially in regional networks).

In a review released in 2009, the Federal Energy Management Commission (FERC, USA) identifies the following barriers to managing demand in the electricity markets: regulatory, economic, technological, and other barriers [5]. The FERC study found that the most significant impediments to the deployment of demand management in California are the lack of Advanced Metering Infrastructure (AMI) systems, inefficient demand management programs, and low consumer interest.

DSM techniques may be implemented by utilities through direct or indirect load control. In the case of direct load control, utility can modify load pattern by switching-off the power supply to specific category of customers at chosen time intervals, or for specified types of electric loads. In the case of indirect control, the utility may use some special methods as loads time schedule, thermal energy storage, efficient end-use technologies, tariff system and electrification technologies (Figure 1.1).

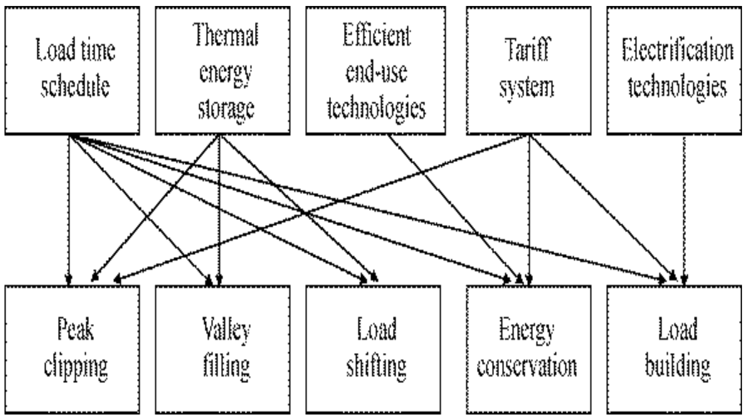


Figure 1.1 – Scheme of Load Shape Objectives

Valley filling (Figure 1.2) is one possible DSM method applied in order to change load curves so to obtain grater load factors in predefined time margins. In such a way the utility may increase its profit, whereas it decreases the costs per kWh of energy. Greater demand in off-peak hours is achieved by encouraging end-customer to spend energy with paying lower tariffs, or to change time schedule of the load demand distribution over the day. This is possible if some controllable devices may operate in different time intervals during the day and the chosen time interval is not relevant to the customer, e.g. for a residential or industrial consumer these might be boilers or storage heaters.

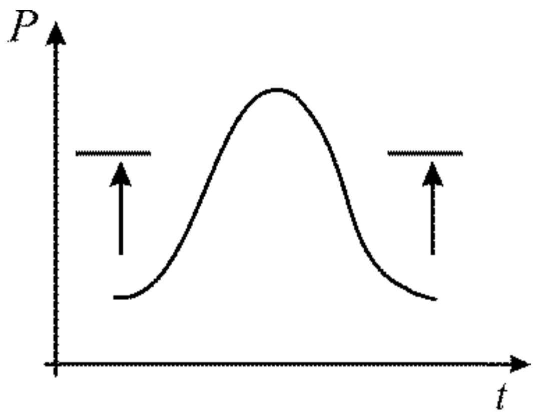


Figure 1.2 – Valley Filling Technique

Demand management can take various forms depending on the volume and mode of consumption. Demand management service providers compete with each other to offer the highest level of service, and consumers should be able to choose the service offer that suits them best. Some demand management service providers are aggregators of demand management: they conclude contracts directly with consumers, and then combine the actions of several consumers in demand management in one pool in order to sell it on the electricity market or to other participants in the energy system.

A variety of consumers can participate in demand management: from large industrial to domestic. To participate in demand management, consumers can shift the load schedule to periods of lower prices, temporarily stop or reduce the intensity of the production process, manage lighting, water heating, ventilation and air conditioning systems, and use their own generating equipment or energy storage. In general, consumers participating in demand management programs do not reduce the integral consumption values, but simply redistribute the load during the day, shifting consumption from peak periods to off-peak periods. Changes in consumption should not lead to a deterioration in the core business of the electricity consumer as an economic entity – that is, to decrease the supply of its marketable products, reduce the quantity or decrease the quality of the services provided, and this is also a joint task of the aggregator and the consumer – to find an opportunity to participate in the demand management program without compromising efficiency technological process.

Now there is a fundamental restructuring of the needs of consumers who expect new ways of interaction from energy companies, new services, new consumer experience. In countries with developed markets, energy companies are actively competing for consumers. And since in most cases they are not able to offer consumers significantly different electricity tariffs, competition moves to the plane of additional services and new consumer experience - the opportunity to participate in demand and energy efficiency management programs, receive more detailed electricity bills, convenient online platforms and mobile applications with elements of gamification. This applies primarily to domestic and small commercial consumers.

Most often, demand management is used to lower electricity prices in the wholesale market, which in turn leads to lower prices in the retail market. This is a short-term effect, but in the long run it avoids the construction of new power plants and networks to cover peak loads. It is impossible not to say about environmental effects: peak generation, being the most “expensive” from an economic point of view, is often the most polluting environment. Demand management can significantly reduce peak power plants.

An important task is to find an opportunity to participate in the demand management program without reducing the efficiency of the process. Most often, demand management is used to lower electricity prices in the wholesale market, which in turn leads to lower prices in the retail market. This is a short-term effect that in the long run avoids the construction of new power plants and networks to cover peak loads, which also has an environmental effect and the use of RES.

The participation of large consumers of the wholesale market in demand management is achieved by opening different segments of the market for their participation - that is, by creating conditions that allow them to compete with generating objects, and appropriate economic incentives [10, 12–15]. The introduction of a demand management mechanism usually starts with the creation of programs for the wholesale market consumers. However, their potential for participation is usually limited: there are relatively few such consumers and, by being skilled market participants, they are already largely utilizing the flexibility of their consumption to optimize costs, even in the absence of explicit demand management mechanisms. At the same time considerable potential of demand management is on the side of retail consumers of electricity - small and medium-sized enterprises [11]. Let us introduce some tools for managing the demand for electricity for industrial enterprises that have been widely used in the practice of energy managers in various industries:

1. System of one-rate tariffs, differentiated by day zones;

2. Hourly differentiation of electricity prices for the day-ahead market;

3. The difference in electricity prices between weekdays and weekends in the market a day in advance;

4. Calculation of the magnitude of the obligations for the purchase of electric power in the wholesale and retail markets based on the actual duration of the daily maximum of the regional grid;

5. Calculation of the magnitude of obligations to buy capacity in the

wholesale and retail markets only on the basis of the calculation of working days;

6. Calculation of the amount of obligations for electricity transmission services on the basis of the choice of single or two-part tariffs;

7. Calculation of the amount of obligations for electricity transmission services based on the planned peak load hours;

8. Calculation of the amount of obligations for electricity transmission services only on the basis of the calculation of working days.

Tools under Nos. 1, 2, 5, 7 and 8 - provide load shifting; tools for Nos. 3 and 4 - flexible form of equipment loading; tool for No. 6 - cutting off the peak load. In this case, the instrument under No. 1 is used mainly by non-industrial enterprises, the instrument under No. 6 is used by all industrial enterprises, the instrument under No. 7 is by industrial consumers having single energy-intensive objects, other selected instruments are used depending on the structure and production capacities. enterprises.

In accordance with the requirements of the ISO50000 series of standards for energy managers, a demand management algorithm has been developed in the region (at the enterprise), which includes a number of administrative and coercive measures that enhance the corresponding motivation of energy companies. This algorithm includes the following actions [16, 17]:

1) selection of promising facilities by prior arrangement with energy management of enterprises;

2) conducting an energy audit at selected sites (with the involvement of specialized organizations);

3) development of demand management programs for the planning period (with a preliminary assessment of their effectiveness);

4) an assessment of the necessary costs (within the program budget);

5) selection of suppliers of energy-efficient equipment, instruments and devices;

6) conclusion of contracts with consumers and suppliers of energy-efficient equipment;

7) control over the implementation of the program (including necessary adjustments);

8) analysis of the results of the implementation of program activities in the reporting period;

9) distribution of financial effects from the demand management program between consumers and energy companies in a given region;

10) development of proposals for the extension of the program and the expansion of the range of facilities in this region.

In world practice, a wide range of load control mechanisms have been developed, some of which are already being successfully implemented in an economic practice (Table 1.1) [15–17]. It should be noted that consumer incentives can provide savings for the system as a whole by reducing the level of environmental risks.

Table 1.1 – Demand Management Programs

Program elements demand management demand management	**Current state**	**Perspective state**
Direct demand management	The consumer, at his discretion, turns the equipment on or off during the hours of the minimum / maximum tariff in accordance with the existing tariff menu	The consumer's equipment is equipped with appropriate devices for remote shutdown at peak times and inclusion at moments of minimum prices
Load Demand Programs or Buyback Programs	The consumer, at his discretion, turns the equipment on or off during the hours of the minimum / maximum tariff in accordance with the existing tariff menu	Based on current market information, a consumer can refuse consumption at a given time and sell capacity
Rate, differentiated by time of day	The consumer, at his discretion, turns the equipment on or off during zone tariffs	The existence of both voluntary and compulsory programs based on the mandatory participation of all consumers in them. The consumer may or must download his equipment during the validity of a tariff
Interrupt programs	Forced shutdowns in force majeure situations	Disconnection by agreement of the consumer with the possibility of lowering payments to the supplier due to the price modification system
Load reduction programs	Forced load reduction in force majeure situations	Reducing the load by agreement of the consumer with the possibility of lowering payments to the supplier due to the price modification system
Real-time billing	Real-time operation in a balancing wholesale electricity and capacity market	Real-time operation in the balancing wholesale electricity and capacity market, as well as at the end-user level in the retail consumer market
Load Demand Programs or Buyback Programs	An industrial consumer, at his discretion, loads capacities in accordance with the mode of operation, depending on the tariff or the terms of a long-term contract	A consumer, based on current information on the state of the market, can refuse consumption at a given time and sell capacity according to one of their options: a variable percentage of wholesale prices, a constant percentage of wholesale prices, a constant or variable price, determined on the basis of competitive selection of consumers.

1.2. Demand Side Management and Smart Grid

Flexibility is nothing new in the electric grid, as supply and demand need to be in perfect balance to ensure a stable electricity supply [18, 19]. The different concepts of offering flexibility are discussed under the key word of DSM as well as options for encouraging producers, which also consume electricity (so called prosumers) to fit their grid-based demand to the needs of flexibility. However, as consumers and prosumers are coordinated or coordinate their consumption (and production) in favor of the grid situation, the question of who should pay for the grid costs has to be raised. There are several concepts discussed and implemented worldwide, all of which have advantages and disadvantages.

Historical flexibility in the electricity system was supplied by conventional power plants. With the beginning fade-out of conventional power plants, the relevance of demand flexibility increases. Influencing the consumer demand behavior is characterized as DSM [19, 20].

The DSM potential in the industry is limited due to the focus on efficient and cheap production of goods. Thus, most processes need to run stably and just-in-time production and delivery is common to all production. However, some limited flexibility can be expected as process speeds can be varied, if production is not constantly running on maximum output. Further, if incentives for flexibility are introduced, several industry companies would optimize their production to minimize costs. Unfortunately, one has to say, that changes in production are always very complicated (if at all possible) within the industry sector, as worker shifts or cooling and heating processes may be affected. Samples show, that flexibility potential in this sector can be found in energy intensive industries, e.g. in electrolysis processes or electric steel production.

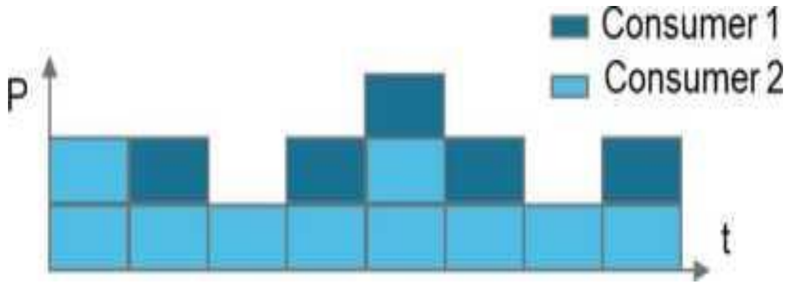
DSM potentials in households In comparison to the industry sector, households tend to be very flexible consumers, from a technological perspective. However, from a socio-economical perspective, willingness to participate in DSM programs seem to be very low. Especially electric heating can be a source of easy to access flexibility and offers options for DSM. Other consuming units (e.g. fridges, freezers, etc.) have only low capacities, thus access to many individual units is needed to reach relevant DSM potentials [19].

In the future, sector integration technologies and decentral energy storages will become more relevant for DSM. These include heat pumps, electro mobility as well as heat storages or batteries. Especially in combination with the decentral production of electricity (prosumer), these technologies offer interesting options, as described in the following chapter.

Prosumers are in general characterized as private consumers also producing electricity with PV plants or other technologies. Sometimes bigger consumers are also included in this definition [18–21]. If it is useful to consume electricity instead of selling it, the question arises, whether a battery storage is useful. If the installation is economical, further DSM potentials are incentivized in the energy system without direct DSM mechanisms. However, this depends on the metering and the overall renewable promotion scheme.

Metering schemes and renewable support schemes do vary considerably between different countries. Furthermore, producers of renewable electricity receive a certain feed-in tariff or a market premium for each kWh. Depending on the size of the production and consumption, there exists several further differentiations. For a typical household prosumer this leads to the situation, where all electricity to and from the grid is measured.

Hence, all three electricity flows, production feed-in, self-consumption and grid consumption can be calculated and are treated independently. In contrast to this metering system, countries like Denmark (beforehand) or some US States use net metering, basically allowing the meter to run “backwards”. However, with an increased renewable feed-in, this “unlimited selling of electricity to end-consumer prices” can lead to problems, as payment of grid costs needs to be rethought, the usage of the grid “as a battery” must be discussed and simultaneous grid usage has to be considered (no incentive for consumption at the place and time of production). Thus, the question of “anti-social” grid use arises – as prosumers in general are paying less for the grid, while they need it the most when everyone else also needs it (see sketch in Figure 1.3).



Units of consumption over time

Figure 1.3 – Who should pay how much grid? Consumer 1 or 2?

While the cost distribution must be discussed in detail, a Smart Meter might allow overcoming nearly all data problems [18–21]. However, one must clarify in every discussion, which definition of a Smart Meter is used - as they vary greatly between authors. In combination with Smart Devices within a household a Smart Home environment can be created, possibly able to offer additional DSM potentials in the electricity system. Especially if automated (de-)activation of devices is possible, an aggregation of several small consumers to a powerful DSM application is possible. Thus, Smart Meter technologies seem to be helpful for the integration of renewables due to the possible increase in DSM potential.

Finally, a combination of several active smart components with each other in a grid will lead to a Smart Grid, integrating consumers and producers efficiently with each other. This also includes "new" technologies such as electric vehicles or heat pumps whose utilization can be automated in favor of grid stability and re-newable integration, consuming electricity when it is available and supplying energy when it is needed.

DSM with Consumers and Prosumers. One has to say, that smart technologies do not have to be implemented, to efficiently access DSM potentials. Consumers, producers, and prosumers can also be incentivized by "classical" DSM programs. These include incentive-based programs like market-based approaches with capacity markets or demand bidding options, as well as classic approaches in-cluding direct load control or curtailable load programs. Furthermore, on the producer side, short-term market closure or curtailment of production (e.g. shut down of renewable electricity production if grid stability is at risk) is possible.

In general, DSM elements can be implemented in nearly every market and under any technical condition. However, smart technologies help to implement DSM elements, as they overcome information gaps and allow access to unused potentials. Furthermore, the development from consumers to prosumers give several options to control the electricity feed in. Not all are based on typical DSM mechanism, but also by applying certain supporting schemes and combining them with corresponding metering schemes for small producers.

DSM offers the chance to stably implement fluctuating energy sources into the system. Today, several potentials for DSM can be found in the system and should be exploited where efficient. Several different programs for accessing this potential already exist [19–21].

Furthermore, smart technologies, such as Smart Meters, Smart Devices combined with Smart Homes, or smart electric cars will offer additional potential in the future if integrated optimization is performed. With the increase of decentral electricity production, the relevance of optimization on a local, decentral level is increasing and can reduce grid costs. This includes an accurate choice of supporting schemes for renewables, including metering discussions as well as grid cost distribution. As wind and solar energy come without any fuel costs, they are cheap (even) compared to conventional energy sources. However, for longer periods of missing feed in, pure DSM does not seem to be an optimal solution.

Furthermore, the implementation of new, in general more efficient technologies (e.g. electric cars) increases the energy system efficiency. But further efficiency gains seem to be needed for many countries, if all energy demand shall be satisfied from renewable sources. Finally, efficiency and demand side flexibility must be developed hand in hand, although they contradict each other from time to time (see above energy efficient industry production). Only this will allow an efficient integration of fluctuating renewable energy sources into energy systems.

1.3. Benefits and barriers efficiency and performance management

The effectiveness of the functioning of the demand management system is evaluated by the final results, which differ for energy companies, energy consumers and the region as a whole [22]:

1. Energy company:

- saving costs for the construction and operation of generating and network capacities;

- market expansion and increasing the sustainability of financial results in the long term;

- Creation of an attractive company image in the region.

2. Energy consumers:

- improving the reliability and quality of energy supply;

- lower and more stable tariffs for electricity and heat;

- reducing the energy intensity of products, services and increasing the level of electrification at a relatively lower cost.

3. Region (long-term public interests):

- more reliable energy supply for economic growth;

- increasing the level of energy independence;

- the socio-economic effect of electrification and heat supply of the national economy;

- improving the environmental situation and environmental and economic safety, as well as the investment climate.

The use of a demand management mechanism is beneficial for all subjects of the energy market.

1. Benefits to consumers. Demand management involves improving the energy and economic parameters of production by increasing energy efficiency, rationalizing energy consumption and reducing the cost of energy supply. Thus, we are talking about eliminating over-optimal demand for energy and capacity per unit volume of products or services.

2. Benefits for energy companies. Firstly, the threat of loss of income of generating and network companies due to the buildup of their own generation in industry is eliminated. Secondly, due to the reduction in demand uncertainty, the quality of planning the development of energy capacities in the regions is

increasing.

3. Benefit for suppliers of energy-efficient equipment and energy-saving services.

Demand management will foster the development of relevant markets. In this case, companies that manage demand act as intermediaries between suppliers of technical equipment and services and consumers.

Consider the factors that determine the social value of demand management for electricity as an organizational and economic innovation, in the aspects of supply and demand [23, 24].

a) On the demand side (consumers):

• rising electricity prices;

• significant energy saving potential not realized by consumers;

• low level of electrification of the national economy;

• tendency to unloading of electrical load schedules;

• increased demand for reactive power (industry);

• poor organization of instrumentation (low-power consumers);

• the need to maintain preferential prices for the population.

b) On the supply side (manufacturers and suppliers):

• a combination of a poor investment climate, high investment risks and an emerging energy shortage;

• lack of peak generators (especially in the European zone);

• critical depreciation of fixed assets of energy enterprises;

• the need for high costs in system reliability and reliability of power supply;

• high losses in the transmission of electricity (especially in regional networks).

The introduction of energy management mechanisms allows you to get effects at all levels of the economy, as illustrated in table 1.2.

It is important that at the same time, increasing energy efficiency and developing generating (network) capacities of a company are considered as complementary ways of energy supply to consumers. The saved energy acts as an additional resource replacing the generation (transmission) of new plants. As a result of the active influence on the formation of demand for energy and power, the energy company is able to provide additional energy needs in any sector of its region with minimal costs [23, 24].

Generation companies will also benefit from demand management in the form of the opportunity to postpone risky investments in new capacities for a while, save operating costs, expand financial opportunities to eliminate depreciation and increase the technical level of power plants operating in this region (power system). Therefore, they should also participate in the financing of CCPs developed and implemented by electric grid companies and receive a certain share of the economic effect of this contribution (in the form of profit on capital).

The fundamental rule of economic incentives: the amount of savings (income) of the consumer from participating in the CCP should exceed all costs necessary to change the load mode (boosting production during off-peak hours, adjusting schedules, organizing night shifts, etc.). At the stage of launching and mastering the CCP in the regions, the best option is when these costs are fully reimbursed by the operator company.

Barriers to effective implementation of DSM programs. Reducing the cost of electricity consumption can potentially lead to a large-scale effect at the level of the national economy, but not all electric power entities are interested in reducing the cost of electricity supplied. Mainly not interested in reducing the cost of electricity [1–4, 22, 25]:

– electricity suppliers: their profits directly depend on the revenue for the supplied electricity;

– representatives of the electric grid infrastructure (their electricity transmission tariffs are related to the general level of electricity consumption tariffs, a decrease in the latter will negatively affect the dynamics of the annual indexation of transmission tariffs);

– energy retail companies (the dynamics of indexation of sales markups is tied to the general level of tariffs for electricity consumption).

Table 1.2 – Directions of the economic effect of demand management for electricity at various levels of the economy

Level, economic the system	Effects
State level	Improving energy security through the release of an additional reserve of generating capacities Improving the energy efficiency of the national economy by reducing the energy costs of all end consumers Reducing the budget load by reducing budget spending on subsidizing consumer spending Increased budget revenues due to the release of energy fuel and the possibility of its export Improving the environmental safety of energy by reducing industry emissions into the environment
Electricity Consumer Level	Reduction of energy tariffs due to equalization of the daily schedule and reduction of losses in electric networks. Improving the quality of electricity, which positively affects the stability of power receiving equipment and the quality of products. Increasing the availability of connection to electric networks due to the release of electric network capacities.
The level of power industry entities	Reduced investment costs in the generating complex due to reduced demand for electricity consumption Reducing fuel costs in the generating complex by reducing the required fuel reserves Reducing operating costs in the generating complex by reducing the volume of required generation and extending the life of the generating equipment Decrease in investment costs in the electric grid complex due to the release of demand for transmission line capacities and extension of the service life of electric grid and switching equipment Reducing operating costs in the power grid complex by reducing the volume of required repairs, reducing accident rate, increasing the life of power grid equipment Improving the reliability of equipment at the ECO level Increasing the operating life of equipment at the ECO level
Level of related industries	Lower prices for primary energy resources (coal, gas, fuel oil) due to reduced demand from the energy sector Development of innovative products (hardware and software) aimed at managing demand for electricity consumption in industrial enterprises

The economic interests of other subjects of the electric power industry, which influence the processes of electric energy circulation and demand management, will not be infringed upon by introducing the SEPS mechanism and lowering the prices of electricity supplied.

Regulatory, economic and technological barriers can be distinguished.

Regulatory barriers are obstacles to the development of demand management, due to the peculiarities of the legislation, the structure and rules of the market and the actual demand management programs. The main regulatory barriers include the lack of a direct relationship between prices in the wholesale and retail markets, difficulties with developing a methodology for measuring and verifying the volume of load reduction, the fear of consumers being able to manipulate the market (overstating basic consumption to increase profits from participation in demand management programs), lack of predictability and reliability of consumer resources, lack of consensus in assessing costs and effectiveness. The involvement of retail consumers may be difficult or impossible due to the state tariff policy, which strictly determines electricity tariffs for such consumers. A poorly designed demand management program (inadequate technical requirements, insufficient economic incentives, etc.) does not cause enough interest from consumers.

Economic barriers are situations where financial incentives for infrastructure organizations, aggregators, or consumers are insufficient to develop demand management programs. These include inaccurate price signals that can lead to consumers unloading during periods of low electricity prices or loading during periods of high prices, as well as cases where the benefits of participating in demand management programs are insufficient to attract consumers.

Technological barriers include the insufficient equipment of consumers' electrical installations with systems of intelligent electricity metering, the lack of cost-effective supporting technologies, which include, first of all, various automation and automation tools that allow efficient consumption management, as well as insufficient interoperability and lack of open standards.

Among other obstacles, an important role is played by the lack of consumer awareness of demand management programs and risk aversion, which manifests itself in the fact that it is more important for the consumer to reduce the risk that his electricity bill will increase than to profit from participation in the demand management program [25, 26].

1.4. Concept of functioning of aggregators of distributed energy resources

Demand management is based on fairly simple ideas. The first idea is that from the point of view of the balance between production and consumption there is no difference between the change in load and the change in generation - that is, the change in load among consumers can be used to ensure a balance. The second idea is that conditions may arise in the energy system when a decrease in consumption is more economically justified than an increase in the production of electricity by power plants - that is, it is sometimes advisable to use a change in the load of consumers to ensure balance .

The ability to manage consumption is not fundamentally new and was discussed at the initial stage of the formation of electric power systems. However, only in recent decades, demand management has become truly massive, thanks to the development of information technology and telecommunications, the automation of technological processes, and the development of energy markets.

One of the fundamental limitations of traditional electricity markets is the inelasticity of demand - electricity consumption is virtually independent of market prices. Under these conditions, electricity producers are the active side determining the final cost of production. At the same time, consumers, including those with their own generating facilities, have significant potential for changing consumption in response to changing market conditions, the use of which could affect electricity prices, increase market competition, and reduce the need to build excess generating and network capacities [8, 9, 24, 29–30].

The participation of large wholesale market consumers in demand management is achieved by opening various market segments for their participation - i.e. the creation of conditions enabling them to compete with generating facilities, and related economic incentives. The implementation of demand management programs usually begins with the involvement of such consumers, but their participation potential is usually limited: there are relatively few such consumers and, being qualified participants in the electricity market, they are already using flexibility potential of its consumption for cost optimization and prior to the implementation of mechanisms for explicit demand management. At the same time, significant demand management potential is on the side of small, including retail, electricity consumers.

Organized electricity markets usually have minimal quantitative requirements for the capacity of participants' equipment. Consumers of the retail (and sometimes wholesale) market on an individual level do not satisfy such requirements. Direct interaction between small and medium-sized consumers and interested infrastructure organizations (such as a system operator) remains impractical, since the costs of such interaction are too high relative to the small amount of unloading provided by these consumers.

There are known mechanisms that will allow them to sell their demand management resource in the wholesale market. For this, it is necessary to create specialized organizations - aggregators of demand management. A variant of this solution may be the creation of specialized organizations - load aggregators. Load aggregators are suppliers of goods and services in the wholesale electricity market that manage (directly or indirectly) the equipment of a group of consumers in order to sell the aggregate of regulatory abilities of consumers as a single object on the market [3].

Load aggregators can be independent companies or electricity suppliers (distribution companies). The aggregator searches for consumers who are potentially capable of changing consumption without sacrificing the technological cycle, evaluates the unloading opportunities available to consumers, develops optimal algorithms for participation in demand management programs, and equips consumers with the necessary automation tools, instruments and devices. The load aggregator enters into agreements with consumers of the retail market for the provision of services to change the load of their equipment by a predetermined amount, the number of times specified by the agreement according to a notice issued in advance. The aggregator receives signals for changes in consumption (in the form of load schedules, dispatch teams, etc.) from infrastructure organizations in accordance with all the requirements on the wholesale market, distributes the necessary amount of unloading between consumers and informs them in a convenient format - an email, SMS, phone call or remote signal directly to the equipment control system. The consumer load changes by a predetermined amount over a given time interval. The aggregator receives payment in the electricity and capacity market (or system services) for reducing electricity consumption. The consumer receives payment for services to change consumption from the aggregator.

Aggregated Demand Resource (Aggregated Demand Resource) - a group of independent consumers providing goods and services of demand management as a single resource of demand management. Aggregators unite many consumers with different characteristics, ensuring compliance with market requirements and redundancy of an individual consumer as part of an aggregated facility, which increases overall reliability and reduces risk for individual consumers [31, 32].

If the aggregator can combine this resource with the resources of other consumers, it can provide their capacity in accordance with the requirements of the market, ensuring that the needs of the consumer are taken into account [3]. Aggregation can achieve a level of efficiency sufficient to meet the requirements of various market segments, and can provide characteristics that correspond to generations and even exceed them. One of the key advantages of aggregation is the distributed nature of the aggregated load, which ensures the delivery of the declared unloading volume by the aggregator even if individual consumers have not fulfilled their obligations (the aggregator never announces the full volume of unloading of the aggregated load on the market, for example, if there are a collection of consumers ready to unload 100 MW, he will declare on the market 70-80 MW, which guarantees reliable performance of obligations) [31].

The aggregator may be an electricity supplier or an independent company. Practice shows that in some markets in the USA more than 80% of demand management volume is provided by independent aggregators (82% in PJM according to 2015 data), despite the fact that suppliers can also act as aggregators. The admission of aggregators to direct participation in the work on the market in the absence of requirements for their joint participation with suppliers or sales companies is considered as one of the most important factors for the successful implementation of demand management in PJM [8]. Similar trends are observed wherever independent aggregators are allowed, including Ireland and Western Australia [9]. The success of independent aggregators depends entirely on the effectiveness of the participation of aggregated loads in demand management programs. This is the main business of the aggregator. Independent load aggregators have a greater financial incentive to engage the maximum number of consumers in demand management. Electricity providers can reliably provide demand management services, but they often receive multidirectional financial incentives [29].

Aggregators combine many consumers with different characteristics, ensuring compliance with market requirements and redundancy of a single consumer as part of an aggregated facility, which increases overall reliability and reduces risk for individual consumers.

Thanks to the demand management aggregator, the retail consumer gets the opportunity to influence the balance of supply and demand in the wholesale market, without becoming the subject of the wholesale market, not understanding its rules, and not carrying out difficultly regulated operational interaction with commercial and system operators. In other words, the aggregator converts the ability of the consumer to change consumption at a certain point in time into goods and services in the markets of electricity, capacity and system services.

The work of aggregators requires a number of very specific competencies that are unique to this type of activity. For example, an aggregator should have significant knowledge of industrial technologies and experience, allowing to identify sources of flexibility in various industries, types of equipment and processes, as well as the limitations of this flexibility in order to ensure compliance with the identified flexibility with specific market needs. Consumers often do not know the real potential for the flexibility of their consumption and therefore need expert support. In addition, aggregators have the technical ability to provide the physical connection of consumers and combine their load into a single cluster. This activity assumes the presence of a complex communication infrastructure and a centralized IT system capable of managing a large set of loads with various properties [31].

Electricity providers may not have such competencies and means of involving consumers. At the same time, it is inexpedient for consumers who pay electricity at a tariff that includes the cost of the supplier's services to pay for the development of the relevant expertise by the supplier [7]. Aggregating the load of retail consumers requires a complex communication infrastructure and a centralized IT system that can manage a large set of loads with various properties. The creation of aggregators as a new function in the electricity market is a key impulse that ensures the growth of the volume of controlled demand, the attraction of private investment and the growth of competition [30].

Conclusions to the chapter 1

1. The analysis allows us to conclude that in the practice of daily activity of enterprises, tools for managing demand for electricity today have not yet found wide application. However, the existing model of the wholesale and retail electricity markets allows enterprises, through flexible management of their own energy consumption load, to align the demand schedule for electricity within the energy system and reduce their own costs for purchased electricity.

2. The main goals of managing demand for electricity are to reduce the peak load in the power system, which is necessary both to reduce prices on the electricity market and to prevent excessive capital-intensive construction of peak power plants and electric networks, emergency control of the power system and integration of renewable energy sources. Demand management is also seen as one of the tools to transition to a low-carbon economy.

3. Benefits from the introduction of demand management mechanisms can be represented in the form of avoided costs (i.e., costs that were avoided) for power, electricity, network construction, in reducing the environmental load and other benefits associated with increasing the flexibility of energy system management. Since the eliminated costs cannot be directly measured, to assess the benefits of demand management, it is necessary to make assumptions about the volume of such costs in the absence of demand management mechanisms, which leads to the appearance of estimation uncertainties.

CHAPTER 2. MODERN DECENTRALIZED (DISTRIBUTED) ELECTRICITY GENERATION SYSTEMS

2.1. Microgrid as modern local power supply systems

In the early 20th century, the centralization of electricity production made huge progress, enabling significant economies of scale and improved power plant efficiency. The 21th century is encountering new challenges that decentralized solutions such as microgrids could help to tackle.

The energy transition encompasses many challenges which are described below. The first one will be a growth of the worldwide energy demand.

According to the International Energy Agency (IEA) the world's electrical energy demand is expected to increase by approximately 40% by 2030 (compared to 2012 [6]), considering the reduction of consumption resulting from energy efficiency efforts. Of course, the short-term evolution might vary according to economic conditions and regions. However, the global trend is driven by significant factors such as:

– demographics: 18% growth by 2030, mostly in developing countries, ultimately reaching 7.1 billion people;

– access to energy for developing countries;

– the ever-growing number of new electrical appliances;

– the expected move of some energy usage toward electricity (for example, electric vehicles);

– the growing global urbanization that shifts where additional energy is needed and the necessary expansion of grid infrastructure.

Energy demand is growing and the paradox is that CO_2 emissions must decrease. CO_2 emissions from electricity generation account for 45% of world energy-related emissions. Carbon emissions from electricity generation depend on both the quantity of electricity produced and the generation mix (or types of sources used). The quantity of electricity is directly related to demand for energy, which is expected to increase globally. Therefore, reducing the amount of CO_2 emitted would require a change to the energy mix in favor of "cleaner" sources.

Moreover, in isolated areas, inhabitants rely primarily on diesel generators and spend a considerable amount of money importing fuels making renewable generation a cost-effective alternative.

In some developed countries, the power grid is aging and has little resilience in the face of disruption or instability, especially those presented by severe weather. The number of power outages lasting more than an hour has increased steadily for the past decade. This is particularly problematic in the US [33] where, according to the US Department of Energy, blackouts cost American businesses more than $100 billion per year, with weather-related disruptions costing the most per event. A main cause of the increasing number of blackouts associated with weather events is aging infrastructure: In the last five years, 68 to 73 percent of all major outages were due to weather and their impact is expected to increase in the future. Even if most interruptions in energy supply are created by local events, the impacts often lead to national or international issues. Need of resiliency is a key expectation but access to energy is a basic human right.

An estimated 17% of the global population–around 1.2 billion people did not have access to electricity in 2013 due to the lack of, or inadequate, infrastructure. In addition, many more people have an energy supply that is unreliable or of poor quality. The bulk of those living without electricity (95%) are in sub-Saharan Africa and developing Asian countries, predominantly in rural areas. Access to modern energy may be a crucial factor to achieving several United Nations Millennium Development Goals, enabling the poor in developing countries to engage in the productive use of energy, and thereby leading to an improvement in their living conditions [6]. Decentralization could help tackle these energy challenges of the 21st century by creating an optimized way to access reliable, green, and resilient energy.

Energy industry predictions include an increase in electrical energy demand, improved access to energy globally, and the reduction of CO_2 emissions and fossil fuel energy. These, as well as the need for increased resiliency, are driving a new energy ecosystem: microgrids. These are local and independent energy supply systems, usually based upon multiple energy sources. Therefore, microgrids could be one of the keystones for the energy transition [33, 34].

Decentralization is one major development that could help address the energy challenges of the 21st century. In the early 20th century, the centralization of electricity production made significant progress, enabling economies of scale and improved plant efficiency. Twentieth-century centralization also increased the overall use of electrical power. Today, however, the situation has evolved considerably and utilities need to provide more and cleaner energy to a larger number of people, with high resiliency.

Major technical and economic changes have also occurred–the energy market has changed dramatically in the last 10 years alone. There has been substantial progress in decentralizing energy resources, such as solar energy and battery storage systems. The IoT (Internet of Things) is operational, driving new cooperation and optimization capabilities. These factors enable the emergence of new energy ecosystems such as microgrids, which offer a way to tackle our energy challenges.

Microgrids contribute to the energy transition by providing practical and accessible answers to improve energy reliability, resiliency, energy accessibility, energy independence, green energy safety, energy cost optimization, energy flexibility, and the ability to participate in demand response or grid-balancing programs [33–36].

Energy resiliency can be achieved through the microgrid's ability to island itself from the main grid and to be self-sufficient.

When the main grid encounters disruption or instability, the microgrid is quickly decoupled and continues to deliver energy from local energy sources. With the microgrid's local management system, load priorities and control strategies may be optimally managed and adjusted. In addition, when the risk of instability is predictable (such as when severe weather is forecasted), the microgrid can be prepared by intentionally adopting a precautionary strategy (like reducing non-critical loads and charging the battery storage) to increase the future resilience of the system. If one of the distributed energy resources (DER) experiences a problem or undergoes maintenance, the microgrid enables the possibility of back-up using autonomous and dynamic reconfiguration.

Energy cost optimization can be achieved through the capability of the microgrid control system to use the best mix of resources such as energy storage, demand- response programs, or grid-balancing services.

To enable self-consumption of green energy, local renewable sources can be used to displace all or part of the energy consumed from the main grid or local fossil fuel generators–helping reduce energy-related greenhouse gas emissions. Adding local energy storage can help further maximize the use of this resource by storing the renewable energy during the daylight (solar), and consuming the stored power at night when solar is not operating.

Secondly, it is possible to use microgrids as a flexible, distributed energy asset. For example, the microgrid can participate in demand response or grid balancing by optimizing the local generation, energy storage, and load management schedules to comply with a curtailment or ancillary services request–while taking customer constraints and utility tariff rates into consideration.

Microgrid control enable to integrate affordable renewable energy, boost safety, reduce CO2 emissions, and lower fuel costs [33–35].

In many cases, a nation's energy needs are met by importing petroleum to satisfy demand. The diesel fuel used for electricity generation creates substantial CO_2 emissions and a high dependency on fuel imports that impact local economies. For example, in the islands of Tonga, about 97% of total generation currently comes from diesel gensets. That represented about 12 megaliters (3.2 million gallons) of fuel in 2012. Only the remaining 3% of generation comes from PV. Microgrid technology can drastically improve situations like this by providing smart power and energy management capabilities that enable a higher penetration of renewables, which until recently were limited by stability and variability problems.

Microgrids enable access to energy at a reasonable cost, when in a remote area or far from the main grid, through the microgrid's self-sufficiency.

Microgrids could drastically accelerate deployment of smart grids to remote areas and increase access to energy in developing countries. Smart grid implementation is complex and calls for considerable adaptation of grid infrastructure, which will take time. Microgrids are a near-term alternative to demonstrate the potential of smart, distributed energy systems now. In developing countries that lack an energy network, decentralization of local renewable sources could be inspired by the expansion of mobile telephony, which can overcome the obstacle of investment in communications infrastructure. Similarly, in the short term, basic microgrids can provide pragmatic solutions for producing and delivering energy.

Micro grid Architecture and components [33, 36]

A micro grid may comprise part of MV/LV distribution systems and clustered loads that are served by single or multiple DERs. From the operation perspective, a micro grid may operate with a point of common connection (PCC) to the rest of the area's electric power system and/or seamlessly transfer between two states of the grid-connected and an isolated grid (IG) mode. While physically connected to the main grid, the operating and control mode of the micro grid may shift between a grid-dependent (GD) mode or a grid-independent (GI) mode (autonomous mode) depending on power exchange and interaction of the micro grid with the backbone system.

A. Distributed Energy Resources.

Distributed energy resource systems are small-scale power generation technologies used to provide an alternative to or an enhancement of the traditional electric power system. DER, including distributed generation (DG) and distributed storage (DS), are sources of energy located near local loads and can provide a variety of benefits including improved reliability if they are properly operated in the electrical distribution system. Micro grids are systems that have at least one distributed energy resource and associated loads and can form intentional islands in the electrical distribution systems. Within micro grids, loads and energy sources can be disconnected from and reconnected to the area or local electric power system with minimal disruption to the local loads.

B. Distributed Generation (DG).

Distributed Generation units are small sources of energy located at or near the point of use. DG technologies typically include photovoltaic (PV), wind, fuel cells, micro turbines, and reciprocating internal combustion engines with generators. These systems may be powered by either fossil or renewable sources. Some types of DG can also provide combined heat and power by recovering some of the waste heat generated by the source such as the micro turbine. This can significantly increase the efficiency of the DG unit. Most of the DG technologies require a power electronics interface in order to convert the energy into grid-compatible ac power. The power electronics interface contains the necessary circuitry to convert power from one form to another. These converters may include both a rectifier and an inverter or just an inverter. The converter is and contains the necessary output filters. The power electronics interface can also contain protective functions for both the distributed energy system and the local electric power system that allow paralleling and disconnection from the electric power system. These power electronic interfaces provide a unique capability the DG units and can enhance the operations of a micro grid.

C. Distributed storage (DS).

Distributed storage technologies are used in micro grid applications where the generation and loads of the micro grid cannot be exactly matched. Distributed storage provides a bridge in meeting the power and energy requirements of the micro grid. Storage capacity is defined in terms of the time that the nominal energy capacity can cover the load at rated power. Storage capacity can be then categorized in terms of energy density requirements (for medium- and long-term needs) or in terms of power density requirements (for short- and very short-term needs). Distributed storage enhances the overall performance of micro grid systems in three ways.

First, it stabilizes and permits DG units to run at a constant and stable output, despite load fluctuations. Second, it provides the ride-through capability when there are dynamic variations of primary energy (such as those of sun, wind, and hydropower sources).

Basic Microgrid architecture is shown in figure 2.1. This consists of a group of radial feeders, which could be part of a distribution system or a building’s electrical system. There is a single point of connection to the utility called point of common coupling. Some feeders, (Feeders A-C) have sensitive loads, which require local generation. The noncritical load feeders do not have any local generation. In our example this is Feeder D. Feeders A-C can island from the grid using the static switch which can separate in less than a cycle [33, 36]. In this example there are four microsources at nodes 8, 11, 16 and 22, which control the operation using only local voltages and currents measurments. When there is a problem with the utility supply the static switch will open, isolating the sensitive loads from the power grid. Feeder D loads ride through the event. It is assumed that there is sufficient generation to meet the loads' demand. When the Microgrid is grid-connected power from the local generation can be directed to feeder D.

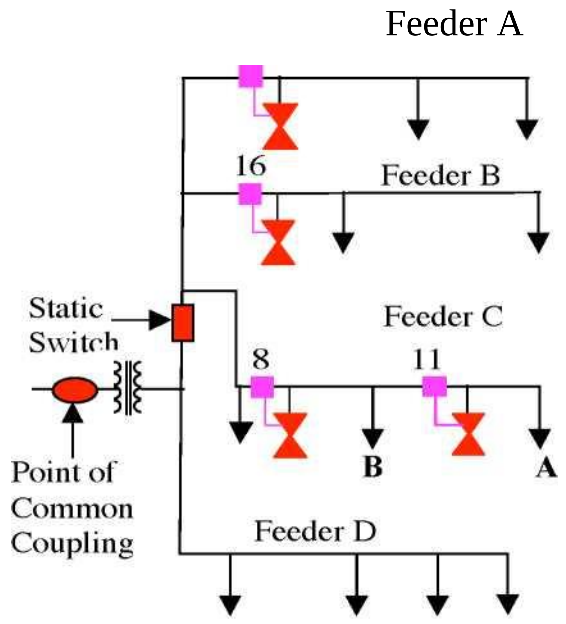


Figure 2.1 –Basic Microgrid architecture

2.2. Analysis of the features of the construction and functioning of modern dispersed generation systems

Electricity supply systems with sources of dispersed generation – distributed electric power systems (DEES) are unified electric power complexes, which include the production, conversion and distribution of electric power to power consumers [33–35]. These systems are distinguished by comparability (comparability in size) of the power of sources and consumers of electricity, significantly shorter cable lines and, therefore, a significantly greater interaction of all elements of the electrical system. For example, when you turn on a powerful consumer, when starting an asynchronous motor, the voltage and frequency in DEES noticeably change, which in turn affects the nature of the work of all other consumers. DEES can receive power from the power system or from its own sources. The main features of DEES in the mode of operation from its own sources are:

- the commensurability of the capacities of sources and receivers of electricity;
- sharp alternating daily and seasonal load schedules of power plants;
- the presence of consumers with different requirements for indicators of the quality of electricity (ICE).

In the mode of operation of DEES from a general-purpose power system, the main features include:

- insufficient reliability of power supply to DEES consumers from the power system and a long break in the power supply;
- the effect of lengthy transients associated with lightning overvoltages and short circuits in the supply circuits on the operation of responsible consumers of DEES ;
- a decrease in the static and dynamic stability of the power system associated with a decrease in power reserve.

An overview of the various types of decentralized power generation systems is given in table 2.1 [33–36, 37].

According to these features, the use of DEES leads to the need in the process of their creation and operation to solve a complex of problems, the main of which are:

- the problem of technical and economic efficiency of DEES when they operate from their own power plants at common (unit) loads;
- the problem of improving the ICE in established and transient modes;
- the problem of overcoming the maximum load without overstating the power and reducing the resources of power plants;
- the problem of static and dynamic stability of DEES in various modes of

operation;

- the problem of electromagnetic compatibility (EMC) of power receivers with different patterns of electricity consumption in a limited power system and stabilization of ICE in various modes of operation of DEES;

- the problem of compatibility of such systems with a general-purpose power system dilation of physical processes occurring in the power circuits of the system, and physical modeling of the main functional elements and nodes, providing an assessment of the reliability of the correctness of the decisions made.

Thus, in the synthesis of DEES structures, it is necessary to take into account the influence on the operational and technical characteristics of the system of values of indicators of performance criteria.

As a rule, indicators of the criterion of economic efficiency (capital investment, operating costs and unit costs per unit of capacity) are the main ones in the design of DEES. The value of these indicators increases significantly if the system is subject to increased requirements for uninterrupted power supply, reliability indicators of functional elements, quality of electricity, efficiency and overall dimensions.

Uninterrupted power supply provides for the presence of two or more sources of electricity, and reliability, in addition, provides for the creation of a reserve of functional elements, nodes, blocks, which, as a rule, are automatically included in emergency operation. The main indicators of the reliability of DEES are the availability factor, the likelihood of uptime and uptime to the first failure.

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Reliability indicators and operational indicators of DEES will significantly improve with modular aggregation of the main functional elements.

Table 2.1 – Connection of system components with WGs and their integration into the network

	Onshore wind farms	Offshore wind farms	Photovo-ltaic Power Plants	Micro-turbines	Fuel cells	Power plants on the Stirling engine	Power plants on piston engines	Steam Cycle Power Plants
Power, kWt	10–3000	3000–6000	<1–100	25–500	5–3000	2–500	50–25000+	10000
Installed costs per 1 kW	950–1500	1100–1650	6000 – 10000	1000–1800	1000–2000	До 1800	250–1500	1000–2000
Operating costs per 1 kW	No	No	Ho	Low	Nearly are absent	low	Low enough	Low enough
On-Demand Availability	Low	Low	Low	High	High	High	High	High
Market status	There are and are widely used	There are and are widely used	there is	There is, come in commercial use	there is	There are new introductions	There are and are widely used	There are and are widely used
Sphere application	Clean energy in remote areas	Clean energy in remote areas	Pure energy, main load	Cogeneration, peak demand backup system	High-quality main load power supply	Cogeneration, peak demand backup system	Reserve peak consumption system	Cogeneration
Fuel	–	–	–	Natural gas	Natural gas	Any heat source	Natural gas, diesel, biofuels	Natural gas, diesel, biofuels

Requirements for the quality of electricity, characterized by stability and the form of voltage, current, duration and nature of transients, are determined by consumers and practically have a significant impact, as well as reliability indicators and economic indicators of DEES.

The design features and circuit decisions of the system depend on the quality of the generated electricity. In addition, increased requirements for power quality indicators, as a rule, lead to a significant deterioration in weight and size indicators, reliability indicators and efficiency of static converters and stabilizers of electric power parameters.

The efficiency criterion, evaluating the overall dimensions, covers both the installed mass and volume of the functional element, unit, block, subsystem, system, and their specific weight, as well as the volume per unit of installed capacity.

The efficiency of the source, electric power converter, other elements and DEES in the complex determines the efficiency of energy conversion and transmission. At the design stage, the value of the DEES efficiency should be calculated for all its operating modes, the determining factor is the efficiency of the main operating mode, the mode, which has the longest time interval for the operation of the system. Improving the efficiency of DEES can be achieved through the use of a new power element base in its structure, as well as through the introduction of local and central control and protection systems, the operation of which is ensured and controlled by computers containing specially developed software.

In the formation of the main tasks of constructing a DEES, it is necessary to select sources, converters, switching equipment and parameters of electricity (nominal value of power and voltage, type of current, frequency, number of phases), taking into account the observance of safety rules, which also affect the operational and technical characteristics of the system.

2.3. Renewable energy integration and component interconnection

Integration is the introduction at the system level of DER (stations of decentralized generation of electricity) into the territorial public grid. Important integration issues are [37]:

- construction of security systems;
- use of power electronics devices;
- reliability modeling;
- ensuring the quality of electricity;
- connection standards;
- modeling, including computer modeling.

The interconnection of the components of decentralized power generation systems can be independent of the network, with parallel connection to the public network and combined, combining both of the first methods. With a combined connection of components in the event of a network failure, the virtual power station is disconnected from the public network, and its internal network continues to operate independently, forming an “island” (isolated mode of operation).

The DER is connected and disconnected by a circuit breaker on the generator side of the main power transformer (main switch). Depending on the power of the power plant, the circuit breaker on the mains side of the transformer can be replaced by a circuit breaker. According to the classification, only according to electrical characteristics, three types of dispersed generation systems are distinguished: synchronous generator; asynchronous generator; inverter.

The first two types are traditional technology based on electric machines with a rotating rotor. The latter type combines systems using converters based on modern power electronics. From the point of view of the methods for interconnecting the components of the wind farm, these three types are characterized by different effects on the public utility network. Requirements for the interconnection of DER components: requirements on the part of energy supply companies that guarantee the reliability of electricity supply, safety, and quality of electricity. These requirements may include protective relay requirements, power quality requirements, the study of power flows, and system analysis.

Over the years, the electricity industry has evolved in such a way that electricity was mainly generated by powerful centralized power plants, transported to consumption areas via power lines, and delivered to consumers via passive distribution infrastructure with low voltage levels. In this system, the power flows had only one direction: from a higher voltage level to a lower voltage level.

The following main features are characteristic of dispersed systems with a large number of decentralized electricity production facilities:

- voltage profiles change as you move through the network depending on the electricity produced at the voltage levels of consumption, which leads the behavior to be different from the standard;
- Transient voltages appear as a result of connecting or disconnecting generators or even as a result of their operation;
- short circuit levels increase;
- Electricity losses vary depending on production and load levels;
- overload in the branches of the system depends on the levels of production and load;
- the quality of electricity and the reliability of its supply are reduced;
- consumer-side protection systems are coordinated with similar systems on the generator side.

When solving the above problems, it is necessary to take into account the fact that the existing design standards of networks and regulatory documents are based on the old unidirectional model. To ensure reliable operation of the power supply system will require several systems for their maintenance. In addition to the actual production of electricity, centralized power supply plants usually have the following services that provide electricity to the network: power management; frequency management; monitoring the load; voltage control; ensuring the availability of power.

The problem of parametric and structural optimization of DER can be presented as a multicriteria (vector) problem of optimization of several partial target (scalar) functions (quality criteria) with restrictions on both the set of variable parameters and optimized functions [37, 38]:

$$\begin{aligned} & F_{opt}(X^*) \to \text{opt};\; F_{opt}(X^*) = (F_{opt,1}(X^*), \\ & F_{opt,2}(X^*),\ldots, F_{opt,k}(X^*)); \\ & X^* \in \Omega^*; \quad X^* = (X^*_1, X^*_2,\ldots, X^*_n); \\ & H_{opt}(X^*) = 0; \\ & H_{opt}(X^*) = (h_{opt,1}(X^*), h_{opt,2}(X^*),\ldots, h_{opt,l}(X^*)); \\ & G_{opt}(X^*) \geq 0; \\ & G_{opt}(X^*) = (g_{opt,1}(X^*), g_{opt,2}(X^*),\ldots, g_{opt,m}(X^*)); \\ & \Omega^* = \{ X^*: x_{a,i} \leq X^*_i \leq x_{b,i},\ i = 1,\ldots,n \}, \end{aligned} \tag{2.1}$$

where $F_{opt}(X^*)$ is the objective function; X^* is the vector of optimized parameters; $H_{opt}(X^*)$, $G_{opt}(X^*)$ – functions that impose restrictions on the scope of variables; $x_{a,i}$, $x_{b,i}$ – the limits of change are optimized parameters that define space. Vector functions X^*, $F_{opt}(X^*)$, $H_{opt}(X^*)$, $G_{opt}(X^*)$ are formed on the basis of component, signal and topological sets, characteristics of the system and corresponding functional operators.

An important component of the solution of problem (2.1) is the minimization of the amplitude and the effective value of the current taken from the generator [38]. This task actually involves minimizing the components of the Frize power by changing the operating modes of the loads. In some cases, compensation of the components of the Frieze Q_F power can be achieved by changing the operating modes of the loads in the system. Let us consider the principles of controlling a system consisting of a generator with voltage $u(t)$ with period T and parallel connected loads, of which n’ controlled and m’ uncontrollable. By load control we mean the ith load with current $i_i^{(k)}(t, t_i^{(k)})$ and a period of energy processes $T_i^{(k)}$ for which a change in the temporal displacement $t_i^{(k)}$ of the conditional start of the period $T_i^{(k)}$ relative to the conditional start of the period T of the voltage generator without changing the amount of consumed active power. By uncontrolled load we mean the j-th load with current $i_j^{(н)}(t, t_j^{(н)})$ and the period of energy processes $T_j^{(н)}$, for which the value $t_j^{(н)}$, which has the same meaning with the value $t_i^{(k)}$ is unchanged. The current of the DEES generator in this case is determined from the relation

$$i(t) = \sum_{i=1}^{n'} i_i^{(к)}\left(t; t_i^{(к)}\right) + \sum_{j=1}^{m'} i_j^{(н)}\left(t; t_j^{(н)}\right). \qquad (2.2)$$

The shape of the curve $i(t)$ in (2.2) depends on the intervals $t_i^{(k)}$; therefore, their use causes changes in the levels of exchange energy and Friese power. The task of the i-load control system is to generate, by changing the intervals $t_i^{(k)}$, the current $i_i^{(k)}(t, t_i^{(k)})$ so that in a controlled section eliminate the return of energy to the generator (compensation Q) or reduce losses during energy transfer (compensation of the components Q_F, $Q_{F\tau}$).

As an example, we note that the optimization problem of minimizing energy losses in the lines and internal supports of wind farm generators has the form:

$$I_{\text{H}} = \sum_{i=1}^{n} I_i; \qquad (2.3)$$

$$P_{\text{BTP}} = \sum_{i=1}^{n} I_i^2 R_i, \qquad (2.4)$$

where I_{H} is the current taken from the DER; I_i is the current of the i-th wind farm generator; n is the number of DER; P_{BTP} – the magnitude of energy losses in the lines and internal supports of DER; R_i is the total resistance in the line and the internal resistance of the i-th generator.

To implement the optimization task of minimizing energy losses (formulas (2.1) – (2.4)) in the lines and internal resistances of DER, the following principles of controlling the distribution of loads between DER generators can be proposed:

centralized, decentralized, adaptive, democratic [37]. Centralized principle provides subordinate control of the main generator of several slave generators, the frequencies of which are synchronized with the main generator through a dedicated parallel operation interface (Master / Slaves principle).

The decentralized principle is the distributed principle of organizing the parallel operation of generators, when they are potential controllers of the information exchange channel, self-regulate according to the adaptive principle in the absence of an intermodular interface.

Adaptive principle – provides synchronization of generators in the absence of additional interface communication channels between them. Each of them monitors only its state, while adjusting its frequency. Each generator monitors its output voltage so that its phase coincides with the voltage phase of the other generator. The democratic principle – each generator is active in regulating its output current, adjusting it in such a way as to bring it closer to a specific set value (for example, to the average).

2.4. Load balancing mechanisms

The problem of uneven graphs of electrical load is well known and characteristic of most power systems. The main ways to solve it are known, among which are the creation of an optimal structure of energy generating capacities and the implementation of restrictive and stimulating measures to attract electricity consumers to align schedules [23]. In this context, the article discusses the use of the potential of distributed cogeneration energy technology sources that generate electricity based on the heat and technological load of the production of asphalt concrete mix. The global problem of aligning the graphs of the electrical load of the energy system is relevant, and in this regard, is considered by many experts [23, 24].

The power consumption mode is the change in the electrical loads of the enterprise (consumers) and its individual power consumers in time: in terms of days, days of the week, season of the year. Power consumption modes are reflected in the corresponding graphs of electrical loads and are characterized by a number of indicators, in particular:

– load factor (filling the daily schedule), defined as the ratio of the average daily load to the maximum (peak);

– annual (daily, monthly) number of hours of using the maximum load (maximum power) of the consumer; it is calculated as the ratio of the power consumption for a given period to the maximum load for this period;

– the coefficient of simultaneity of the load (or the demand coefficient), which is equal to the ratio of the combined maximum load of the enterprise to the sum of the loads of its individual power consumers [39].

The load graphs in most cases are an uneven line consisting of many segments, with peaks in the morning (8–11) and evening (18–22) hours. Figure 2.2 shows a typical daily graph of the load on the power system.

The unevenness of the load schedule becomes a factor in the growth of final prices and tariffs for electricity, because:

- it is necessary to seek investments and funds for the maintenance of additional generating capacity, as well as the capacity of networks and transformer substations, which ultimately is paid by the consumer;

- many power plants are forced to collect and reduce the load several times during the day, which increases the specific fuel consumption, reduces the operating life and, as a result, also affects the increase in prices;

- peaks in consumption, especially in the evening, in low-voltage networks lead to an increase in the risk of accidents and blackouts, a deterioration in the quality of electricity, and an increase in losses in the lines.

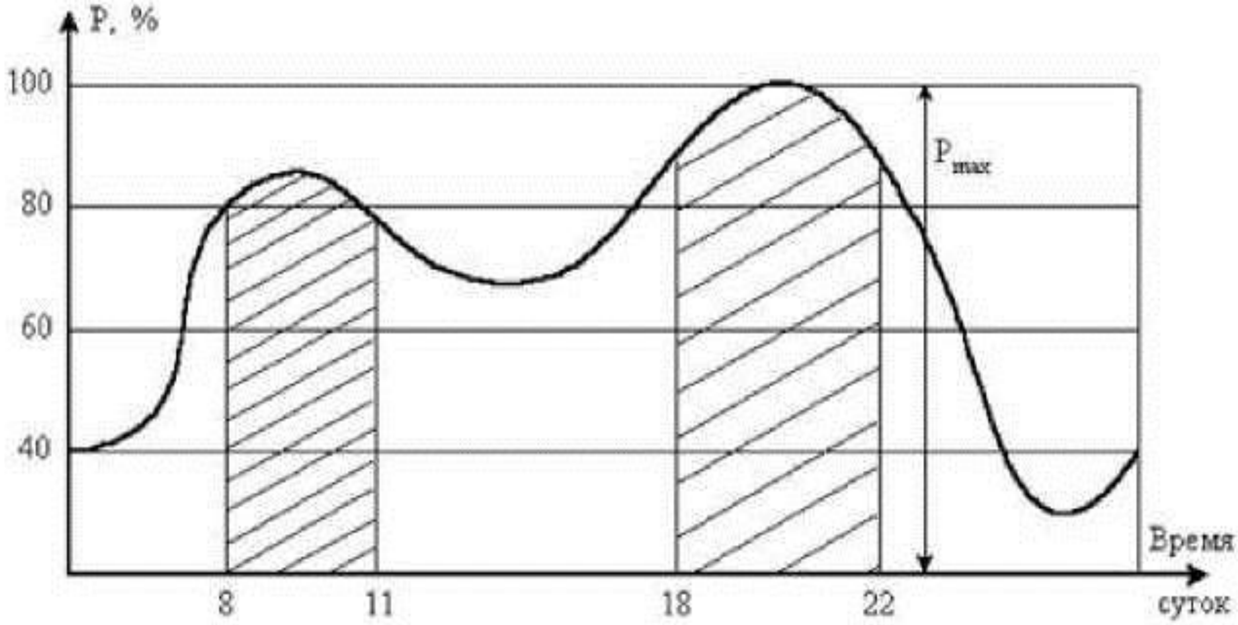


Figure 2.2 – Typical daily power system load schedule

Therefore, balancing the load schedule is an important task to reduce average prices for electric energy and increase the reliability of energy supply.

Let us analyze the load balancing graphs. The following methods exist:

1) creation of an optimal structure of generating capacities of the power system;
2) the use of flows with neighboring power systems;
3) attracting consumers to align the load schedules of the power system due to administrative (restrictive) and economic (incentive measures). The spread of the two-part tariff, the tariff differentiated by the zones of the day, and hourly prices, and some other measures stimulate the reduction of peak consumption or transfer it to other hours and days of the week.

If the method of economic stimulation effectively affects industrial enterprises, then the housing and communal complex is not fully amenable to such an impact. Not every one of us can be forced not to include an electric kettle, microwave or electric oven, TV, etc. upon arrival at home.

Regulation of the load schedule of the household complex is the most difficult task, which it is advisable to solve in a technological way. This is the most optimal way to solve the problem, because:

1) there is no need to be safe and maintain huge amounts of reserve generating capacities;

2) enterprises will cease to tie their work schedules to time with “cheap” energy;

3) generating companies will not have to react so sharply to changes and changes in energy consumption.

It is possible to install devices that accumulate energy during the hours of a night dip or on weekends and deliver it to the network or directly to the consumer during peak hours. Similarly, backup and uninterruptible power devices for computers and servers, alarm, communication and video surveillance devices, batteries in laptops and cell phones work.

Electric energy can be accumulated centrally – on the generation side (for example, the construction of a large pumped storage power plant (PSP), near thermal power plants (TPPs), nuclear power plants (NPPs), etc. Decentralized storage involves the installation of batteries directly at the consumer.

As can be seen from the analysis, you can align the graph of the electrical load in various ways. In order to get the economic effect of equalizing the schedule, it is necessary to competently approach the implementation of equalization measures, create conditions to support those consumers who use modern accumulating and generating equipment, and conduct such a pricing policy that it would be beneficial for consumers to install accumulator installations.

The search for new non-traditional methods for solving problems and equalizing peak and half-peak loads is necessary. There is no doubt that the state approach is most effective, in which the problem of covering the unevenness of the electrical load schedules can be solved in the following main ways:

– creation of an optimal structure of generating capacity of the power system,

– using overflows with neighboring power systems

– involving consumers in balancing the load schedule of the power system due to administrative (restrictive) and economic (stimulating) measures.

A typical daily schedule of electric load (SGB), which reflects the daily rhythms of society and is characteristic of many energy systems, is shown in Figure 3. Based on the presented graph, three time zones are distinguished: the zone of minimum load (night hours or night dip) with a capacity of not more than $P_{\min}$, the zone of average or half-peak load with a power of P_{hp} in the range of $P_{\min} \leq P_{hp} \leq P_{\max}$ and the zone of maximum or peak load with power no more than $P_{\max}$.

The half-peak zone is characterized by a significant one-time increase in the load in the morning hours and its deep decline at the end of the day, and the peak - near relatively small rises (to the maximum load level) and drops (to the half-peak zone) of the load in the daytime. Usually there are one or two maximums of electricity consumption: morning and evening. The first is most often associated with the morning shift of work of industrial enterprises. The second is the combination of the consumption of workers working in the evening shift with the consumption of electricity in the residential sector and the public services sector. Therefore, the second peak in magnitude always exceeds the first [23, 24].

In the general case, the daily load schedule of the power system has alternating dips, rises, falls, and peaks, which determine its generally uneven nature. This, in fact, is the sum of the daily load schedules of various consumers [40].

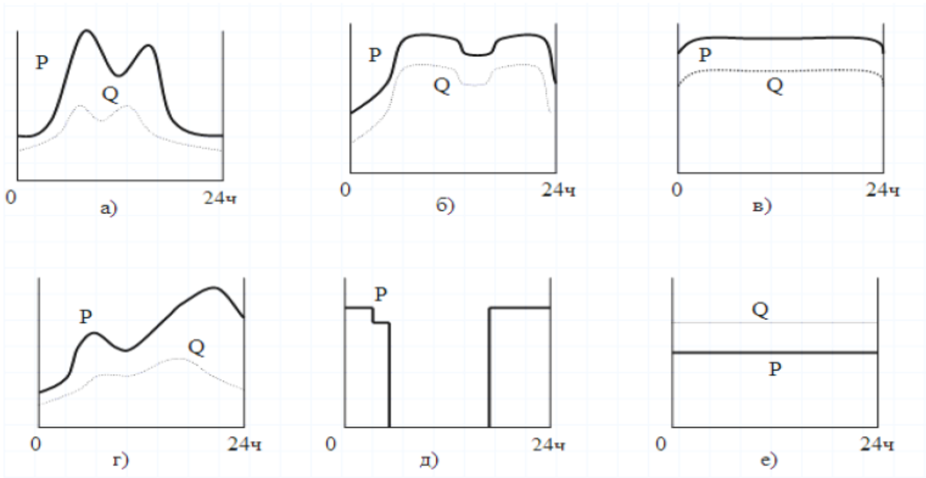


Figure 2.3 – Daily schedules of active and reactive load: a – one-shift enterprise; b – two-shift enterprise; c – a three-shift enterprise; g – utility load; d – street lighting; e – water supply and pumping stations

We especially note the following factor. The analysis of load schedules of various consumers shows that the nature of the schedule of utility loads actually qualitatively repeats the load schedule of the power system. That is, the load of household consumers has a significant impact on the overall load schedule of the power system. How important this will be shown above.

Let us dwell in more detail on the possible ways of covering and leveling the load schedule of the power system. The main law of the functioning of any energy system is to continuously ensure the balance of supply and demand for electricity by quickly covering the load schedule with the corresponding generation of electricity from generating sources with guaranteed supply to the consumption nodes. In case of violation of this law, the frequency of the alternating current network and the calculated voltage levels change in the power system, which can lead to mass blackouts of consumers or failure of generating, transmission and distribution equipment and electrical installations of consumers.

The effectiveness of covering uneven load schedules of the power system is primarily determined by the composition and characteristics of the power units of power plants in the power system. The effect of a possible equalization of the load schedule can and should be received by each of the three participants in this process: the state, the energy system, and consumers. In this regard, balancing the load schedule of the power system cannot be a spontaneous, random process, but requires targeted measures with appropriate material and financial support.

The power system load schedule is the sum of many consumer load schedules. Therefore, it can be balanced only with the help of consumer regulators, which are able to limit or transfer part of their electric load from one hours of the day to others (with daily regulation) or from working days to days off (with weekly regulation). All consumer regulators (CR) can conditionally be divided into two groups: a group of CRs that are part of the power system and implement the combined function of production and consumption of electricity, and a massive group of CRs that are outside the power system and use electricity for their own purposes.

Under the conditions of the electricity market, the difference between its supplier and consumer is erased: each of the parties, depending on current conditions, can become a supplier or a consumer. The first group of PR includes, first of all, various storage power plants. The main advantage of which is the consumption of electricity during hours of minimum load of the power system. Due to this, within the daily load schedule, a reduction in the night dip is achieved, the irregularity of the schedule is reduced, and there is no need to unload or stop large blocks of TPPs at night. The advantages can also be attributed to their highly maneuverable generation during hours of maximum load of the energy system due to the previously accumulated energy resource.

A special place belongs to PSPPs, which, unlike other stations, including TPPs and HPPs, have a double regulatory effect. So, almost the same installed power (in the generation mode and in the pump mode) is used in one case to raise the night dip of the daily load curve (when operating in the station charging mode), and in the other to cover peaks (in the discharge mode) . Therefore, such stations are one of the most effective tools for balancing and covering the daily load schedule in power systems with the predominance of large generating capacities of nuclear power plants and thermal power plants. Their efficiency is 72–75%, and nighttime electricity is used to charge the stations, which is usually 3–5 times cheaper than peak.

Let us return to the similarity of the uneven load curve of the power system with the uneven consumption of electricity in housing and communal services. This implies the following important position: the real possibility of equalizing the load schedule by using electric energy to solve the problem of energy supply of housing and communal services, in particular, centralized hot water supply of residential buildings. At the same time, it becomes possible to solve two related problems: covering the night dip and reducing the consumption of electric energy during peak hours, not to mention the social significance of solving this problem.

2.5. Experimental data approximation methods and construction of models

Approximation is the replacement of some mathematical objects by others, in one sense or another, close to the original ones [41]. Approximation allows one to study the numerical characteristics or qualitative properties of an object, reducing the problem to the study of simpler or more convenient objects (for example, those whose characteristics are easily calculated or whose properties are already known). Approximation is the same as approximation; the term “approximation” is sometimes used in the sense of an approximating object [41]. The approximation of functions is the finding for a given function ***f*** of a function ***g*** from a certain definite class (for example, among algebraic polynomials of a given degree), in one sense or another close to ***f***, giving its approximate representation.

Model (fr. Modele, from lat. Modulus – measure, sample) – any image of any object, process or phenomenon ("original" of this model), used as its "deputy," representative ". A mathematical model is an approximate description of a class of phenomena of the external world, expressed using mathematical symbolism [41]. A physical model is an approximate description of an object or phenomenon using an image that has the same physical nature.

One of the important stages of studying a phenomenon using its mathematical model is to determine whether the accepted hypothetical model satisfies the practice criterion, that is, to clarify the question of whether the results of observations are consistent with the theoretical consequences of the model within the accuracy of observations. In this regard, it is necessary to check the adequacy (correspondence to the properties of a real object) of this mathematical model, moreover, the accuracy of the model should be more than the accuracy of the observations (the error of the model should be less than the error of the observations).

Adequacy (from lat. Adaequatus - equal, equal) - conformity, fidelity, accuracy. Measurement accuracy is a measurement characteristic reflecting the degree of proximity of its results to the true value of the measured quantity.

Unfortunately, there is practically no modern literature on the general theory of approximation; some sections of approximation are described in the literature [42–45]. Conditionally, approximation can be divided into two types:

1) a rigorous theory of mathematical approximation;

2) physical (technical) approximation.

The rigorous theory of mathematical approximation includes the following approximation methods [41, 44, 45]:

1) polynomials (polynomials);

2) splines;

3) by segments of the Fourier series;

4) polynomials in orthogonal polynomials;

5) eigenfunctions of boundary value problems.

The main task of approximation theory is the problem of finding for a fixed n such a system of functions $\varphi_1, ..., \varphi_n$ for which the best approximations of functions of a given class by polynomials

$$\sum_{\kappa=1}^{n} \alpha_k \varphi_k(x) \qquad (2.5)$$

would be the smallest (the problem of the diameter of a class of functions).

A less rigorous approximation is a physical (technical) approximation or mathematical model of a physical phenomenon, process (physical model), technical device (its characteristics), signal (its parameters), environment, matter, etc. Physical (technical) approximation includes many methods of approximation and approximating functions, selected on the basis of a specific physical (technical) task.

With the help of physical (technical) approximation (for example, using expression (2.5)), a wide range of tasks that are relevant at the moment in time, related to specific problems and applied (technical) issues, are quickly solved. A rigorous theory of mathematical approximation is constructed as a fundamental, global theory of approximation, which may not be useful for solving current applied practical problems. This can occur due to either the loss over time of the relevance of the problem being solved, or the complexity of the theory (approximating function), or a large number of approximation coefficients.

Conventionally, one can compare the rigorous theory of mathematical approximation with “general”, and the physical (technical) approximation with “particular”. We give the obvious requirements for the approximating function for the technical form of approximation.

As a rule, the characteristics of many complex processes and phenomena are obtained experimentally, much less often they can be found from theoretical analysis. To study the processes, it is necessary, first of all, to display the characteristics in a mathematical form suitable for calculations. A simple and very accurate way can be to present the characteristics in a table. This method is convenient for analyzing processes using a computer; the argument and function form a two-dimensional array of numbers in the storage device. In some cases, the characteristics of real processes and phenomena have a complex form and are presented in the form of graphs.

Very often, the direct application of experimental data in the form of tables or graphs is inconvenient, and the data tend to be described using fairly simple analytical relationships, at least qualitatively reflecting the nature of the considered dependencies. In this case, it is necessary to solve the approximation problem, i.e., replace the complex function (constructed from experimental data) with approximate analytical expressions.

If the study should be carried out not by numerical, but by analytical methods, then it is necessary to select an approximating function that, being quite simple, would reflect all the most important features of the experimentally measured characteristic with a sufficient degree of accuracy.

The general approximation problem includes two independent problems:

1) the choice of the class of a suitable approximating function;

2) determination of the values included in the approximating function of constant coefficients (determination of approximation coefficients).

The choice of the class of the approximating function. Solving this problem, it is necessary to observe requirements that are largely contradictory:

1) the simplicity of the function (in the sense of mathematical operations and computer implementations);

2) sufficient accuracy (the approximation error should be of the same order with the spread of the parameters of the characteristics of individual implementations in the ensemble of implementations);

3) visibility, allowing to judge the change in the approximation coefficients when changing the characteristics of the process;

4) clarity of understanding of processes in the phenomenon and identification of properties and characteristics of interest in a particular case.

Thus, a function that approximates a characteristic is chosen either based on physical ideas about the process under study, or purely formally, based on the external similarity of the characteristic with a graphic image of a particular function. Conflicting requirements are imposed on the approximating function: providing a good approximation quality, it should be relatively simple and convenient for further use.

A good example is the method for approximating the current – voltage characteristics of a nonlinear bipolar in the form of an exponential (exponential) approximation. In radio engineering, to approximate characteristics, the following functions are most often used:

1) power polynomial (power or polynomial approximation);

2) an exponential polynomial (a special case of which is an exponential or exponential approximation);

3) piecewise linear function (approximation);

4) piecewise nonlinear function (approximation);

5) power function;

6) transcendental functions (hyperbolic tangent and sine, Gauss function, trigonometric functions, etc.).

Due to the fact that the characteristics of various implementations (ensemble of implementations) of the process differ from each other due to the scatter of parameters by implementations and measurement error, it is inexpedient to seek approximating expressions whose accuracy significantly exceeds the accuracy of determining individual parameters and the limits of their dispersion over the ensemble of implementations. Thus, when solving the approximation problem in the same way as when solving any problem associated with the choice of the computational model, it is necessary to compromise between the accuracy and complexity of the model.

The determination of approximation coefficients is closely related to the required accuracy. The accuracy is determined by the criteria of approximation; criteria of uniform, mean square and interpolation (point approximations) are usually applied. If the number of given points exceeds the number of determined approximation coefficients, then the least squares method can be used, in which the mean square error is minimal. The least squares method is used when high accuracy of approximation is required, requires cumbersome calculations, but has a constructive approach for the analytical determination of model coefficients (approximations). The least squares method provides the smallest sum of squares of deviations of the values of the approximating function from the values of the original function (the smallest residual) in an arbitrary number of points not associated with the number of unknown coefficients.

Conclusions to the chapter 2

1. Microgrids' future is difficult to predict at this stage, but it seems possible that we are moving into an era where microgrids will be the norm and not the exception. Prospective studies show that this future is technically feasible and could be a way to introduce widespread adoption of intermittent generation such as solar or wind. Microgrids could be one of the keystones for energy transition.

2. In the conditions of uncontrolled growth of world prices for fossil fuels, one of the factors restraining the growth of tariffs for electric energy in power systems with the predominance of nuclear power plants and thermal power plants is, along with energy saving, the alignment of schedules of electric loads of the power system.

3. The compilation of the electrical load schedules in daily, weekly and seasonal intervals is an interdisciplinary problem, the solution of which should be addressed by three parties: the state, the energy system, and consumers. This is due to significant investments (credit resources) in the energy sector and other energy-intensive sectors of the economy, in which there are potential consumers-regulators of load balancing. The search for alternative methods can also be very effective.

4. An effective way to equalize the network load may be to use excess electricity to organize centralized hot water supply to residential buildings. At the same time, consumers using electrical installations for heating water can become controlled by consumer regulators for electric power plants, storing energy during off-peak hours of electricity consumption and using it during peak hours, thereby aligning the schedule of electricity consumption in the energy system.

5. The analysis and classification of approximation methods for experimental data and model building were carried out. The requirements for the approximation problem are specified and formulated;recommendations are given when constructing models.

CHAPTER 3. EVALUATION OF TOTAL ENERGY LOSSES IN LOCAL ELECTRIC NETWORKS

3.1. Components of energy losses in the system

When electric energy is transferred, losses occur in each element of the electric network.

Actual (reported) losses of electricity are defined as the difference between the electricity received in the network and the electricity supplied from the network to consumers [46, 47]. These losses include components of various nature: losses in network elements that are purely physical in nature; energy consumption for the operation of equipment installed in substations and providing electricity transmission; errors in the fixation of electricity by meters; theft of electricity, non-payment or incomplete payment of meter readings, etc.

Taking into account the physical nature and specificity of methods for determining quantitative values, actual losses can be divided into four components:

1) technical losses of electricity caused by physical processes in wires and electrical equipment that occur during transmission of electricity through electrical networks.

2) energy consumption for auxiliary needs of substations, necessary to ensure the operation of the technological equipment of substations and the life support of service personnel, determined by the readings of meters installed on transformers of auxiliary needs of substations;

3) energy losses due to instrumental errors in their measurement (instrumental losses);

4) commercial losses due to the theft of electricity, inconsistency of meter readings with payment for electricity by household consumers and other reasons in the organization of control over energy consumption.

Reducing energy losses to the level established by regulatory documents can be achieved by improving the quality of electric energy in general purpose networks.

The quality of electric energy has now become a familiar and clear concept in the field of supplying consumers of electric energy.

An increase in the number and an increase in the installed capacity of power receivers with a non-linear and asymmetric nature of the load on transport, in everyday life, the development of technological installations in industry leads to a deterioration in the quality of electric energy in power supply systems and, as a result, to a decrease in the efficiency of both the power supply systems and consumers, connected to them. As a result, electrical equipment designed to operate in an electrical system at a certain level of electrical energy characteristics is, in many cases, operated in inefficient modes, which leads to a number of negative consequences [46–48]:

1) increased losses in all elements of the system;
2) increase in electricity consumption;
3) the increase in the required power of electrical equipment;
4) reduction of the service life (failure) of electrical equipment;
5) an increase in capital investment in power supply systems;
6) false alarms of relay protection and automation;
7) malfunctions of electronic control devices and computer equipment;
8) interference in the communication lines;
9) violation of the normal operation of production, defective products.

One of the factors that increase losses in networks and electric energy distribution elements is the asymmetry of currents and voltages.

The economic damage from lowering the quality of electricity resulting from the effects of current asymmetry and voltage is caused by the deterioration of energy performance and the reduction in the life of electrical equipment, a general decrease in the reliability of the operation of electric networks, an increase in losses of active power and consumption of active and reactive capacities.

Technical losses of electricity caused by physical processes occurring during the transmission of electricity through electric networks and expressed in the conversion of part of the electricity into heat in the elements of the networks.

The energy consumption for the auxiliary needs of substations, necessary to ensure the operation of the technological equipment of substations and the life of the staff. Electricity consumption for auxiliary needs of substations is recorded by meters installed on auxiliary transformers.

Loss of electricity due to errors in its measurement (underestimation of electricity, metrological losses). This component of losses is determined on the basis of data on metrological characteristics and operating modes of metering system devices. Commercial losses do not have a mathematical description and therefore cannot be determined independently. Traditionally, commercial losses are understood as theft of electricity and its underestimation due to problems in the organization of accounting for electricity consumption. The error of a particular metering device is a random variable and can take both negative (underestimation of electricity) and positive (counting electricity) values.

In DC circuits, the values of instantaneous and average power for a certain period of time coincide, but the concept of reactive power is absent. In AC circuits, this only happens if the load is purely active. With such a load in the AC circuit, the voltage phase and current phase coincide and all the power is transferred to the load [46–48].

If the load is inductive (transformers, electric motors), then the current lags the phase of the voltage, if the load is capacitive (various electronic devices), then the current phase outpaces the voltage. Since the current and voltage do not coincide in phase (reactive load), only part of the power that could be transferred to the load is transferred to the load (consumer) if the phase shift was zero.

Part of the total power S^2 ($S^2 = P^2 + Q^2$) that was transferred to the load during the alternating current period is called active power P. Power, which was not transferred to the load, but led to losses in heating and radiation, is called reactive power *Q*.

The cost of producing reactive power is lower than the cost of producing active power, but it is not economically feasible to produce the maximum amount of reactive power. The transfer of reactive power from the busbars of power plants to consumers via power grids leads to additional costs.

Reactive power has an even greater effect on voltage modes. Voltage losses due to the transfer of reactive power make up about 1/3 of the total voltage losses in networks of 6–10 kV and about 2/3 in networks of higher voltages. The resulting reduction in voltage in the network leads to an even greater increase in energy losses and a decrease in the throughput of lines and transformers. Voltage losses in transformers are almost completely determined by the transmitted reactive power. In addition to influencing the economic performance of networks, the transfer of reactive power can lead to a violation of technical restrictions on permissible voltages at nodes of energy consumption.

Reducing electrical losses in the power system is a very complex, paramount and complex problem. The solution to this problem requires significant investment, optimization of development, modernization of electricity metering systems, the introduction of new diagnostics and control systems for the power grid, raising the level of staff and providing it with modern means of checking electricity [48, 50].

In measures to reduce technical losses, there are:

- organizational measures that practically do not require additional funds for implementation;
- technical measures that require additional capital investments.

Measures to improve the electricity metering system include measures to reduce commercial losses, since the main direction of reducing commercial losses is to improve the metering of electricity supplied to the network and useful to consumers. Within this group, it is also possible to single out both technical measures that require additional investment, as well as organizational measures.

Organizational measures include: optimization of the operating modes of electric networks for voltage and reactive power; optimization of the working schemes of networks and the composition of the switched-on equipment: selection of places for opening closed circuits, redistribution of loads between substations, disconnection of part of parallel-connected equipment in the mode of low loads; line phase load balancing; improving the level of maintenance of electrical networks; reduction of electricity consumption for own needs of substations.

Technical measures include measures related to the installation of additional equipment to reduce losses: reactive power compensation; regulation of power flows in closed networks by installing longitudinal compensation devices and regulating transformers; installation of on-load tap-changers on power transformers; replacement of existing overloaded transformers and wires of power lines; the construction of downsizing lines and substations; increase in rated voltage of a network.

Networks of local systems contain a large number of asymmetric and non-linear loads and consumers sensitive to voltage level distortions. When voltage quality decreases, the working conditions of asynchronous and synchronous motors, power transformers, capacitor banks, lighting systems and other electrical equipment deteriorate, which leads to an increase in active power losses.

Load losses of active power in a network element with resistance *R* at voltage *U* are determined by the formula:

$$\Delta P = \frac{P^2 + Q^2}{U^2} \times R \quad . \qquad (3.1)$$

In most cases, the values of *P* (active power) and *Q* (reactive power) on the network elements are initially unknown. As a rule, loads at network nodes (at substations) are known. The values of these values are determined by measurements according to standard procedures, which allow to determine these parameters for different periods of loads – seasonal minimums and maximums.

The formula shows that in order to reduce power losses, it is important to take measures to reduce or limit the consumption of reactive power by consumers.

3.2. Analysis of the structure of additional electricity losses

For given P and U, the minimum value of the operating current of the generator corresponds to the instantaneous current $i_a(t) = Pu(t)/U^2$, where $i_a(t)$ is the active component of the current $i(t)$. For the square of the effective current value I^2, the relation [37, 38, 51]

$$I^2 = \left(\int_0^T i^2(t)dt\right)/T = \left(\int_0^T [i_a(t) + i_p(t)]^2 dt\right)/T = I_a^2 + I_p^2.$$

Insofar as $I_a = P/U$, then the expression

$Q_F = U[I^2 – I_a^2]^{1/2} = UI_p$.

The reasons for the occurrence of additional energy losses in the REES can be systematized in the following directions [38]:

- distortion of the quality of electricity generated by generators – many factors causing the appearance of additional losses $\{A\}$;

- the influence of the operating modes of other systems (the presence of electromagnetic interference, violation of electromagnetic compatibility) – many factors $\{B\}$;

- change in technological processes (change in modes or parameters of technological processes, in particular, change in the structure and parameters of loads) – many factors $\{C\}$.

Let the cardinalities of the sets $\{A\}$, $\{B\}$ and $\{C\}$ be determined by the quantities $n_{Φ,A}$, $n_{Φ,B}$ and $n_{Φ,C}$. Then, the appearance of additional energy losses is affected by $n_Φ = n_{Φ,A} + n_{Φ,B} + n_{Φ,C}$ factors from the sets $\{Φ\} = \{A\} \cup \{B\} \cup \{C\}$.

Suppose that for each with $n_Φ$ of the selected set of factors for the appearance of additional electric energy losses {Φ}, it is possible to single out the changes $\alpha_j[x_1^j$, ..., x_i^j, ..., $x_{ns}^j]$, j = 1, ..., n_Φ, of the signal spectrum $x(t)$ (n_s is the number of orthogonal components of the signal $x(t)$ taken into account when considering losses; x_i^j is the variable of the *i*-th orthogonal component of the signal $x(t)$ from the influence of the jth factor) [38]. Note that, for example, factors of low-quality electricity (set {*A*}) are determined on the basis of GOST 13109–97 and GOST 23875–88, etc. and are caused by processes both in the system (at the input of an individual element of the system) and in the system as a whole. The factors of the set {*B*} include energy indicators and characteristics of the electromagnetic compatibility of elements and systems, changes in operating conditions (for example, temperature), changes in the structure of DEES. The factors of the set {*C*} reflect the characteristics of various sides of the flow of technological (energy-technological) processes.

Components of additional energy losses. Behind the characteristics $\alpha_j[x_1^j, ..., x_i^j, ..., x_{ns}^j]$ is quite simple determine the appropriate component of additional electricity losses. For this, according to the characteristics of the change $\alpha_j[x_1^j, ..., x_i^j, ..., x_{ns}^j]$, j = 1, ..., n_Φ, the current values of the current $i_p(t)$ are separated as follows:

$$I_p^2 = \sum_{j=1}^{n_\Phi} I_{j,p}^2 . \tag{3.2}$$

Taking into account (3.2), the square of the Frize power Q_F at $u(t) = U_m \sin t$ is divided into a number of additive warehouses

$$Q_F^2 = \sum_{j=1}^{n_\Phi} U^2 I_{j,p}^2 = \sum_{j=1}^{n_\Phi} Q_{F,j}^2, \tag{3.3}$$

where $Q_{F,j}$ – component of additional losses from the influence of the *j*-th, j = 1, ..., n_Φ, factor.

In the general case, in accordance with (3.3) for

$$u(t) = \sum_{j_1=1}^{n_\Phi} u_{(j1)}(t) = \sum_{j_1=1}^{n_\Phi} U_{m(j1)} sin(\omega t + \varphi_{j1})$$

for n_{Φ} selected factors, the relation

$$Q_F^{\,2} = \sum_{j_1,j_2=1}^{n_\Phi} U_{j1}^{\,2} I_{j2,\text{p}}^{\,2} = \sum_{j_1,j_2=1}^{n_\Phi} Q_{Fj1,j2}^{\,2}, \qquad (3.4)$$

where $Q_{Fj1,j2}$ is the component of additional losses, which is determined by the influence of the j_1-st factor from the set {Φ} on the voltage $u(t)$ and the j_2-th factor on the current $i(t)$. And all this should take into account and reflect the counter.

When decomposing the effective values of voltage and current in the form

$U^2 = U_1^{\,2} + U_A^{\,2} + U_B^{\,2} = U_{1A}^{\,2} + U_B^{\,2}$; $I^{\,2} = I_1^{\,2} + I_A^{\,2} + I_B^{\,2} = I_{1A}^{\,2} + I_B^{\,2}$,

where the indices "*A*" and "*B*" reflect the separation of the higher harmonic components of the signals into two sets whose elements do not intersect, by analogy with the above, we can write

$$Q_F^{\,2} = (U_{1A}^{\,2} + U_B^{\,2})(I_{1A}^{\,2} + I_B^{\,2}) = U_{1A}^{\,2} I_{1A}^{\,2} + U_{1A}^{\,2} I_B^{\,2} + U_B^{\,2} I_{1A}^{\,2} + U_B^{\,2} I_B^{\,2} =$$
$$= Q_{F1A}^{\,2} + Q_{F\text{B}}^{\,2} + Q_1^{\,2} K_{\Pi\text{B},I}^{\,2} + Q_1^{\,2} K_{\Pi\text{B},U}^{\,2} + Q_{FA}^{\,2}(I_B/I_A)^2 + Q_{FB}^{\,2}(I_A/I_B)^2, \qquad (3.5)$$

where $Q_{\text{F}1A} = U_{1A} I_{1A}$; $Q_{F\text{B}} = U_B I_B$; $K_{\Pi\text{B},I} = I_B / I_1$; $K_{\Pi A,I} = I_A / I_1$; $Q_{FA} = U_A I_A$.

Without highlighting the current and voltage values behind the first harmonic:

$$Q_F^{\,2} = Q_{F1A}^{\,2} + Q_{F\text{B}}^{\,2} + U_{1A}^{\,2} I_{1A}^{\,2}\,((I_B/I_A)^2 + (U_B/U_{1A})^2) =$$
$$= Q_{F1A}^{\,2}\,(1 + \Delta_I^{\,2} + \Delta_U^{\,2}) + Q_{F\text{B}}^{\,2},$$

where $\Delta_I = I_B/I_A$ та $\Delta_U = U_B/U_{1A}$ – reduced ripple coefficients for current and voltage.

Depending on the nature of the change in the supply voltage, the quality indicators of the electric power and the flow of technological processes (type $u_\Gamma(t)$ and $u_\text{H}(t)$), the determination of the value of $Q_{F\tau}$ (at $\tau = T_\text{T}$) and its components provides for the following. First, the average active power *P* in the interval $\tau = T_\text{T}$ is calculated. Then, the current components $i_\text{a}(t)$ and $i_{\text{p}\tau}(t) = i_\tau(t) - i_{\text{a}\tau}(t)$ are determined, which allow calculating the power $Q_{F\tau}$.

Determination of the components of necessary and additional losses for a particular type of DEES requires the formation of load models for the entire period of the T_T technological process. For the most common *RL*-loads of REES, the following types of equivalent circuit models are possible: 1) *R*(*t*) = var, *L* = 0; 2) *R*(*t*) = var, *L* = const; 3) *R*(*t*) = var, *L*(*t*) = var.

3.3. Analysis of additional and necessary power losses in three-phase DEES

In three-phase DEES, there are several definitions of apparent power [38, 51]. The most commonly used concept of arithmetic apparent power type: $S_A = S_A + S_B + S_C$. With a symmetrical stress system $S_A = U\left(I_A + I_B + I_C\right)$, где I_A, I_B, I_C – current values of phase currents; U – effective value of phase voltage. Algebraic apparent power defines the largest active power that could be transmitted at the same current values of currents and voltages. Another modification is geometrical apparent power $S_{\hat{A}}^2 = \left(P_A + P_B + P_C\right)^2 + \left(Q_{\hat{o}A} + Q_{\hat{o}\hat{A}} + Q_{\hat{o}\hat{A}}\right)^2$, where P_A, $P_{\hat{A}}$, $P_{\tilde{N}}$ – active, a $Q_{\hat{o}A}$, $Q_{\hat{o}\hat{A}}$, $Q_{\hat{o}\tilde{N}}$ – Frize reactive power of three phases. Third Modification – Actual Gross Power $S_{\grave{o}} = \sqrt{\left(U_A^2 + U_B^2 + U_C^2\right)\cdot\left(I_A^2 + I_B^2 + I_C^2\right)}$, где U_A, U_B, U_C – current values of phase voltages. With a symmetrical stress system $S_{\grave{o}} = \sqrt{3U^2 \cdot \left(I_A^2 + I_B^2 + I_C^2\right)}$.

The meaning of the concept of real apparent power becomes clear from the following reasoning. Losses in the active elements of a three-phase DEES with an asymmetric load, which has a phase resistance, are equal $P_B = 3R_{\ddot{e}} \cdot \left(I_A^2 + I_B^2 + I_C^2\right)$. If the system of voltages and resistance of the phases of the load is symmetrical, and the phase currents have the same shape as the voltages, then only the active power is transferred to the load, and the losses in the network are minimal. We define the current value of the current of such a load, provided that the losses in the DEES with symmetric and asymmetric loads are equal:

$$I = \frac{1}{\sqrt{3}} \cdot \sqrt{\left(I_A^2 + I_B^2 + I_C^2\right)}. \qquad (3.6)$$

Then the active power of the three-phase symmetrical load $P = 3UI = \sqrt{3}U \cdot \sqrt{\left(I_A^2 + I_B^2 + I_C^2\right)} = S_m$. So, the actual apparent power determines the largest active power that could be transferred optimally to the load with the same losses in the active elements of the DEES. To determine the components of losses, we consider DEES when a non-linear, asymmetric load is connected to a symmetric three-phase generator. Imagine the load current of each phase as a sum of active and passive components. For the effective values of phase currents and their components, the following relations are valid $I_{\grave{A}} \neq I_B \neq I_C$; $I_{A_a} \neq I_{B_a} \neq I_{C_a}$; $I_{A_ð} \neq I_{B_ð} \neq I_{C_ð}$. When transferring active power to the load $P = U \cdot \left(I_{A_a} + I_{B_a} + I_{C_a}\right)$ losses [51]

$$P_{\hat{A}} = R_{ë}\left(I_{\grave{A}}^2 + I_B^2 + I_C^2\right) = R_{ë}\left(I_{A_a}^2 + I_{B_a}^2 + I_{C_a}^2\right) + R_{ë}\left(I_{A_ð}^2 + I_{B_ð}^2 + I_{C_ð}^2\right), \qquad (3.7)$$

where the second term determines the additional losses due to the presence of phase reactive currents.

Separation of losses into components of the type (3.7) reduces to calculating additional losses in each phase with their subsequent addition and does not take into account the asymmetry of the load. To eliminate this drawback, we also turn to the transfer of active power to a symmetrical load. Phase currents are described by the following formula: $I_a = \frac{1}{3}\left(I_{A_a} + I_{B_a} + I_{C_a}\right)$, losses are created in the active elements of the RES, which are equal. Difference

$$R_{ë}\left(I_{A_a}^2 + I_{B_a}^2 + I_{C_a}^2\right) - 3R_{ë}I_{\grave{a}}^2 = \frac{1}{3}R_{ë}\left[\left(I_{A_a} - I_{B_a}\right)^2 + \left(I_{B_a} - I_{C_a}\right)^2 + \left(I_{C_a} - I_{A_a}\right)^2\right] = R_{ë}I_{\grave{a}_í}^2 . \qquad (3.8)$$

determines the additional losses caused by the asymmetry of active power consumption. Here $I_{\grave{a}_í} = \frac{1}{\sqrt{3}}\sqrt{\left(I_{A_a} - I_{B_a}\right)^2 + \left(I_{B_a} - I_{C_a}\right)^2 + \left(I_{C_a} - I_{A_a}\right)^2}$ has a current dimension. In view of (3.8), expression (6.2) will have the form:

$$P_{\hat{A}} = \frac{1}{3} R_{\ddot{e}} \frac{S_m^2}{U^2} = \frac{1}{3} \frac{R_{\ddot{e}} P^2}{U^2} + \frac{1}{3} \frac{R_{\ddot{e}} Q_{\hat{o}_{\acute{i}}}^2}{U^2} + \frac{1}{3} \frac{R_{\ddot{e}} Q_{\hat{o}}^2}{U^2}, \qquad (3.9)$$

where, are reactive capacities introduced by analogy with the Frieze reactive power of a single-phase DEES, which show the presence of additional losses in the transmission of electricity to a three-phase load, [51]

$$Q_{\hat{o}_{\acute{i}}} = \sqrt{\frac{3U^2}{I_a^2}} = \sqrt{3}U\sqrt{\left(I_{A_a} - I_{B_a}\right)^2 + \left(I_{B_a} - I_{C_a}\right)^2 + \left(I_{C_a} - I_{A_a}\right)^2}, \; Q_{\hat{o}} = \sqrt{3U^2\left(I_{A_\eth}^2 + I_{B_\eth}^2 + I_{C_\eth}^2\right)}.$$

Power and determine additional losses due to the asymmetry of the load and the presence of phase reactive currents. The coefficient indicates that energy is transmitted along three lines.

The separation of losses into components (3.9) corresponds to the decomposition of the actual apparent power:

$$S_m = P^2 + Q_{\hat{o}_{\acute{i}}}^2 + Q_{\hat{o}}^2, \qquad (3.10)$$

where for a three-phase DEES with a symmetric voltage generator

$$S_m^2 = 3U^2\left(I_{\hat{A}}^2 + I_B^2 + I_C^2\right); \; Q_{\hat{o}}^2 = 3U^2\left(I_{A_\eth}^2 + I_{B_\eth}^2 + I_{C_\eth}^2\right); \; P^2 = U^2\left(I_{A_a} + I_{B_a} + I_{C_a}\right)^2;$$

$$Q_{\hat{o}_{\acute{i}}}^2 = U^2\left[\left(I_{A_a} - I_{B_a}\right)^2 + \left(I_{B_a} - I_{C_a}\right)^2 + \left(I_{C_a} - I_{A_a}\right)^2\right]. \qquad (3.11)$$

With an asymmetric system of generator voltages, energy is transferred to the load with the least loss if the phase currents have the same shape as the voltage, and for their effective values the relations

$$\frac{I_{\hat{A}}^{`}}{U_A} = \frac{I_B^{`}}{U_B} = \frac{I_C^{`}}{U_C}; \; I_{\hat{A}}^{`} = \frac{U_A P}{U^2}; \; I_B^{`} = \frac{U_B P}{U^2}; \; I_C^{`} = \frac{U_C P}{U^2}.$$

If the load is nonlinear and asymmetric, then the loss components also have the form (3.11). The capacity system (3.11) in this case is written as:

$$S_m^2 = \left(U_{\hat{A}}^2 + U_B^2 + U_C^2\right)\left(I_{\hat{A}}^2 + I_B^2 + I_C^2\right);$$

$$Q_{\hat{o}}^2 = \left(U_{\grave{A}}^2 + U_B^2 + U_C^2\right)\left(I_{A_{\eth}}^2 + I_{B_{\eth}}^2 + I_{C_{\eth}}^2\right);$$

$$P^2 = \left(U_{\grave{A}} I_{A_a} + U_B I_{B_a} + U_C I_{C_a}\right)^2;$$

$$Q_{\hat{o}_{\acute{i}}}^2 = \left[\left(U_A I_{B_a} - U_B I_{A_a}\right)^2 + \left(U_A I_{C_a} - U_C I_{A_a}\right)^2 + \left(U_B I_{C_a} - U_C I_{B_a}\right)^2\right]. \qquad (3.12)$$

Expressions (3.8) – (3.12) show the complex nature of the change in the component losses in local power supply systems from the influence of asymmetric load parameters.

3.4. The value of the total energy loss in local electrical networks

The calculated value of the total energy losses in local electric networks should be determined regardless of their configuration based on the obtained dependences of the heating coefficient on the coefficient of the shape of the load graph, which allows analysis of the excess of losses on heating conductors depending on the shape of the load graph [49, 50, 52].

Particularly noteworthy are energy losses in electric networks, which are an extremely negative phenomenon that cannot be avoided, but in the case of regulation of electricity consumption, their reduction is achieved. The bulk of these losses is due to the thermal heating of the conductors, which is proportional to the square of the current flowing in them.

It was found that with the uniform transfer of an equal amount of energy along the same line, at the same voltage, but for different times $I_1T_1 = I_2T_2$ (I_1, I_2 are the current in the conductor for the time T_1 and T_2, respectively).

The ratio of energy losses can be represented as:

$$\frac{W_2}{W_1} = \frac{\int_0^{T_2} P_2(t)dt}{\int_0^{T_1} P_1(t)dt} = \frac{I_2^2 R T_2}{I_1^2 R T_1} = \frac{I_1^2 (T_1/T_2)^2 R T_2}{I_1^2 R T_1} = \frac{T_1}{T_2}, \qquad (3.13)$$

where W_1 and W_2 are the energy losses due to heating of the conductors in case of transmission during the time T_1 and T_2, respectively; R is the resistance of the conductor.

From the expression (3.12) it can be seen that in the simplest case of load balancing, the power consumed for heating the conductors is characterized by the ratio of the load supply time. Obviously, to calculate the reduction of losses, you can use the expression, which is defined as the coefficient of heating of conductors ($K_{НП}$). If we are talking about maximum load balancing to even consumption, the $K_{НПМ}$ index is added, which is a special case of $K_{НП}$. In general terms, $K_{НП}$ is represented by formula (3.14):

$$K_{НП} = 1 - \frac{W_2}{W_1} = 1 - \frac{\int_0^{T_2} P_2(t)dt}{\int_0^{T_1} P_1(t)dt} = 1 - \frac{I_2^2 R T_2}{I_1^2 R T_1} = 1 - \frac{I_1^2 (\frac{T_1}{T_2})^2 R T_2}{I_1^2 R T_1} = 1 - \frac{T_1}{T_2}. \quad (3.14)$$

In practice, uniform load schedules are extremely rare. Usually use load graphs with an averaging interval ($T_{ОСР}$ – averaging time). In this case, the $K_{НП}$ will take the form:

$$K_{НП} = 1 - \frac{\sum_{i=1}^{n} P_{i2} T_{оср}}{\sum_{i=1}^{n} P_{i1} T_{оср}}. \quad (3.15)$$

The coefficient of the form of the graph of the load ($K_{Ф}$). It characterizes the loss of heating of conductors with uneven consumption of relatively uniform load.

To calculate the heating losses due to the irregularity of the graph, the relationship between $K_{НПМ}$ and $K_{Ф}$ was determined:

$$K_{НПМ} = 1 - \frac{1}{K_{ф}^2}. \quad (3.16)$$

The value of $K_Ф$ increases with the peak nature of the load curve. Therefore, in principle, for individual power consumers operating in intermittent modes, this value is greater than for a group of such power consumers.

It should be noted that the reduction in losses in the lines that make up the load node (with the exception of the supply ones) will probably be greater than in the supply networks. This is explained by the fact that lines feeding the smaller consumers, whose load schedules are more uneven and have a larger shape factor, are connected to the load node.

Typically, the value of $K_Ф$ (expression (3.16)) varies from 1.02 to 1.15 depending on the parameters of the load node (group of industrial consumers, workshop, enterprise). In this case, the $K_{НПМ}$ ranges from 0.04 to 0.24.

Using the dependence of $K_{НПМ}$ on $K_Ф$ (expression (3.16)), it is possible to quickly assess the change in losses in electric networks while balancing electricity consumption. For this, the schedule of the enterprise load is sufficient, and power supply schemes are not required.

Thus, losses in electric networks can be significantly reduced by equalizing the load schedule, which can lead to a significant reduction in electricity losses and increase energy efficiency of the enterprise.

The choice of the structure and parameters of the system of electric energy storage using batteries used to regulate the load schedule should be based on the required degree of load balancing, shape factor, heating coefficient, characteristics of the connection points of the drives with the greatest possible reduction in energy losses, which will increase the energy efficiency of the enterprise’s electrical complex.

One of the features of energy storage devices in the form of rechargeable batteries is their ability to store electrical energy during hours of minimum consumption and return it to the network during hours of maximum electricity consumption.

The choice of the coordinates of the connection of the energy storage device is due to many technical and economic factors associated with finding compromises between them and the tasks that the energy storage device must solve for this network or load node.

The use of energy storage to regulate the load in an existing electrical complex will allow:

- align the load curve;
- reduce energy losses in power grids;
- reduce the cost of paying for electricity;
- reduce voltage loss;
- connect additional consumers (if necessary);
- improve the quality of electrical energy.

Conclusions to the chapter 3

1. Reducing electrical losses in the power system is a very complex, paramount and complex problem. The solution to this problem requires significant investment, optimization of development, modernization of electricity metering systems, the introduction of new diagnostics and control systems for the power grid, raising the level of staff and providing it with modern means of checking electricity.

2. The reasons for the occurrence of additional energy losses in the REES can be systematized in the following directions: distortion of the quality of electricity generated by generators; the influence of the operating modes of other systems (the presence of electromagnetic interference, violation of electromagnetic compatibility); change in technological processes (change in modes or parameters of technological processes, in particular, change in the structure and parameters of loads).

3. It is shown that the analysis of the structure of additional electricity losses and the analysis of additional and necessary power losses in three-phase DEES can be effectively performed using the modification of the active power of Frize.

4. The analysis showed that the calculated value of the total energy losses in local electric networks should be determined regardless of their configuration based on the obtained dependences of the heating coefficient on the coefficient of the shape of the load graph, which allows analysis of the excess of losses on heating conductors depending on the shape of the load graph.

CHAPTER 4. EVALUATION OF LEVELS OF OPTIMALITY OF ENERGY CONSUMPTION TAKING INTO ACCOUNT PARAMETERS OF LOCAL POWER SUPPLY SYSTEMS

4.1. Refinement of non-optimality processes when consuming active power at higher harmonics (presence of the same voltage and current harmonics.

For the case of active power consumption at higher harmonics (presence of the same voltage and current harmonics, the active power P is represented by the sum of the two components $P = P_1 + \Delta P$, where, respectively, P_1 and ΔP are the active power consumption at the first and highest harmonics. In this case, we can write:

$$Q_F^2 = S^2 - P^2 = S^2 - (P_1 + \Delta P)^2. \qquad (4.1)$$

Given that $S^2 = U^2 I^2 = U_1^2(1 + \delta^2_u) I_1^2(1 + \delta^2_i)$, $S_1^2 = U_1^2 I_1^2$ then the ratio (4.1) can be represented as:

$$Q_F^2 = S^2 - P^2 = U_1^2 I_1^2(1 + \delta^2_u)(1 + \delta^2_i) - (P_1 + \Delta P)^2, \qquad (4.2)$$

where δ_u и δ_i – Harmonics factor for voltage and current.

Given the ratio $Q_1^2 = S_1^2 - P_1^2$ and conditions $\delta^2_u \ll \delta^2_i$ и $\Delta P^2 \ll P_1^2$, relation (4.2) can be converted to:

$$Q_F^2 = Q_1^2 + U_1^2 I_1^2(\delta^2_u + \delta^2_i) - (P_1^2 + 2P_1\Delta P)^2.$$

To assess the non-optimal processes in systems, taking into account the negative influence of active power at higher harmonics, it is advisable to apply Frize power modification in the recording $Q_{F(1)}^2 = S^2 - P_1^2$, which for the formula (4.2) is represented in the form

$$Q_{F(1)}^2 = S^2 - P_1^2 = U_1^2 I_1^2(1 + \delta^2_u)(1 + \delta^2_i) - P_1^2. \qquad (4.3)$$

A comparison of relations (4.2) and (4.3) allows us to determine the "contribution" of the presence of active power consumption ΔP in the system:

$$Q_{F(\Delta P)}{}^{2} = Q_{F(1)}{}^{2} - Q_{F}{}^{2} = 2P_{1}\Delta P + \Delta P^{2}. \qquad (4.4)$$

To estimate the interference ΔP at the non-optimal level of power transmission P1 using (4.4), we can use the relation:

$$Q_{F(\Delta P)}{}^{2} / P_{1}{}^{2} = 2(\Delta P / P_{1}) + (\Delta P / P_{1})^{2}. \qquad (4.5)$$

Using relations (4.4) and (4.5), we will calculate the quantities that can be used to clarify non-optimal processes when consuming active power at higher harmonics. An assessment of the effect of ΔP on the non-optimality level of power transmission P_1 for specific values of these values is given in Table 4.1 – 4.6.

Table 4.1 (P_1 = 1 кВт)

Величина	ΔP, кВт							
	0,05	0,1	0,125	0,15	0,175	0,2	0,225	0,25
$Q_{F(\Delta P)}{}^{2}$, (кВАр)^2	0.1025	0.21	0.26563	0.3225	0.38063	0.44	0.50063	0.5625
$Q_{F(\Delta P)}{}^{2} / P_{1}{}^{2}$	0.1025	0.21	0.26563	0.3225	0.38063	0.44	0.50063	0.5625

Table 4.2 (P_1 = 2 кВт)

Величина	ΔP, кВт							
	0,1	0,2	0,25	0,3	0,35	0,4	0,45	0,5
$Q_{F(\Delta P)}{}^{2}$, (кВАр)^2	0.41	0.84	1.0625	1.29	1.5225	1.76	2.0025	2.25
$Q_{F(\Delta P)}{}^{2} / P_{1}{}^{2}$	0.1025	0.21	0.26563	0.3225	0.38063	0.44	0.50063	0.5625

Table 4.3 (P_1 = 5 кВт)

Величина	ΔP, кВт							
	0,05	0,1	0,125	0,15	0,175	0,2	0,225	0,25
$Q_{F(\Delta P)}{}^2$, (кВАр)^2	0.5025	1.01	1.265625	1.5225	1.780625	2.04	2.300625	2.5625
$Q_{F(\Delta P)}{}^2$ / $P_1{}^2$	0.0201	0.0404	0.050625	0.0609	0.071225	0.0816	0.092025	0.1025

Table 4.4 (P_1 = 10 кВт)

Величина	ΔP, кВт							
	0,05	0,1	0,125	0,15	0,175	0,2	0,225	0,25
$Q_{F(\Delta P)}{}^2$, (кВАр)^2	1.0025	2.01	2.515625	3.0225	3.530625	4.04	4.550625	5.0625
$Q_{F(\Delta P)}{}^2$ / $P_1{}^2$	0.010025	0.0201	0.02515625	0.030225	0.03530625	0.0404	0.04550625	0.050625

Table 4.5 (P_1 = 20 кВт)

Величина	ΔP, кВт							
	0,05	0,1	0,125	0,15	0,175	0,2	0,225	0,25
$Q_{F(\Delta P)}{}^2$, (кВАр)^2	2.0025	4.01	5.015625	6.0225	7.030625	8.04	9.050625	10.0625
$Q_{F(\Delta P)}{}^2$ / $P_1{}^2$	0.00500625	0.010025	0.012539063	0.01505625	0.017576563	0.0201	0.022626563	0.02515625

Table 4.6 (P_1 = 50 кВт)

Величина	ΔP, кВт							
	0,05	0,1	0,125	0,15	0,175	0,2	0,225	0,25
$Q_{F(\Delta P)}{}^2$, (кВАр)^2	5.0025	10.01	12.515625	15.0225	17.530625	20.04	22.550625	25.0625
$Q_{F(\Delta P)}{}^2$ / $P_1{}^2$	0.002001	0.004004	0.00500625	0.006009	0.00701225	0.008016	0.00902025	0.010025

In Figures 4.1 – 4.6 graphs are constructed in accordance with the data in table.

4.1 – 4.6. The graphs on Figures 4.1 – 4.6 show the complex relationship relations (4.4) and (4.5).

For case $2P_1\Delta P >> \Delta P^2$, there is an approximate relation:

$$Q_{F(\Delta P)}^2 \approx 2P_1\Delta P. \qquad (4.6)$$

The approximate expression (4.6) reflects the linear dependence of the quantity $Q_{F(\Delta P)}^2$ on the quantities P_1 and ΔP.

4.2. Accounting for the internal resistance of the generator and the resistance of the power lines

For the time interval τ, the formula $Q_F = U[I^2 - I_a^2]^{1/2} = UI_p$ can be represented as [38, 51]

$$Q_{\Phi\tau}^2 = U_\tau^2 I_{p\tau}^2, \qquad (4.7)$$

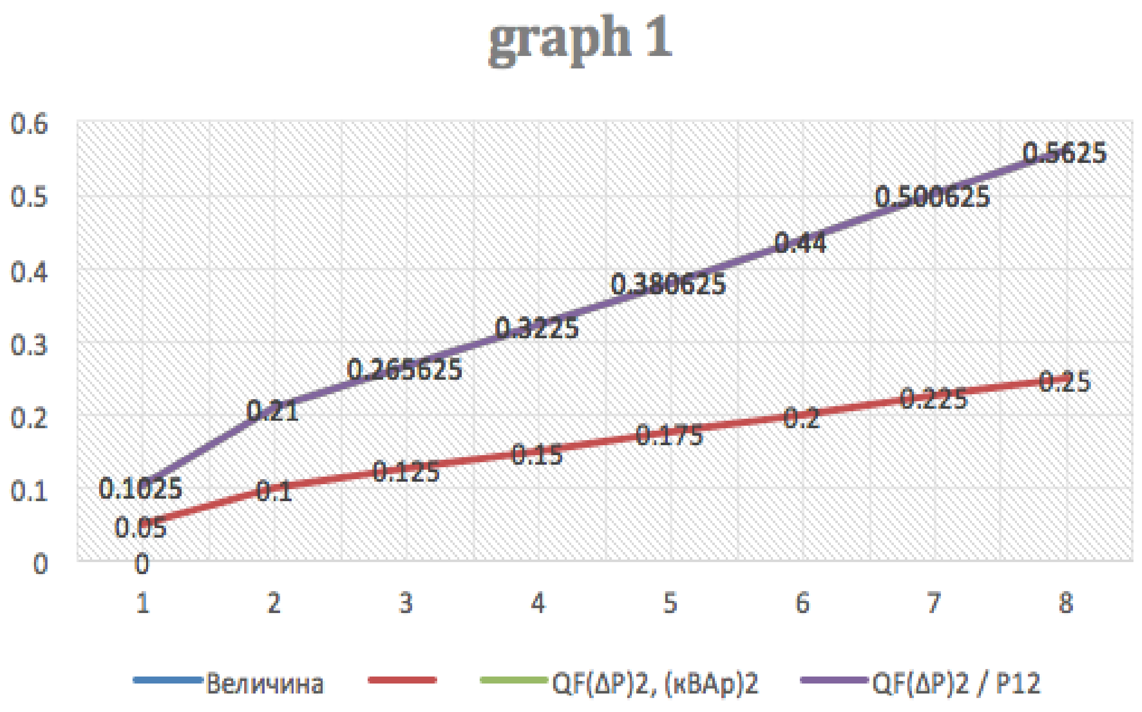
where $I_\tau^2 = I_{a\tau}^2 + I_{p\tau}^2$;

$$I_\tau = \left(\int_0^\tau i^2(t)dt/\tau\right)^{1/2}; \quad I_{a\tau} = \left(\int_0^\tau i_{a\tau}^2(t)dt/\tau\right)^{1/2}; \quad I_{p\tau} = \left(\int_0^\tau i_{p\tau}^2(t)dt/\tau\right)^{1/2}.$$

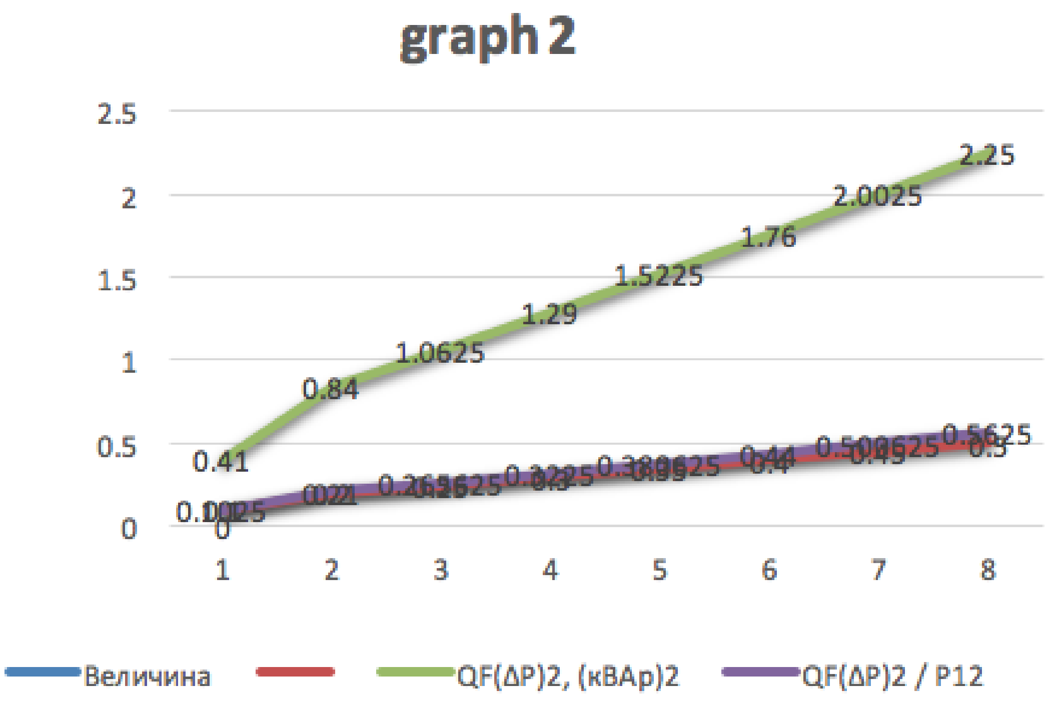
Thus, the additional losses in the transmission of electricity to non-stationary low-level over a time interval are proportional to Q_F. The separation of Q_F (turn (4.7)) into components due to various factors of low-quality electricity will be different for different time intervals.

In the case of the extension of the concept of Frize power Q_F to an arbitrary time interval $\tau = T_T$, the power $Q_{F\tau}$ determines the average quadratic discrepancy between non-optimal ($S > P$) and optimal ($S = P$) levels of active power load consumption.

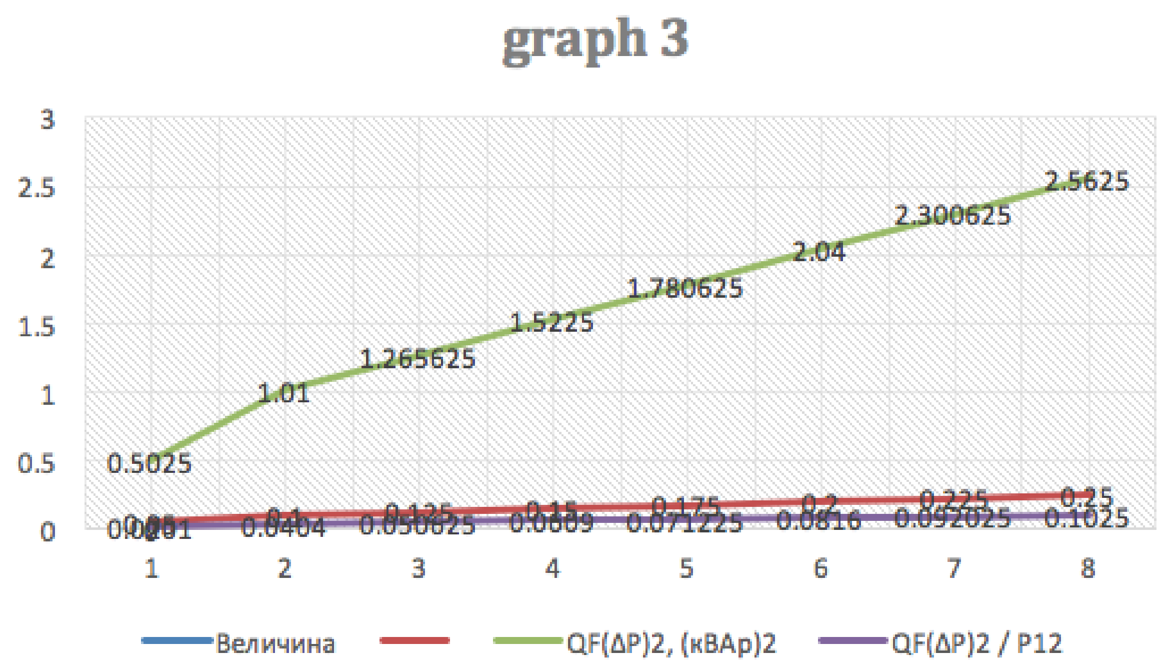
The reactive current $i_{P\tau}(t)$ in the interval $\tau = T_T$, characterizing the non-optimality of electric power transmission, is determined from the relation:



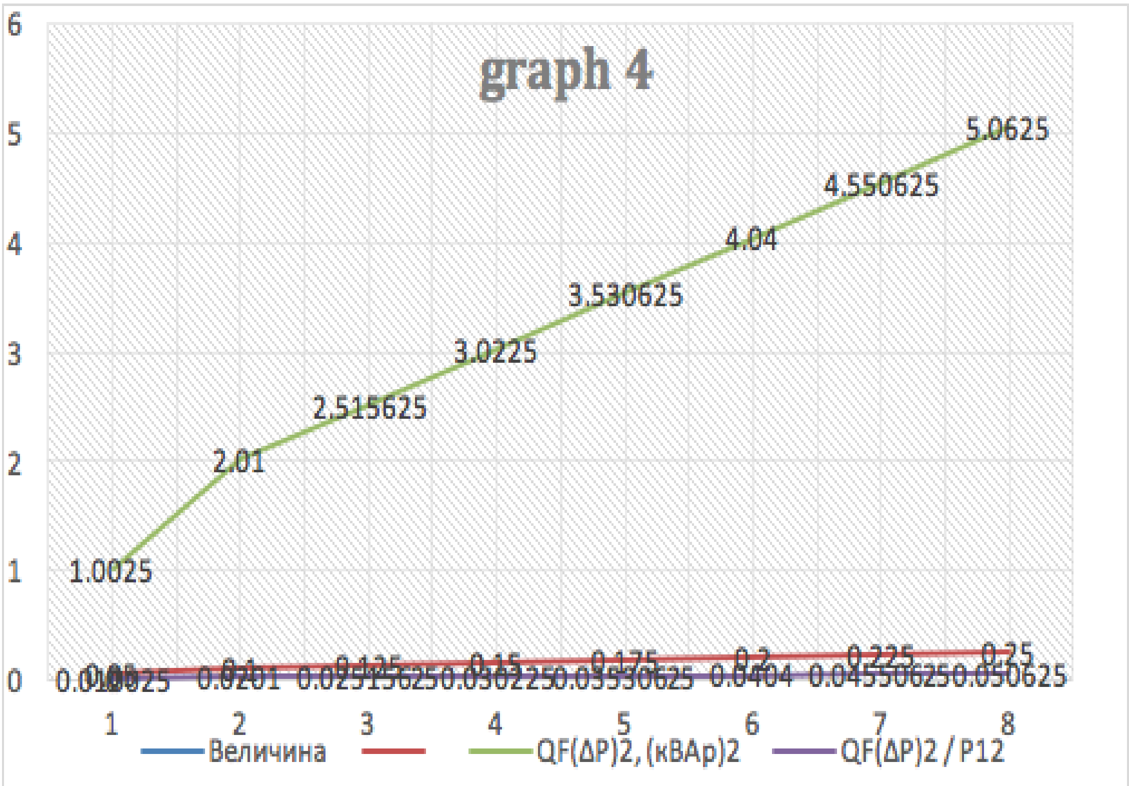
Figures 4.1 – graphs are constructed in accordance with the data in table. 4.1



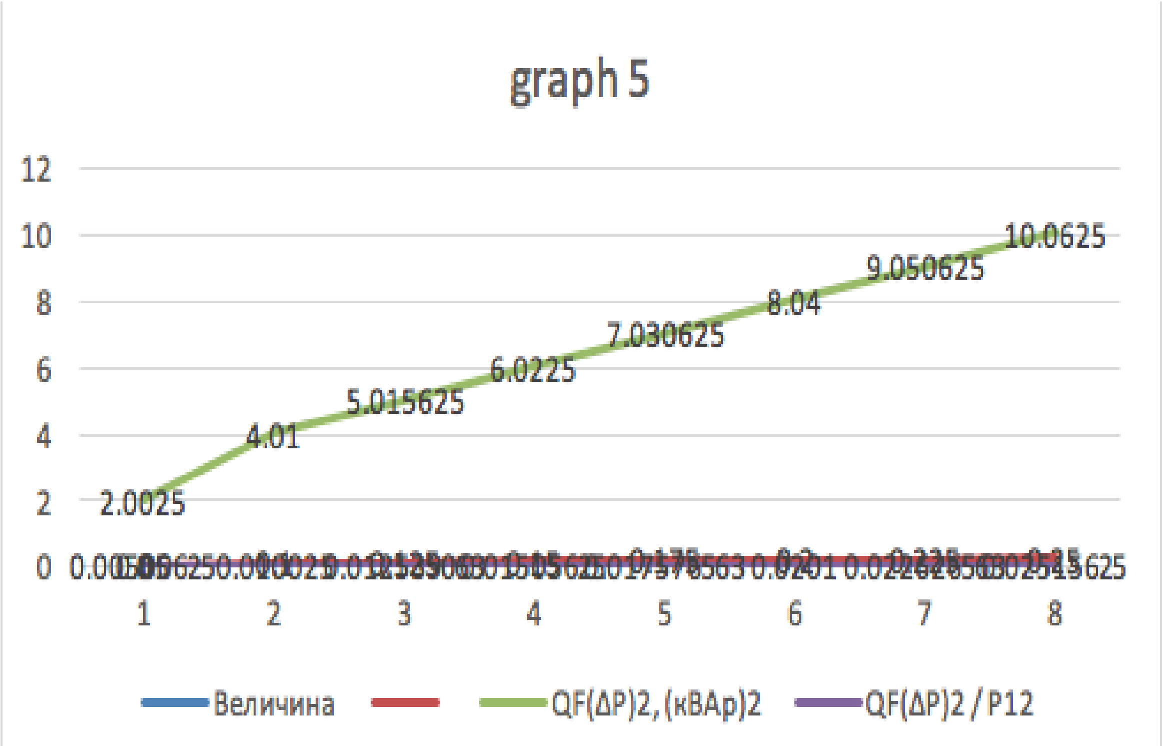
Figures 4.2 – graphs are constructed in accordance with the data in table. 4.2



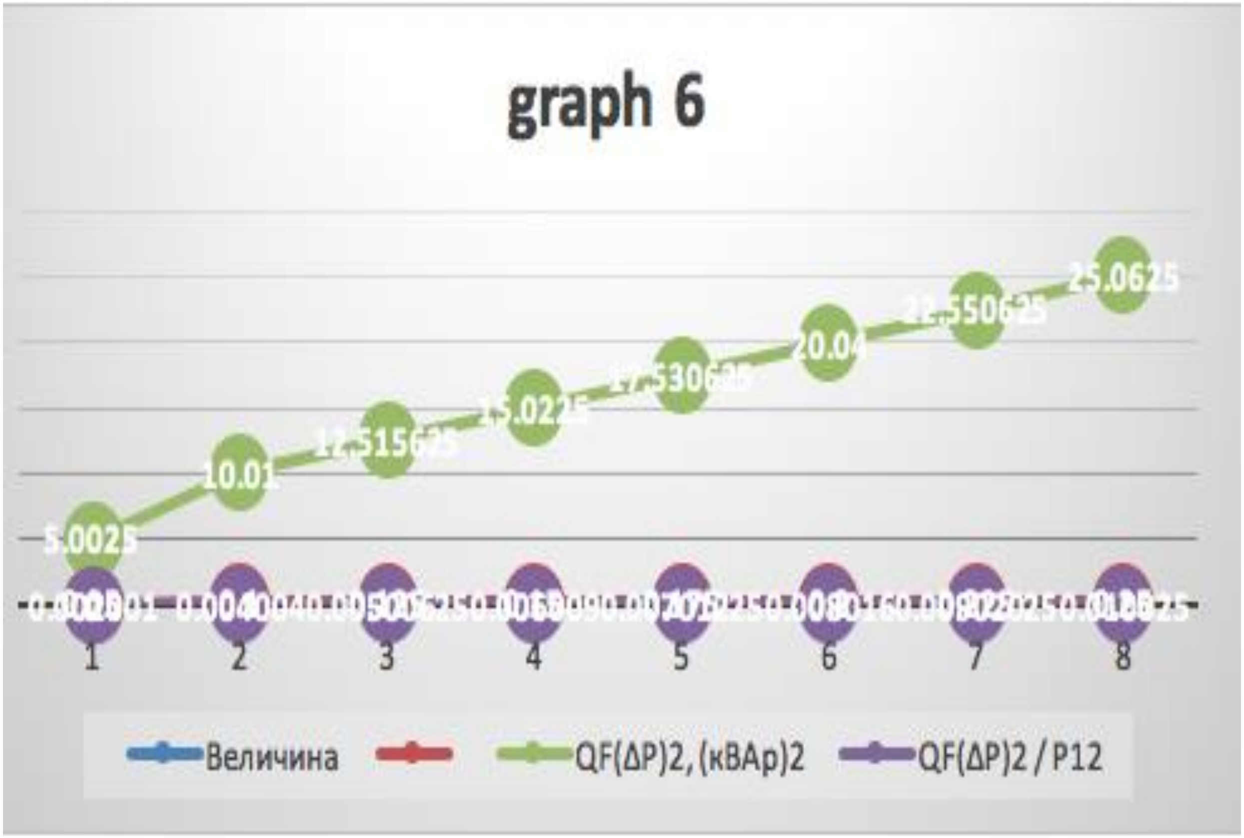
Figures 4.3 – graphs are constructed in accordance with the data in table. 4.3



Figures 4.4 – graphs are constructed in accordance with the data in table. 4.1



Figures 4.5 – graphs are constructed in accordance with the data in table. 4.5



Figures 4.6 – graphs are constructed in accordance with the data in table 4.6

$$i_{p\tau}(t) = i(t) - \frac{\left(\int_0^\tau u(t)i(t)dt\right)u(t)}{\int_0^\tau u(t)dt}. \qquad (4.8)$$

In fact, the power $Q_{F\tau}$ from the mathematical point of view is the mean-square residual between two functions on the interval τ (relations (4.7), (4.8)) [38]. The concept of "non-optimality characteristic" can be used when we consider one of the functions as optimal (in this case, it is a function of active power consumption).

The use of Q_F to assess the non-uniformity of processes will be shown by the example of a mode characterized by the current Values of voltage and current,, is the duration of the ith interval, provided for the interval, where is the period of the network, in the case; we can write the expression for the power of Frize Q_F in the form

$$Q_\Phi = \sqrt{\sum_{i=1}^{n} U_i^2 \delta_i \cdot \sum_{i=1}^{n} I_i^2 \delta_i - (\sum_{i=1}^{n} U_i I_i \delta_i)^2}. \qquad (4.9)$$

For the distinguished type of systems, in assessing the levels of non-optimality of their operation, in most cases it is necessary to take into account the internal resistance of the generator R_G and the resistance of the transmission line R_L. Put $R = R_G + R_L$.

In the general case, for ΔU and ΔI, there is a functional dependence $\Delta U = f(\Delta I)$, which, when R_{BH} and R_L is taken into account, we can write $\Delta U = \Delta I \cdot (R_{BH} + R_L) = \Delta U = \Delta I \cdot R$. Consider the cross section of the system at the initial values of voltage U_1 and current I1. If the current changes by ΔI ($I_2 = I_1 + \Delta I$), the voltage U_2 for the selected section will be equal to $U_2 = U_1 - \Delta I \cdot (R_{BH} + R_L)$, or if $R_{BH} = 0$, the relation $U_2 = U_1 - \Delta I \cdot R$.

The value of the Frieze reactive power Q_F for this case when considering two intervals (relation (4.9)), (δ1 + δ2 = 1) will be determined from the relation:

$Q_F^2 = (U_1^2\delta_1 + U_2^2\delta_2)\,(I_1^2\delta_1 + I_2^2\delta_2) - (U_1 I_1\delta_1 + U_2 I_2\delta_2)^2 =$
$= (U_1^2\delta_1 + (U_1 - \Delta I\cdot R)^2\delta_2)\,(I_1^2\delta_1 + (I_1 + \Delta I)^2\delta_2) -$
$- (U_1 I_1\delta_1 + (U_1 - \Delta I\cdot R)\,(I_1 + \Delta I)\delta_2)^2 =$
$= (U_1^2\,(1 - \delta_2) + (U_1 - \Delta I\cdot R)^2\delta_2)\,(I_1^2\,(1 - \delta_2) + (I_1 + \Delta I)^2\delta_2) -$
$- (U_1 I_1(1 - \delta_2) + (U_1 - \Delta I\cdot R)\,(I_1 + \Delta I)\delta_2)^2\,.$ (4.10)

After algebraic transformations, relation (4.10) can be transformed to the form:

$Q_F^2 = \Delta I\cdot\delta_2\,[\delta_1\cdot\Delta I\cdot(U_1^2 + 2U_1\cdot R\cdot I_1 + R^2\cdot I_1^2) +$
$+ \Delta I\cdot R(2U_1\cdot\Delta I - 2U_1\cdot I_1 - \Delta I^2\cdot R)] =$
$= \Delta I^2\delta_2\,[\delta_1\cdot(U_1 + R\cdot I_1)^2 - R(2U_1\cdot(I_1 - \Delta I) + \Delta I^2\cdot R)].$ (4.11)

or

$Q_F^2 = \Delta I^2\delta_2\delta_1\cdot(U_1 + R\cdot I_1)^2 - 2\Delta I^2\delta_2\,RU_1\cdot(I_1 - \Delta I) - \Delta I^4\delta_2\cdot R)].$ (4.12)

If the third term on the right-hand side of relation (4.12) can be neglected, then the value of Q_F^2 is determined by the approximate equality

$Q_F^2 = \Delta I^2\delta_2\delta_1\cdot(U_1 + R\cdot I_1)^2 - 2\Delta I^2\delta_2\,RU_1\cdot(I_1 - \Delta I).$ (4.13)

Relations (4.11) – (4.13) show a complex dependence of the level of non-optimality of energy consumption in the system on changes in ΔI, δ_2, U_1, R, and I_1.

To assess the influence of these quantities on the value of Q_F^2, we construct a series of dependences (functions) of $Q_F^2(\delta_2)$ on the parameters I_1, R, and ΔI (see tables 4.7 and 4.8).

Change in value δ_2:

0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9

Table 4.7 – U_1 = 200 B:

№ dependences (functions) $Q_F^2(\delta_2)$	Value I_1, A	Value R, Ом	Value ΔI, A
1	2	0,2	0,2
2	2	0,2	0,5
3	2	0,2	1
4	2	0,5	0,2
5	2	0,5	0,5
6	2	0,5	1
7	2	1	0,2
8	2	1	0,5
9	2	1	1
10	5	0,2	0,2
11	5	0,2	0,5
12	5	0,2	1
13	5	0,5	0,2
14	5	0,5	0,5
15	5	0,5	1
16	5	1	0,2
17	5	1	0,5
18	5	1	1
19	10	0,2	0,2
20	10	0,2	0,5
21	10	0,2	1
22	10	0,5	0,2
23	10	0,5	0,5
24	10	0,5	1
25	10	1	0,2

26	10	1	0,5
27	10	1	1

Table 4.8 – U_1 = 1000 B:

№ dependences (functions) $Q_F^2(\delta_2)$	Value I_1, A	Value R, Ом	Value ΔI, A
28	10	1	1
29	10	1	5
30	10	1	10
31	10	2	1
32	10	2	5
33	10	2	10
34	10	5	1
35	10	5	5
36	10	5	10
37	20	1	1
38	20	1	5
39	20	1	10
40	20	2	1
41	20	2	5
42	20	2	10
43	20	5	1
44	20	5	5
45	20	5	10
46	50	1	1
47	50	1	5
48	50	1	10
49	50	2	1

50	50	2	5
51	50	2	10
52	50	5	1
53	50	5	5
54	50	5	10

Below are 18 graphs (see Figures 4.7 – 4.24), each of which shows three dependencies (functions):

Schedule № 1: dependencies 1, 2 and 3;

Schedule № 2: dependencies 4, 5 and 6;

Schedule № 3: dependencies 7, 8 and 9;

Schedule № 4: dependencies 10, 11 and 12;

Schedule № 5: dependencies 13, 14 and 15;

Schedule № 6: dependencies 16, 17 and 18;

Schedule № 7: dependencies 19, 20 and 21;

Schedule № 8: dependencies 22, 23 and 24;

Schedule № 9: dependencies 25, 26 and 27;

Schedule № 10: dependencies 28, 29 and 30;

Schedule № 11: dependencies 31, 32 and 33;

Schedule № 12: dependencies 34, 35 and 36;

Schedule № 13: dependencies 37, 38 and 39;

Schedule № 14: dependencies 40, 41 and 42;

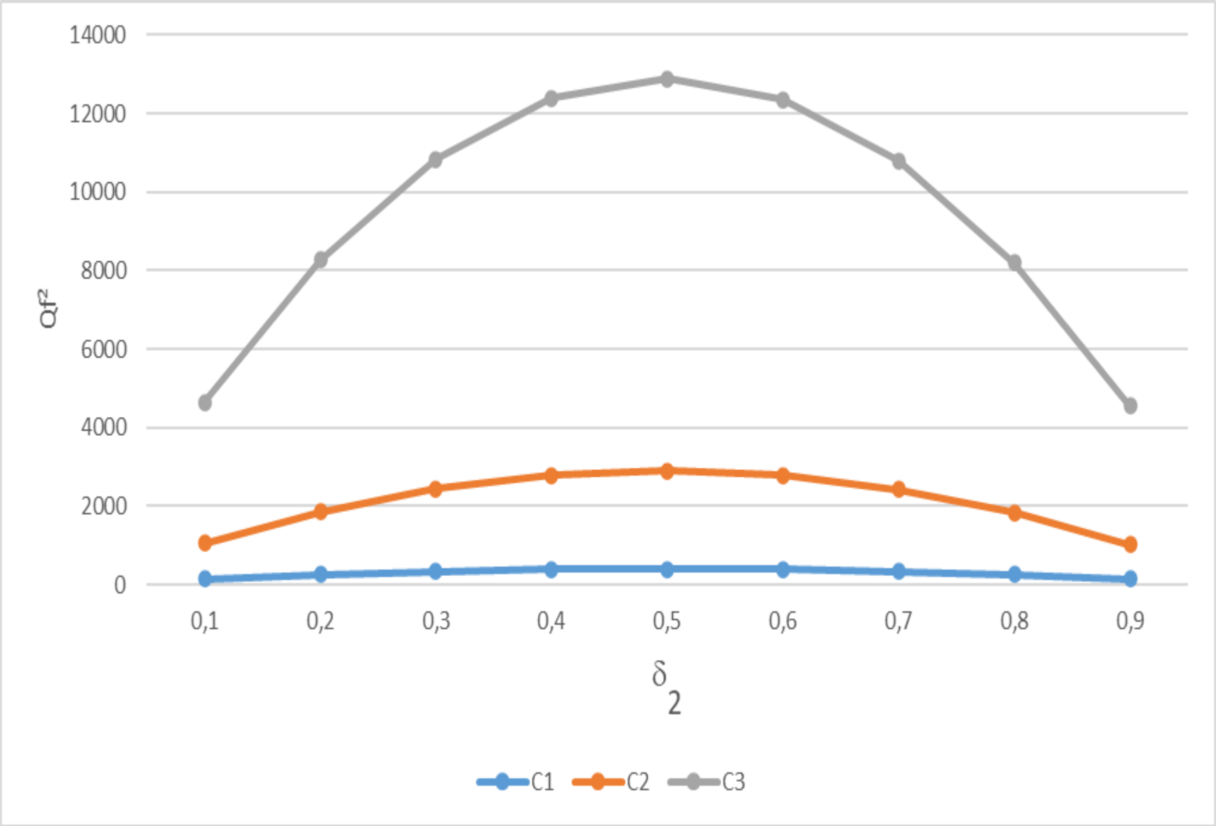
Schedule № 15: dependencies 43, 44 and 45;

Schedule № 16: dependencies 46, 47 and 48;

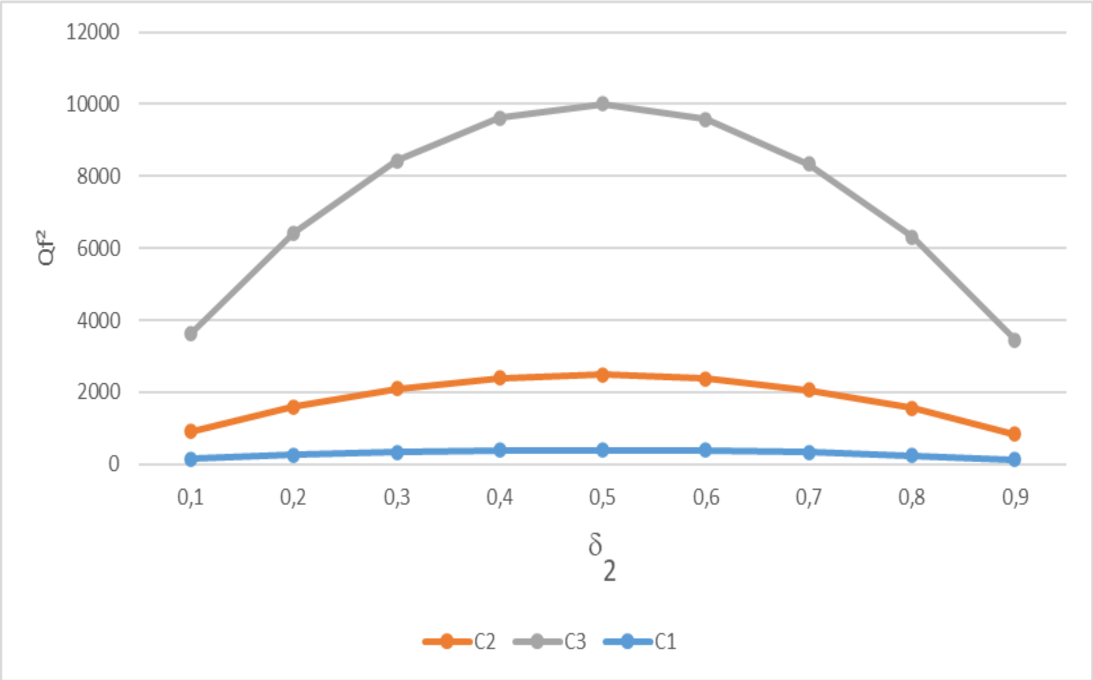
Schedule № 17: dependencies 49, 50 and 51;

Schedule № 18: dependencies 52, 53 and 54.

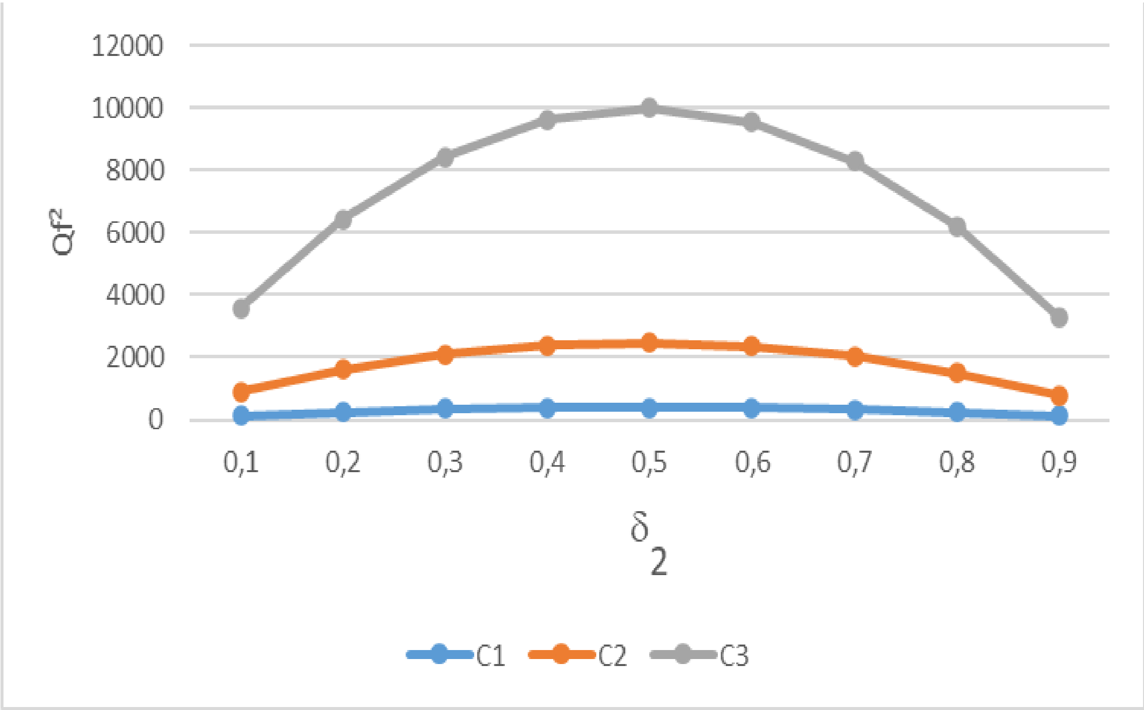
A series of dependences (functions) of $Q_F^2(\delta_2)$ on the parameters I_1, R, and ΔI show the complex nature of the dependencies on the selected parameters. The constructed curves have a pronounced maximum. It is advisable to use the obtained many graphs in assessing the levels of losses in the selected class of systems.



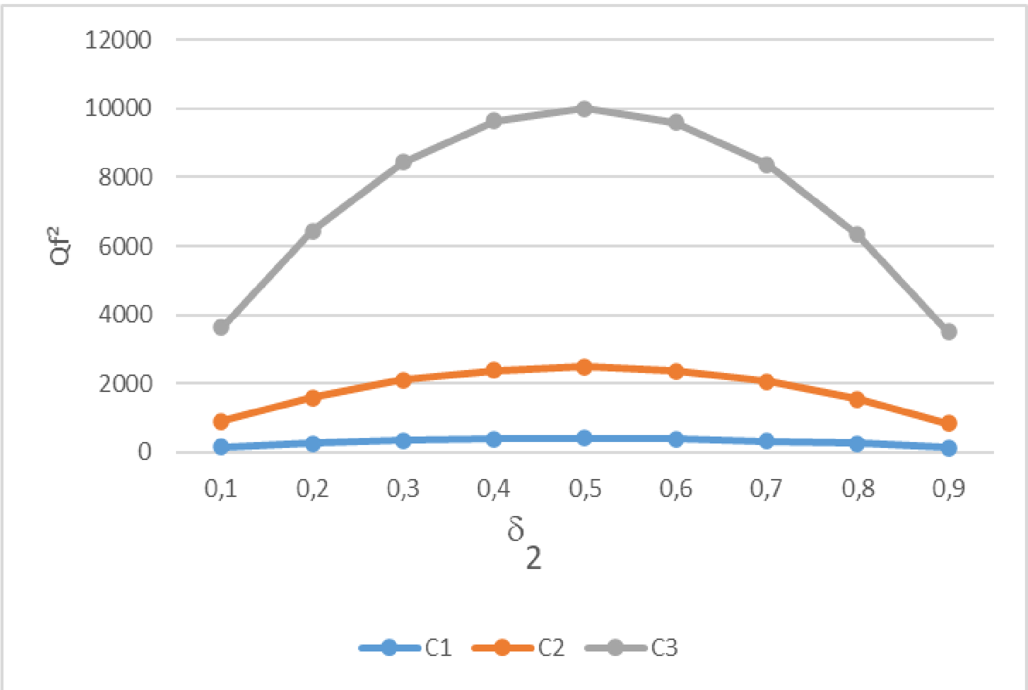
Figures 4.7 – Graphs are constructed in accordance with the data in table 4.7 (dependencies 1, 2 and 3)



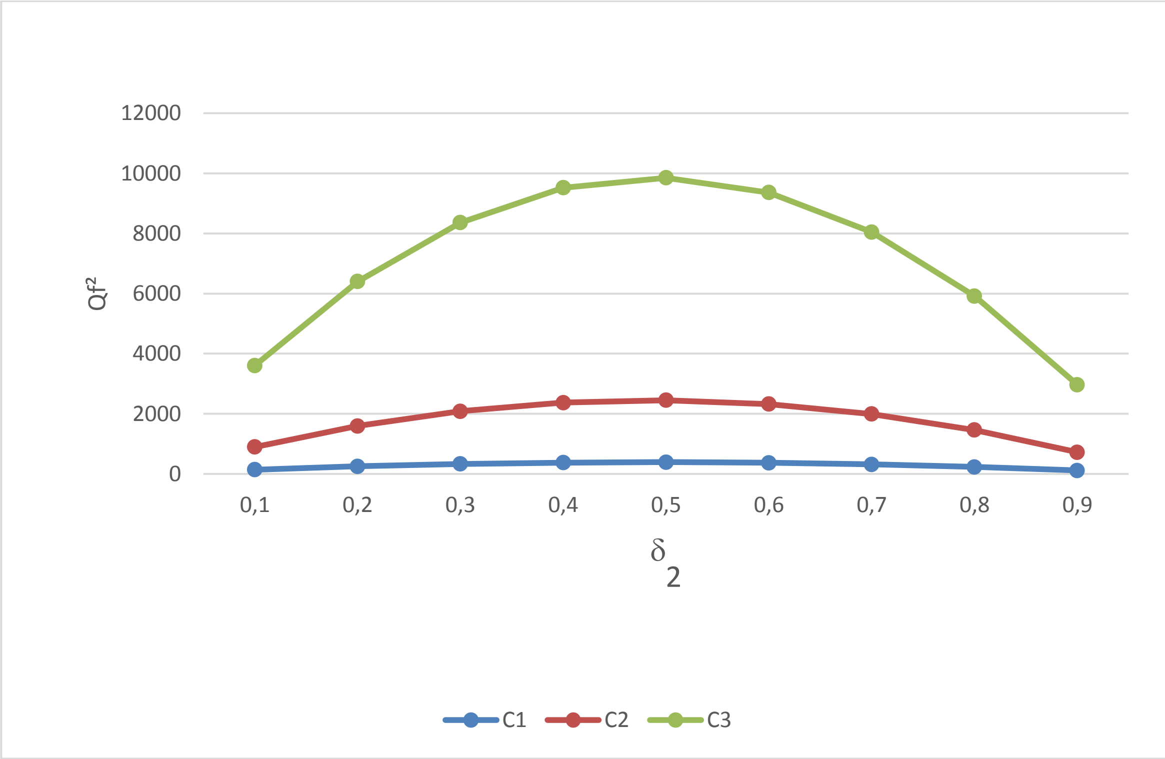
Figures 4.8 – Graphs are constructed in accordance with the data in table 4.7 (dependencies 4, 5 and 6)



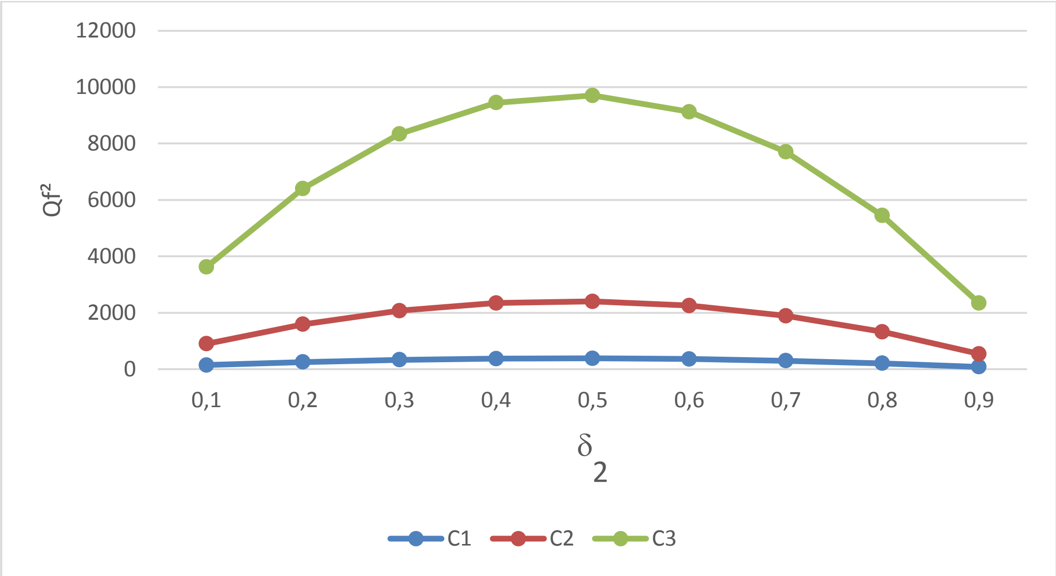
Figures 4.9 – Graphs are constructed in accordance with the data in table 4.7 (dependencies 7, 8 and 9)



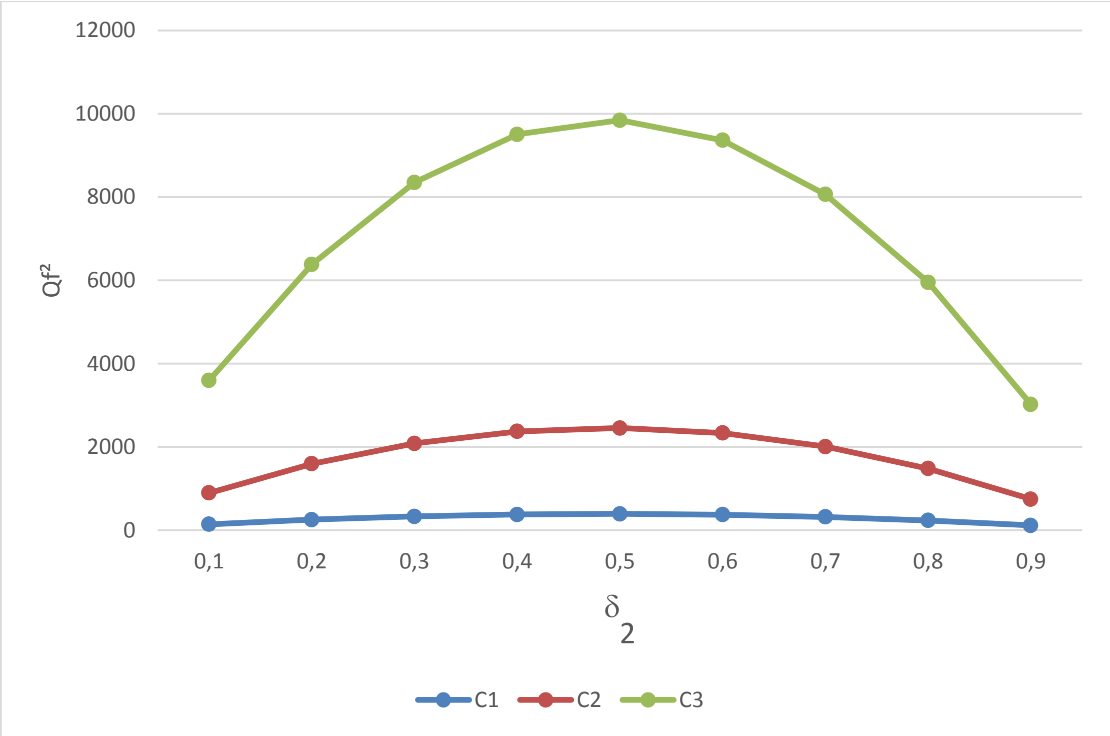
Figures 4.10 – Graphs are constructed in accordance with the data in table 4.7 (dependencies 10, 11 and 12)



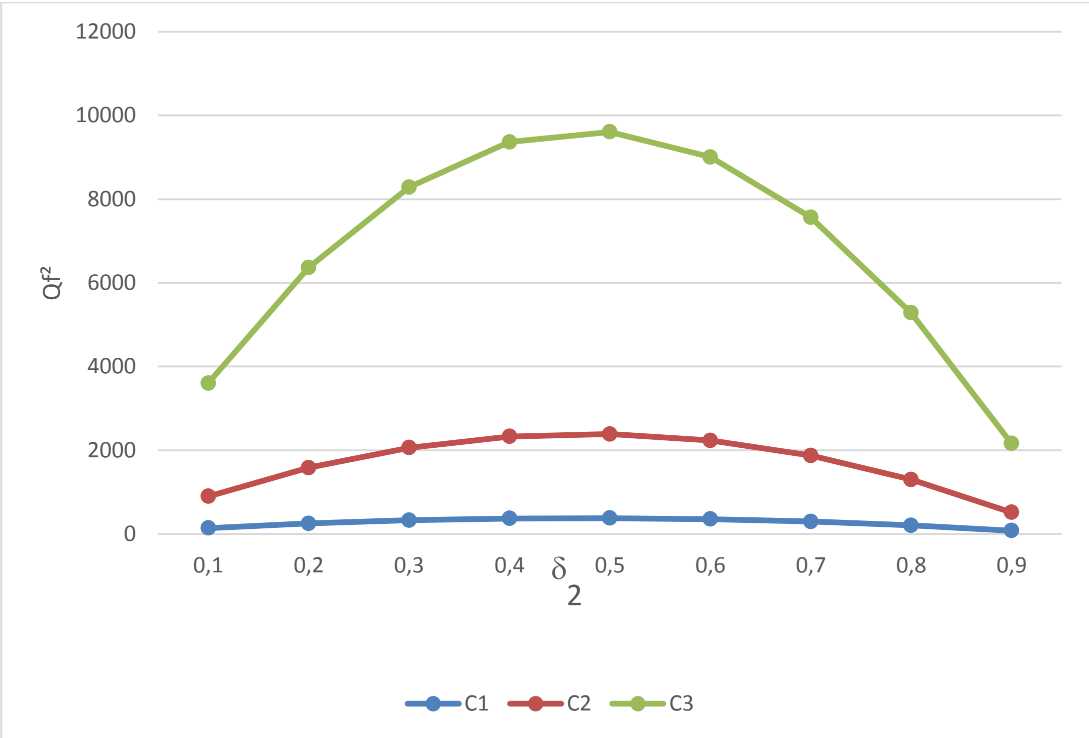
Figures 4.11 – Graphs are constructed in accordance with the data in table 4.7 (dependencies 13, 14 and 15)



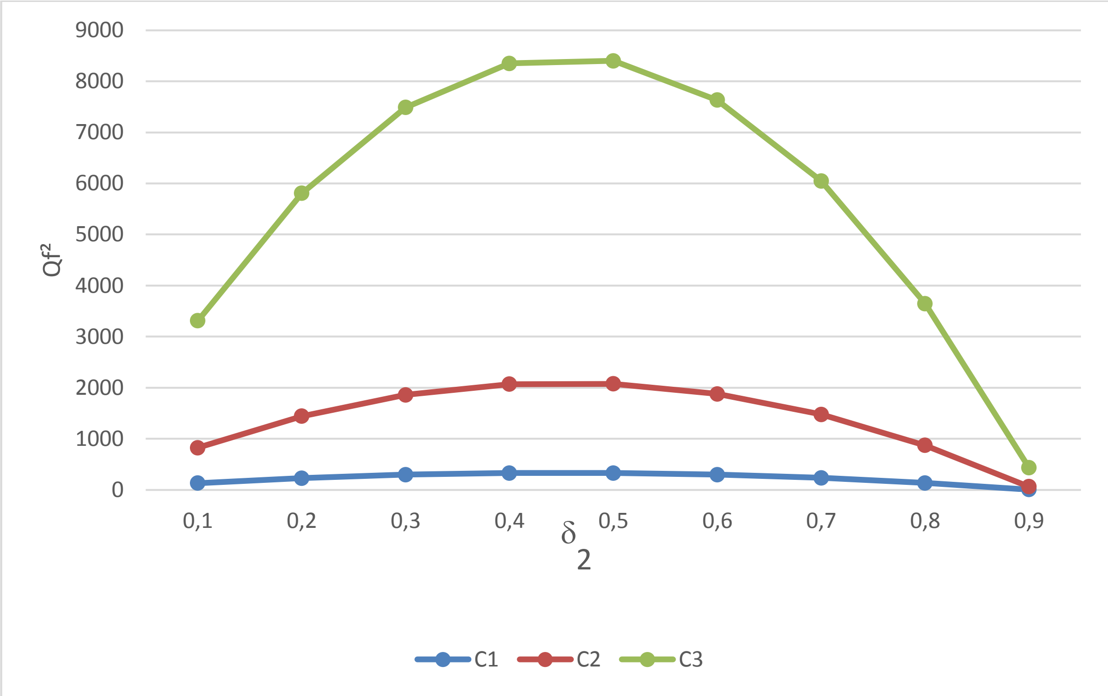
Figures 4.12 – Graphs are constructed in accordance with the data in table 4.7 (dependencies 16, 17 and 18)



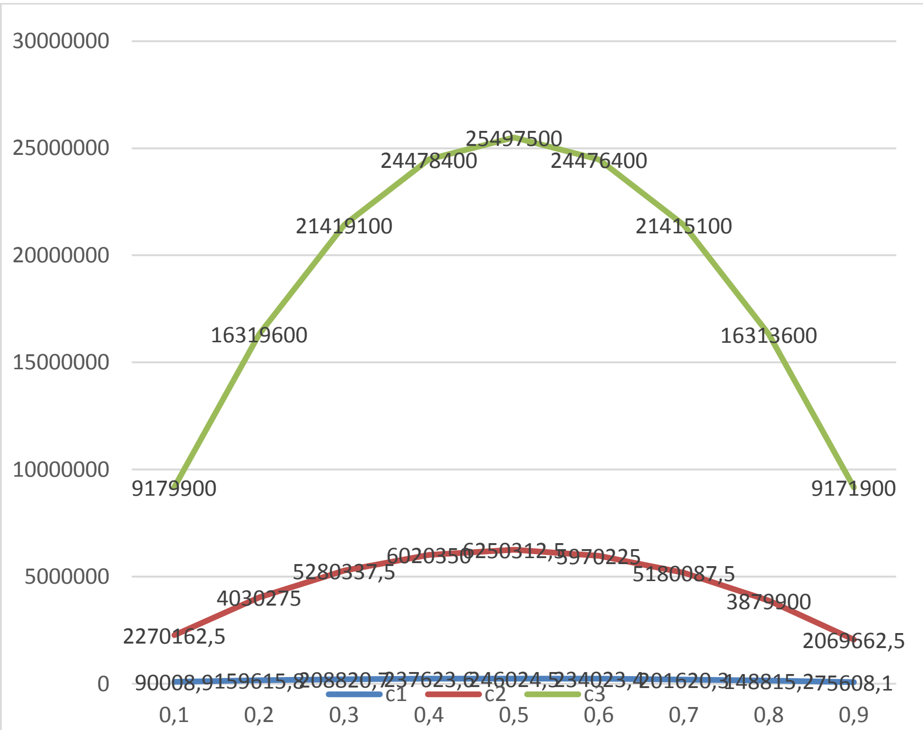
Figures 4.13 – Graphs are constructed in accordance with the data in table 4.7 (dependencies 19, 20 and 21)



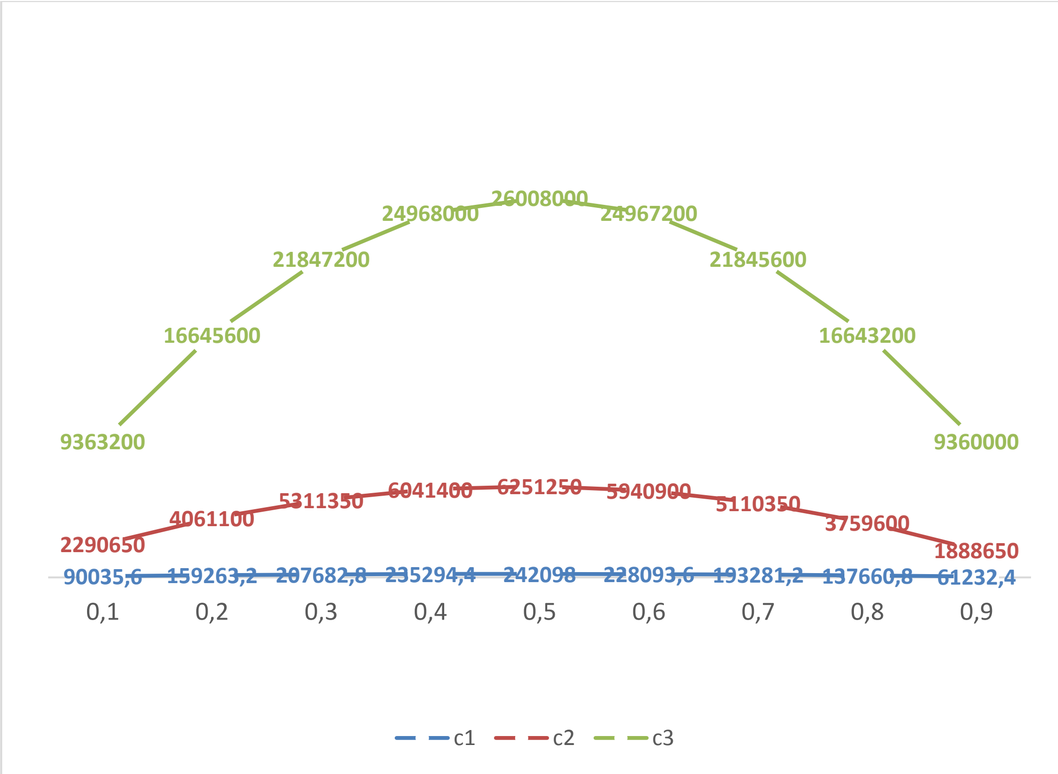
Figures 4.14 – Graphs are constructed in accordance with the data in table 4.7 (dependencies 22, 23 and 24)



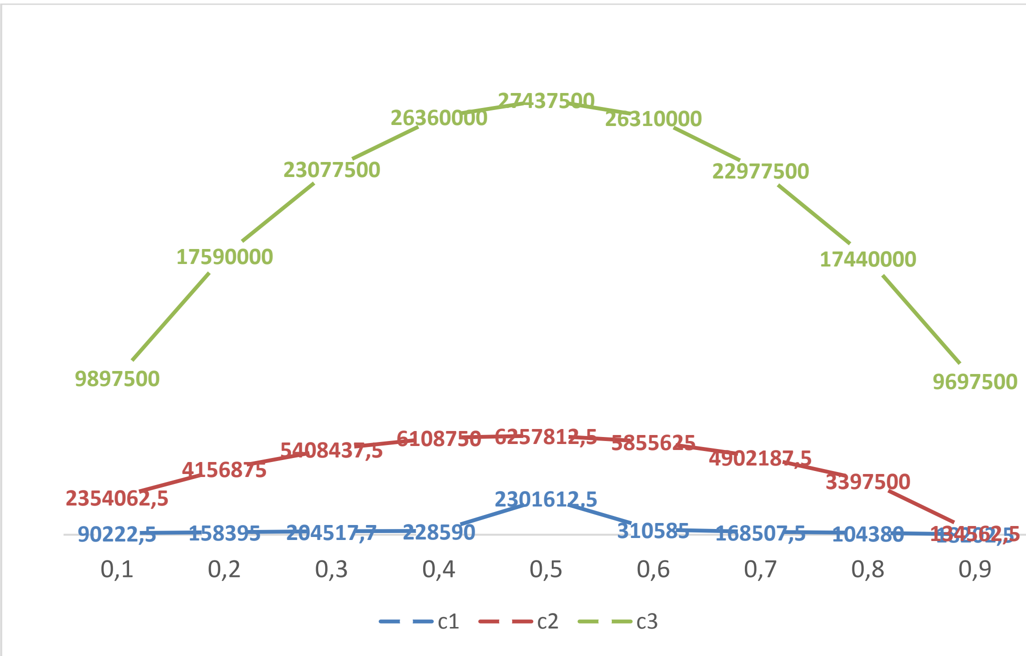
Figures 4.15 – Graphs are constructed in accordance with the data in table 4.7 (dependencies 25, 26 and 27)



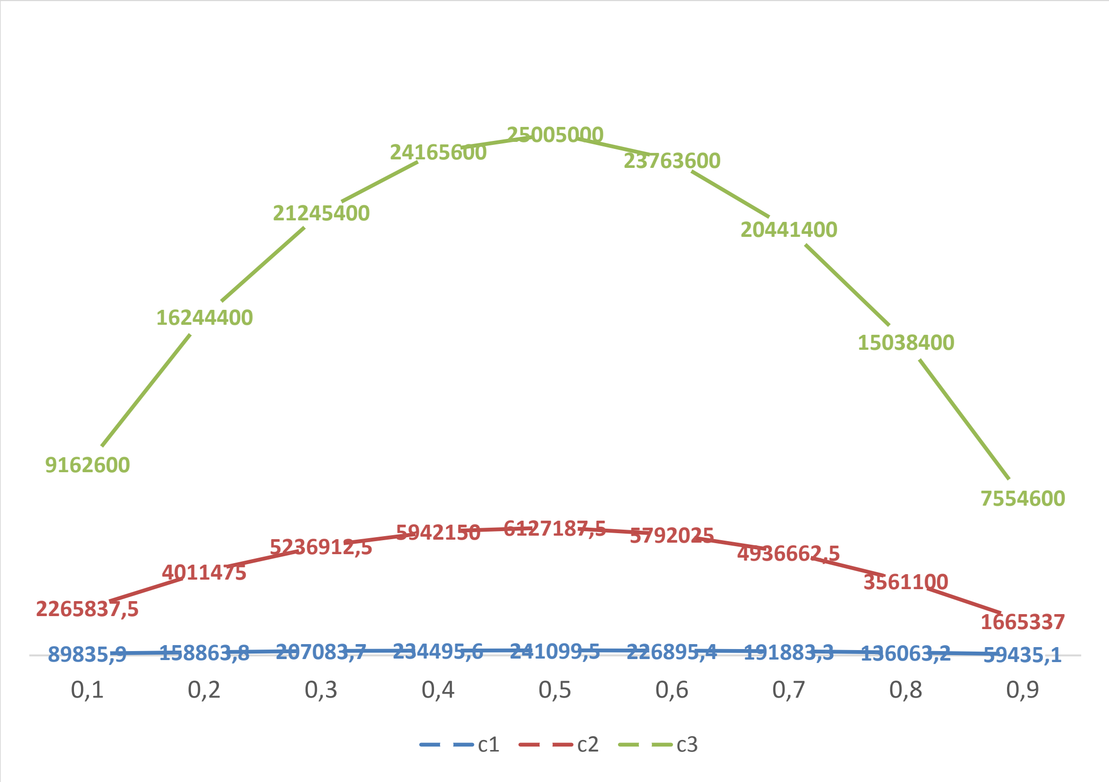
Figures 4.16– Graphs are constructed in accordance with the data in table 4.8 (dependencies 28, 29 and 30)



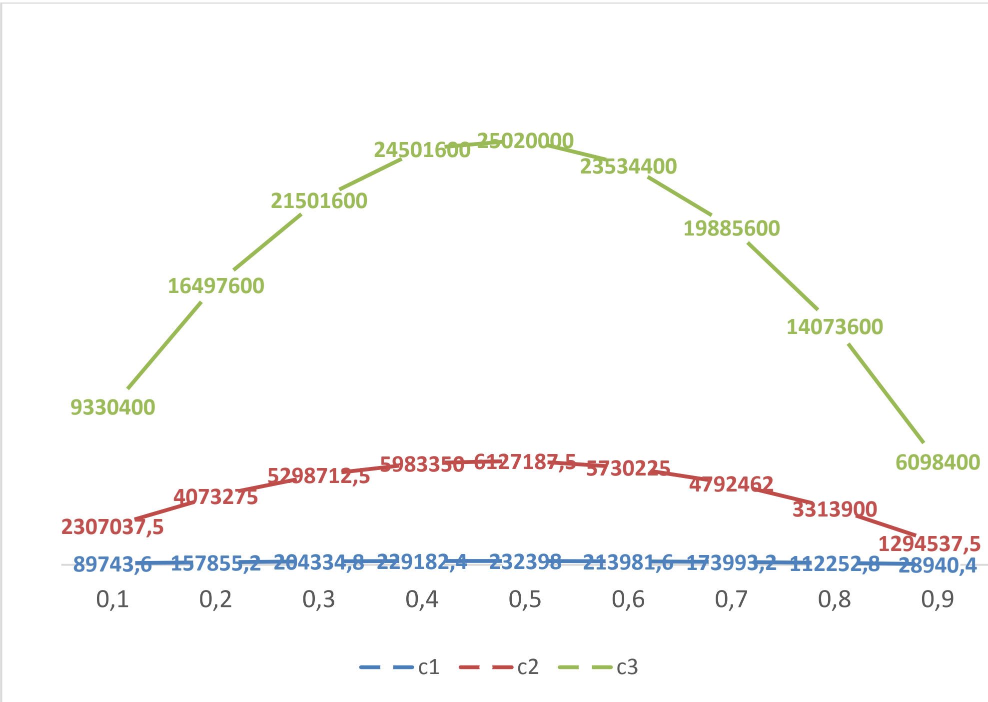
Figures 4.17 – Graphs are constructed in accordance with the data in table 4.8 (dependencies 31, 32 and 33)



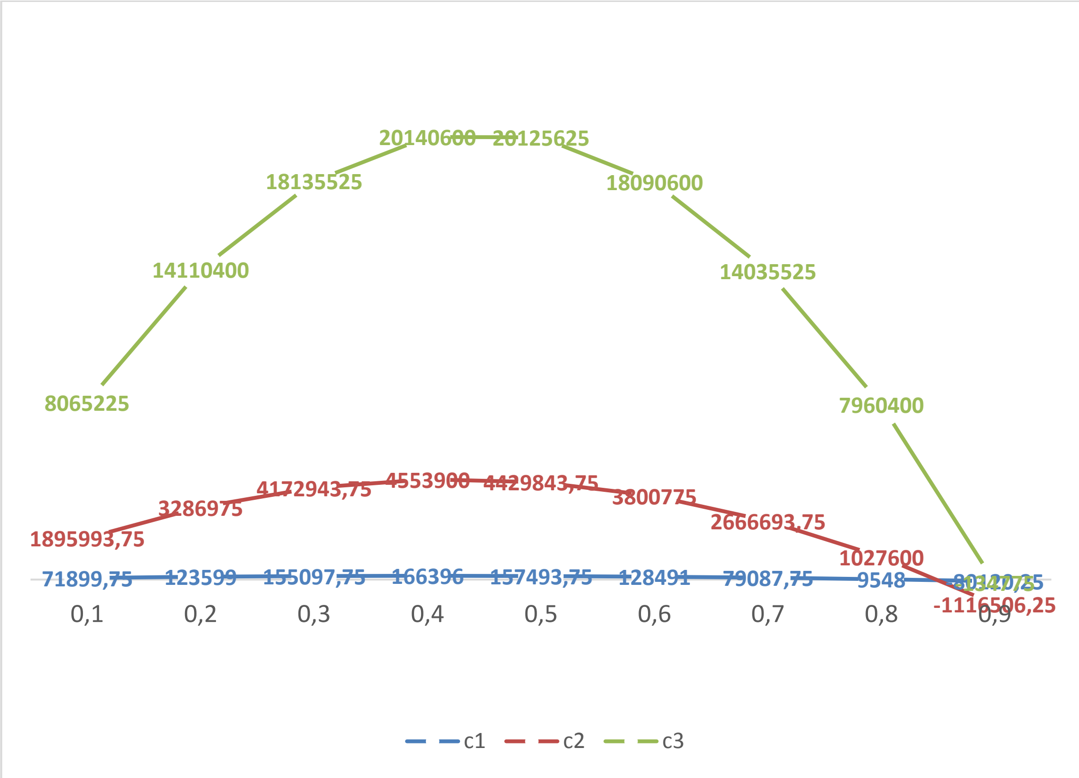
Figures 4.18 – Graphs are constructed in accordance with the data in table 4.8 (dependencies 34, 35 and 36)



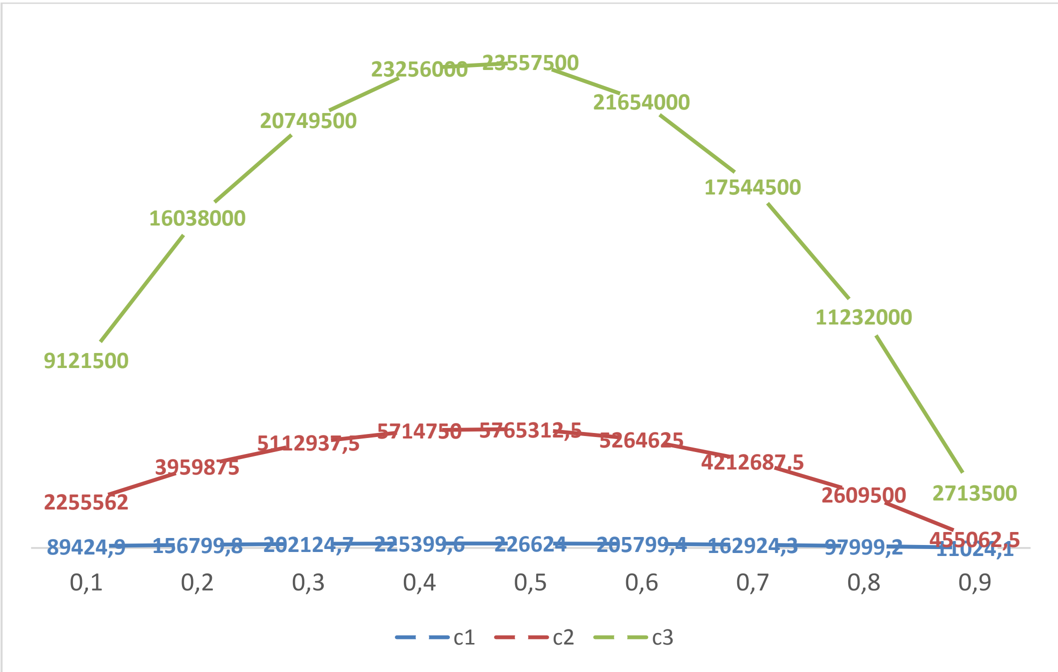
Figures 4.19 – Graphs are constructed in accordance with the data in table 4.8 (dependencies 37, 38 and 39)



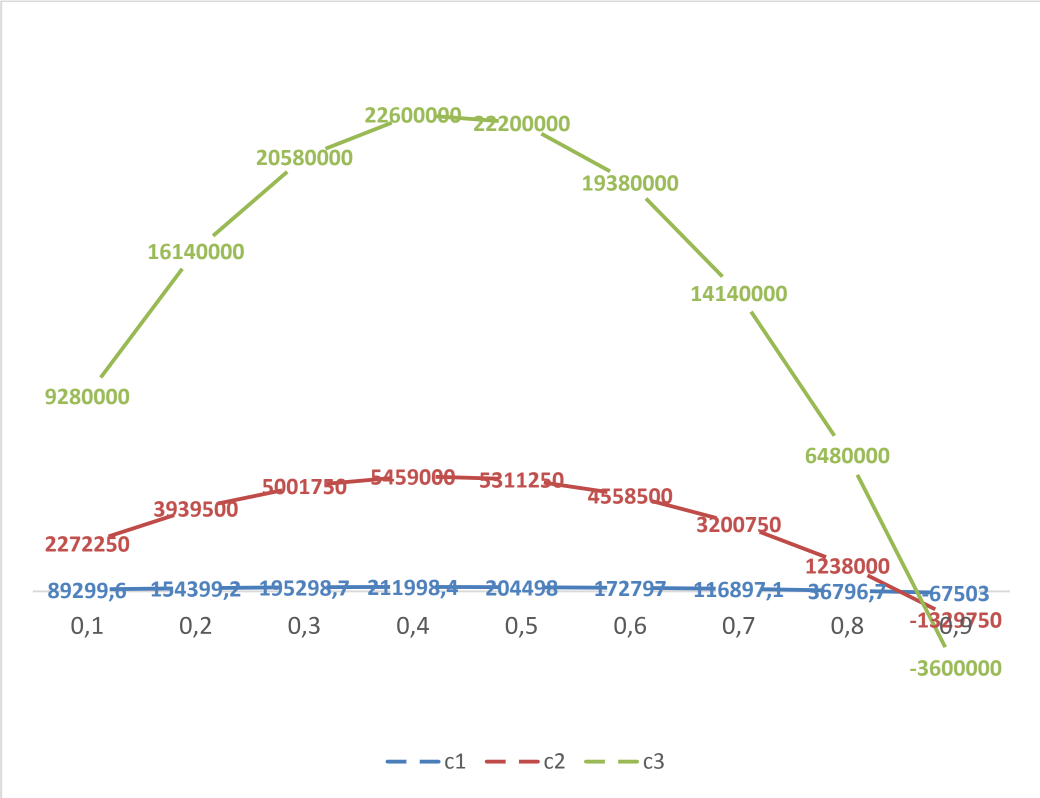
Figures 4.20 – Graphs are constructed in accordance with the data in table 4.8 (dependencies 40, 41 and 42)



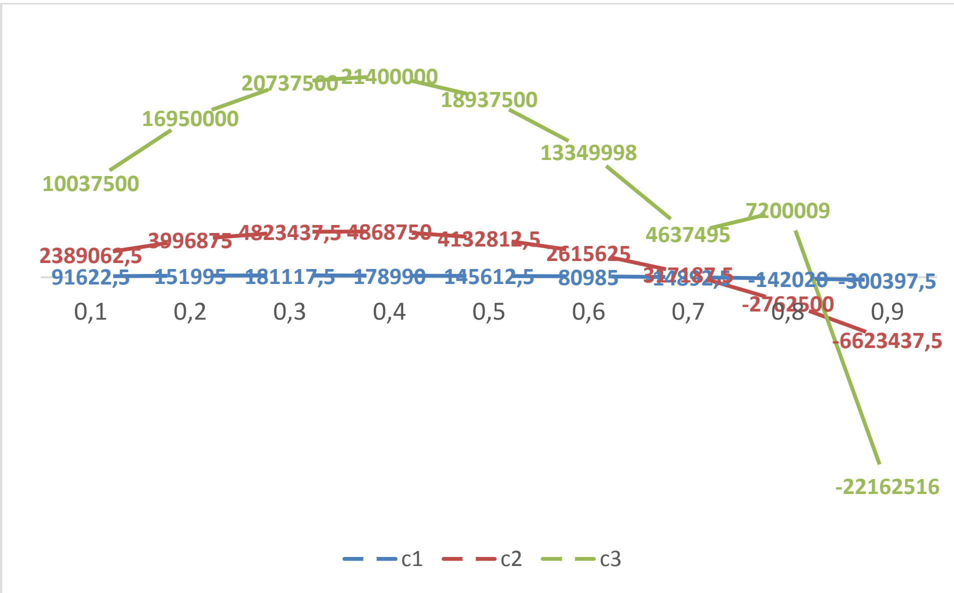
Figures 4.21 – Graphs are constructed in accordance with the data in table 4.8 (dependencies 43, 44 and 45)



Figures 4.22 – Graphs are constructed in accordance with the data in table 4.8 (dependencies 46, 47 and 48)



Figures 4.23 – Graphs are constructed in accordance with the data in table 4.8 (dependencies 49, 50 and 51)



Figures 4.24 – Graphs are constructed in accordance with the data in table 4.8 (dependencies 52, 53 and 54)

4.3. Algorithms for measuring reactive power of Frize in local power supply systems

We present two algorithms for calculating the reactive power of Frize.

Algorithm No. 1. Calculation of reactive power Q_F

1. Identification of generator and network parameters – determination of resistance values $R_{ВН}$ и R_L; determination of magnitude $R = R_{ВН} + R_L$.

2. Definition of nominal dress $U_Н = U_1$ (Mode 1).

3. Identification of load and load current measurements I_1 (Mode 1).

4. Fixing the moment of changing the power supply mode of the load t_R (Mode 2).

5. Estimation of the value of the interval of retrospective analysis Δt_1 (Mode 1) to determine the non-optimal processes in the system.

6. Determination of the interval Δt_2 of the duration of Mode 2:

7. Definition of quantities δ_1 и δ_2:

$\delta_1 = \Delta t_1 / (\Delta t_1 + \Delta t_2)$; $\delta_2 = \Delta t_2 / (\Delta t_1 + \Delta t_2)$.

8. Determination of the function of the load current consumption in the interval Δt_2 and its averaging, т.е. determination of magnitude I_2.

9. Determination of averaged voltage U_2 according to the expression

$U_2 = U_1 – R \cdot (I_2 – I_1) = U_1 – \Delta I \cdot R$.

10. Component definition

$Q_F{}^2{}_{(1)} = (U_1{}^2 (1 – \delta_2) + (U_1 – \Delta I \cdot R)^2 \delta_2) (I_1{}^2 (1 – \delta_2) + (I_1 + \Delta I)^2 \delta_2)$.

11. Definition of the component

$Q_F{}^2{}_{(2)} = (U_1 I_1 (1 – \delta_2) + (U_1 – \Delta I \cdot R) (I_1 + \Delta I) \delta_2)^2$.

12. Determination of the reactive power of Frieze in the interval Δt_2

$Q_F{}^2 = Q_F{}^2{}_{(1)} – Q_F{}^2{}_{(2)}$.

13. Assessment of the level of non-optimality of energy processes in the local power supply system for the selected Modes 1 and 2.

Algorithm No. 2. Evaluation of the forecast of non-optimality of processes in the power supply system

1. Identification of generator and network parameters - determination of resistance values $R_{ВН}$ и R_L; determination of magnitude $R = R_{ВН} + R_L$.

2. Definition of nominal dress $U_Н = U_1$ (Mode 1).

3. Identification of load and load current measurements I_1 (Mode 1).

4. Fixing the moment of changing the power supply mode of the load t_R (Mode 2).

5. Estimation of the value of the interval of retrospective analysis Δt_1 (Mode 1) to determine the non-optimal processes in the system.

6. Definition of a set $M_{t2} = \{\Delta t_{2,1}, \Delta t_{2,2}, \ldots, \Delta t_{2,i}, \ldots, \Delta t_{2,nt}\}$ interval lengths Δt_2 – Duration Mode 2.

7. Definition of Sets $M_{t\delta 1}$ и $M_{t\delta 2}$ changes in quantities $\delta_{1,i}$ и $\delta_{2,j}$ using ratios $\delta_1 = \Delta t_1 / (\Delta t_1 + \Delta t_2)$; $\delta_2 = \Delta t_2 / (\Delta t_1 + \Delta t_2)$:

$M_{t\delta 1} = \{ \delta_{1,1}, \delta_{1,2}, \ldots, \delta_{1,i}, \ldots, \delta_{1,n\delta 1}\}$;

$M_{t\delta 2} = \{ \delta_{2,1}, \delta_{2,2}, \ldots, \delta_{2,j}, \ldots, \delta_{2,n\delta 1}\}$.

8. Definition of a set $M_{I2} = \{I_{2,1}, I_{2,2}, \ldots, I_{2,i}, \ldots, I_{2,nt}\}$ load current consumption functions in the interval $\Delta t_{2,j}$, $j = 1, \ldots, n_t$, and its averaging, т.e. determination of a plurality of load current changes I_2 for Mode 2.

9. Definition of a set $M_{\Delta I} = \{\Delta I_1, \Delta I_2, \ldots, \Delta I_{,i}, \ldots, \Delta I_{nt}\}$ current change ΔI in the system according to the expression $\Delta I = I_2 - I_1$.

10. Definition of a set $M_{U2} = \{U_{2,1}, U_{2,2}, \ldots, U_{2,i}, \ldots, U_{2,nt}\}$ averaged stresses U_2 at according to the expression

$U_2 = U_1 - R\cdot(I_2 - I_1) = U_1 - \Delta I\cdot R$.

11. Definition of a set $M_{QF1} = \{Q_{F1,1}, Q_{F1,2}, \ldots, Q_{F1,i}, \ldots, Q_{F1,nt}\}$ the first component of the expression (4.10):

$Q_F{}^2{}_{(1)} = (U_1{}^2 (1 - \delta_2) + (U_1 - \Delta I\cdot R)^2\delta_2)\ (I_1{}^2 (1 - \delta_2) + (I_1 + \Delta I)^2\delta_2)$.

12. Definition of a set $M_{QF2} = \{Q_{F2,1}, Q_{F2,2}, \ldots, Q_{F1,i}, \ldots, Q_{F1,nt}\}$ the second

component of the expression (4):

$$Q_{F}{}^{2}{}_{(2)} = (U_1 I_1(1 - \delta_2) + (U_1 - \Delta I \cdot R)(I_1 + \Delta I)\delta_2)^2 .$$

13. Definition of constituent elements $M_{QF} = \{Q_{F1}, Q_{F2}, \ldots, Q_{Fj}, \ldots, Q_{F,nt}\}$ in accordance with the expression (4.10):

$$Q_{F}{}^{2}{}_{j} = Q_{F}{}^{2}{}_{(1),j} - Q_{F}{}^{2}{}_{(2),j}. \qquad (4.14)$$

14. Based on the sets $M_{QF} = \{Q_{F1}, Q_{F2}, \ldots, Q_{Fj}, \ldots, Q_{F,nt}\}$ (expression (4.14)) given the elements of the set $M_{t\delta 2}$, $M_{\Delta I}$ and M_{U2} assessment of permissible and unacceptable areas of change in energy consumption in the system from the point of view of ensuring optimal modes of power consumption.

15. Determining the list and the corresponding mechanisms for implementing energy efficiency measures (the formation of the DSM program elements by the consumer) of the consumer (allocated load).

16. Evaluation of the effectiveness of the operating modes of the local power supply system (formation of DSM program elements from the generator side).

17. Evaluation of the economic effect.

Conclusions to the chapter 4

1. When assessing the levels of suboptimal energy consumption in local power supply systems, the author proposed to refine the suboptimal processes in the case of active power consumption at higher harmonics (the presence of the same voltage and current harmonics).

2. The author derives formulas for calculating additional losses in local power consumption systems taking into account the internal resistance of the generator and the resistance of power lines. The constructed graphs illustrate the complex nature of the influence of the parameters of the elements of the system and its operating modes on the amount of additional electricity losses.

3. Developed by two algorithms for measuring reactive power of Frize in local power supply systems allow efficiently Determining the list and the corresponding mechanisms for implementing energy efficiency measures (the formation of the DSM program elements by the consumer) and performance evaluation of the effectiveness of the operating modes of the local power supply system (formation of DSM program elements from the generator side).

CONCLUSIONS

In the master's dissertation work the mechanisms of electricity demand management in local power supply systems based on the use of Frize power modification are improved and further developed.

1. To reach the delivered mark in the dissertation research, the following tasks were addressed: analyze the mechanisms of demand management in modern energy supply systems; evaluate special features of modern decentralized (dispersed) power generation systems; take a look at the methods for assessing the total energy loss in local electrical networks; evaluate the levels of non-optimality of energy consumption taking into account the parameters of local power supply systems, in particular, when active power is consumed at higher harmonics (the presence of voltage and current harmonics of the same name), as well as taking into account the internal resistance of electric power generators and power line resistances; to develop algorithms for measuring the reactive power of Frize in local power supply systems.

2. It is shown that the benefits from demand management can vary significantly depending on the configuration of the power system, the assessment methodology, and especially on the approaches taken to the construction of generating facilities. Where generation and networks are built to cover peak loads, the peak load may be higher than optimal if market prices do not fully reflect the cost of delivery during peak hours. In such circumstances, demand management can effectively eliminate the inadequacy of price signals and help avoid the construction of excess generation.

3. The first chapter analyzes the mechanisms for managing demand in modern energy supply systems, in particular, the set of mechanisms for managing demand for electricity, the benefits and barriers of managing efficiency and effectiveness. The comparison of the Demand Side Management mechanisms and the provisions of the Smart Grid concession is carried out, the concept of the functioning of the aggregated

generating company is characterized.

4. The second chapter presents the characteristics of modern decentralized (dispersed) power generation systems, the development of Microgrid as modern local power supply systems. The analysis of the features of the construction and functioning of modern dispersed generation systems, the integration of renewable energy sources and the internal connection of components, the alignment mechanisms of load schedules and methods for approximating experimental data and building models.

5. Chapter 3 provides an assessment of the total energy losses in local electric networks, in particular, the components of electric energy losses in the system, and analyzes the structure of additional electric losses, additional and necessary power losses in three-phase local systems, as well as total energy losses in local electric networks.

6. An assessment of the optimality levels of energy consumption taking into account the parameters of local power supply systems is presented in the fourth chapter. The practical significance of the obtained results is: (1) in the formation of a number of ratios to assess the levels of suboptimal transmission and consumption of electricity at active power consumption at higher harmonics (presence of the same voltage and current harmonics) and taking into account the internal resistance of power generators and transmission lines; (2) in the development of software-oriented algorithms for measuring the reactive power of Frieze in local power supply systems, allowing to upgrade the DSM program.

Software modeling, in particular Microsoft Excel spreadsheets, was used to verify the obtained data and original relationships.

7. The annex gives the characteristics of the basic definitions that are used in the work, assesses the features of introducing renewable energy sources in Algeria, gives a description of the basic DSM programs.

8. The results of the study were published at two international scientific and

technical conferences and included in the collections of works:

1) Denysiuk S.P., Chouakria Abdeldjalil "Mechanisms for managing the demand for electricity of industrial enterprises" (7 pages) – Annual scientific-practical international conference "PERSPECTIVE SCIENTIFIC TRENDS‘2020"; April 21–22, 2020, Beltsu, Moldova;

2) Denysiuk S.P., Chouakria Abdeldjalil "Demand-side management mechanisms for industrial enterprises" (6 pages) – XIV International Scientific and Practical Conference "ACTUAL PROBLEMS OF SCIENCE AND PRACTICE"; April 27–28, 2020, Stockholm, Sweden.

LIST OF REFERENCES

1. IEA (International Energy Agency), «Re-Powering Markets. Market design and regulation during the transition to low-carbon power systems», Second Edition, (March 2016), https://www.iea.org/publications/freepublications /publication/ REPOWERINGMARKETS.PDF

2. Navigant Research, «Global Demand Response Capacity is Expected to Grow to 144 GW in 2025», 2016, https://www.navigantresearch.com/newsroom/ global-demand-response-capacity-is-expected-to-grow-to-144-gw-in-2025

3. PA Consulting Group, «Aggregators - Barriers and External Impacts», prepared for Ofgem (Office of Gas and Electricity Markets), May 2016, https://www.ofgem.gov.uk/system/files/docs/2016/07/aggregators_barriers_and_external_impacts_a_report_by_pa_consulting_0.pdf

4. Денисюк С.П., Таргонський В.А. Енергоефективність України: проблеми та шляхи її зростання // Енергетика: економіка, технології, екологія : науковий журнал. – 2017. – № 4 (50). – С. 7–28.

5. http://www.ieadsm.org/

6.Technology Roadmap "SmartGrids", 2015; Ten Year Network Development Plan, 2014.

7. Synapse Energy Economics, «Best Practices in Utility Demand Response Programs», Prepared for Regroupement national des conseils régionaux de l'environnement du Québec (RNCREQ), 31.03.2017, http://www.synapse-energy.com/sites/default/files/Utility-DR-17-010.pdf

8. Brattle Group «International Review of Demand Response Mechanisms», prepared for the Australian Energy Market Commission, October 2015, http://files.brattle.com/files/5887_aemc_report.pdf

9. SEDC (Smart Energy Demand Coalition), «Mapping Demand Response in Europe Today 2015», 30.09.2015, http://www.smarten.eu/wp-content/uploads/2015/09/Mapping-Demand-Response-in-Europe-Today-2015.pdf

10. Дзюба А.П., Соловьева И.А. Управление спросом на электроэнергию в России: состояние и перспективы // Стратегические решения и риск-менеджмент. – 2018. – 2018. – № 1 (106). – С. 72–79.

11. Нехороших И.Н., Добринова Т.В., Анисимов А.Ю., Жагловская А.В. Мировая практика управления спросом на электроэнергию // Экономика в промышленности. – 2019. – Том.12, № 3. – С. 280–287.

12. https://www.ferc.gov/legal/staff-reports/06-09-demand-response.pdf

13. https://www.navigantresearch.com/newsroom/global-demand-response-capacity-is-expected-to-grow-to-144-gw-in-2025

14. https://www.ofgem.gov.uk/system/files/docs

15. http://www.smarten.eu/explicit-demand-response-in-europe-mapping-the-markets-2017/

16. Demand-side Management Strategies and the Residential Sector. Lessons from International Experience / Haney A. B., Jamasb T., Platchkov L. M., Pollitt M. G. [Электронный ресурс]. URL: www.eprg.group.cam.ac.uk

17. Understanding Cost-Effectiveness of Energy Efficiency Programs: Best Practices, Technical Methods, and Emerging Issues for Policy-Makers. [Электронный ресурс]. URL: http://www.epa.gov/cleanenergy/documents/suca/cost-effectiveness.pdf

18. Open Power System Data. 2017. Data Package Time series. [Online] Version: 2017-07-09, 20. 11 2017. https://data.open- power-system-data.org/time_series/2017-07- 09/. (Primary data from various sources, for a complete list see URL).

19. Demand Planing in the '80s. *EPRI JOURNAL - The Customer Behind the Demand*. Palo Alto, California : s.n., 1984. Bd. 09, 10.

20. Erneuerbare Energien in Zahlen - Nationale und internationale Entwicklung im Jahr 2016. Berlin: Bundesministerium für Wirtschaft und Energie (BMWi), 2017.

21. Nachholeffekte bei der Erbringung von Regelleistung durch flexible

Lasten. Berlin : TU Berlin, 2017.

22. Nadel, Steven «Demand response programs can reduce utilities' peak demand an average of 10%, complementing savings from energy efficiency programs», 09.02.2017, http://aceee.org/blog/2017/02/demand-response-programs-can-reduce

23. Гуртовцев А., Забелло Е. Электрическая нагрузка энергосистемы. Выравнивание графика. – Новости электротехники. 2008. № 5, 6.

24. Аюев Б.И. Методы и модели эффективного управления режимами управления Единой электроэнергетической системы России: Дис. На соиск. учен. Степени д-ра техн. наук. Екатеринбург, УПИ, 2008.

25. Peak Load Management Alliance «Demand Response Acronyms & Glossary. Training Course Resource», 1st Edition (May 2017), https://www.peakload.org/assets/PLMADR%20_AcronymsGlossary_053117.pdf,

26. IEA (International Energy Agency), «Digitalization & Energy», 2017,

http://www.iea.org/publications/freepublications/publication/Digitalizationand Energy3.pdf

27. Схема и программа развития Единой энергетической системы Росси на 2014–2020 годы. Утверждена Приказом Минэнерго России 01.08.2014. (http://www.minenergo.gov.ru/documents/fold13/index.php? ELEMENT_ID=19356)

28. Виртуальную электростанцию рассмотрели с разных точек зрения // Энергетика и промышленность (http://www.dveuk.ru/press/2/2013-04-16_.htm, http://www.e-c-m.ru/seminars/doc/UER_2013_11.pdf)

29. Hurley D., Peterson P., Whited M. (Synapse Energy Economics), «Demand Response as a Power System Resource: Program Designs, Performance, and Lessons Learned in the United States», prepared for Regulatory Assistance Project (RAP), May 2013, https://www.raponline.org/wp-content/uploads/ 2016/ 05/synapse-hurley-demandresponseasapowersystemresource-2013-may-31.pdf

30. SEDC (Smart Energy Demand Coalition), «Enabling independent

aggregation in the European electricity markets. Roles and Responsibilities: Keeping the BRP whole after a demand response event. Position Paper», February 2015, http://smartenergydemand.eu/wp-content/uploads/2015/02/SEDC-Enabling-Independent-Aggregation.pdf

31. SEDC (Smart Energy Demand Coalition), «Explicit Demand Response in Europe. Mapping the Markets 2017», 2017, http://www.smarten.eu/explicit-demand-response-in-europe-mapping-the-markets-2017/

32. DREAM-GO, «Identified Short and Real-Time Demand Response Opportunities and the Corresponding Requirements and Concise Systematization of the Conceived and Developed DR Programs», March 2017, http://dream-go.ipp.pt/PDF/DREAM-GO_Deliverable2.1.pdf

33. Lasseter, R.H., P. Piagi, "Microgrid: A Conceptual Solution," PESC'04 Aachen, Germany, 20-25 June 2004

34. Horowitz, S, A. Phadke, B. Renz, "The Future of Power Transmission," IEEE Power and Energy, vol.8, no.2, pp. 34-40, March/April 2010.

35. Nourai, Ali and David Kearns, "Batteries Included," IEEE Power and Energy, vol.8, no.2, pp. 49-54, March/April 2010.

36. Nikkhajoei, H., R. Lasseter, "Distributed Generation Interface to the CERTS Microgrid," IEEE Transactions on Power Delivery, vol. 24, issue 3, pp. 1598-1608, July 2009/

37. Жаркин А.Ф., Денисюк С.П., Попов В.А. Системы электроснабжения с источниками распределенной генерации. – К.: Наукова думка. – 2017. – 230 с.

38. Zhuykov V.Ya., Denisyuk S.P. Energy processes in electrical systems with key elements. – K .: Text, 2010 . – 264 p.

39. Маркович И.М. Режимы энергетических систем. – М.: Энергия, 1969.

40. Некрасов С.А., Матюнина Ю.В., Цырук С.А. О подходах к решению проблемы неравномерности графика нагрузки // Промышленная энергетика. - 2015. - № 5. - С. 2-8.

41. Математика: Энциклопедия / под ред. Ю.В. Прохорова.– М.: Большая Российская энциклопедия, 2003.

42. Ахиезер Н.И. Лекции по теории аппроксимации / Н.И. Ахиезер.– М.: Наука. Гл. ред. физ.-мат. лит., 1965.

43. Тихомиров В.М. Некоторые вопросы теории приближений / В.М. Тихомиров. М.: Наука. Гл. ред. физ.-мат. лит., 1976.

44. Корн Г. Справочник по математике (для научных работников и инженеров) / Г. Корн, Т. Корн. – М.: Наука. Гл. ред. физ.-мат. лит., 1973.

45. Бронштейн И.Н. Справочник по математике для инженеров и учащихся ВТУЗов / И.Н. Бронштейн, К.А. Семендяев.– М.: Наука. Гл. ред. физ.-мат. лит., 1980.

46. Гуртовцев А.Л., Забело Е.П. Выравнивание графиков электрической нагрузки энергосистемы // Энергетика и ТЭК. − 2008. − № 7/8. − С. 13−20.

47. Гуртовцев А.Л., Забелло Е.П. Электрическая нагрузка энергосистемы. Выравнивание графика // Новости электротехники. − 2008. − № 5(53). − С. 108−114.

48. http://interenergoportal.ru/regulirovanie-rezhimov-elektropotrebleniya.html. «Энергетический бизнес» (7.04.2013 г.).

49. http://www.energetika.by/arch/~page__m21=10~news__m21=169 Выравнивание графика электрической нагрузки энергосистемы.

50. http://electrolibrary.narod.ru/3/37.htm . Графики нагрузок потребителей электрической энергии.

51. Тонкаль В.Е. Баланс энергии в электрических цепях / В.Е. Тонкаль, А.В. Новосельцев, С.П. Деисюк и др. – К.: Наук. Думка. – 1992. – 312 с.

52. Шклярский Я.Е., Пирог С. Влияние графика нагрузки на потери в электрической сети предприятия // Записки Горного института. – 2016. – Т.222. – С. 858–863.

ANNEXES

Annexes A. Basic definitions

1) Demand Side Management:

Energy demand management, also known as demand-side management (DSM) or demand-side response (DSR), is the modification of consumer demand for energy through various methods such as financial incentives and behavioral change through education. Usually, the goal of demand-side management is to encourage the consumer to use less energy during peak hours, or to move the time of energy use to off-peak times such as nighttime and weekends. Peak demand management does not necessarily decrease total energy consumption, but could be expected to reduce the need for investments in networks and/or power plants for meeting peak demands. An example is the use of energy storage units to store energy during off-peak hours and discharge them during peak hours. A newer application for DSM is to aid grid operators in balancing intermittent generation from wind and solar units, particularly when the timing and magnitude of energy demand does not coincide with the renewable generation. The American electric power industry originally relied heavily on foreign energy imports, whether in the form of consumable electricity or fossil fuels that were then used to produce electricity. During the time of the energy crises in the 1970s, the federal government passed the Public Utility Regulatory Policies Act (PURPA), hoping to reduce dependence on foreign oil and to promote energy efficiency and alternative energy sources. This act forced utilities to obtain the cheapest possible power from independent power producers, which in turn promoted renewables and encouraged the utility to reduce the amount of power they need, hence pushing forward agendas for energy efficiency and demand management. The term DSM was coined following the time of the 1973 energy crisis and 1979 energy crisis. Governments of many countries mandated performance of various programs for demand management. An early example is the National Energy Conservation Policy Act of 1978 in the U.S., preceded by similar actions in California and

Wisconsin. Demand-side management was introduced publicly by Electric Power Research Institute (EPRI) in the 1980s. Nowadays, DSM technologies become increasingly feasible due to the integration of information and communications technology and the power system, new terms such as integrated demand-side management (IDSM), or Smart Grid.

Demand side flexibility is needed in order to effectively integrate renewables and distributed generation in the future energy system. The enabling of flexibility involves many different aspects from the technical capabilities of equipment (e.g. heat-pumps, storages, photovoltaic systems), consumer behavior to aggregation for market participation – and will lead to new services for the energy system.

2) Energy Efficiency:

Energy efficiency, means using less energy to provide the same level of energy. It is therefore one method to reduce human greenhouse gas emissions.

For example, if a house is insulated, less energy is used in heating and cooling to achieve a satisfactory temperature. Another example is installing fluorescent lights or skylights, instead of incandescent lights, to attain the same level of illumination. Efficient energy use is achieved primarily by means of a more efficient technology or process. Energy efficient buildings, industrial processes and transportation could reduce the world's energy needs in 2050 by one third, and help controlling global emissions of greenhouse gases.

Making homes, vehicles, and businesses more energy efficient is seen as a largely untapped solution to addressing global warming, energy security, and fossil fuel depletion. The 1973 oil crisis, where oil prices were very high, focussed attention on energy efficiency. For example, the state of California began implementing energy-efficiency laws in the mid-1970s, including building code and appliance standards with strict efficiency requirements.

3) Distributed Generation:

Distributed generation is an approach that employs small-scale technologies to produce electricity close to the end users of power. DG technologies often consist of modular (and sometimes renewable-energy) generators, and they offer a number of potential benefits. In many cases, distributed generators can provide lower-cost electricity and higher power reliability and security with fewer environmental consequences than can traditional power generators.

In contrast to the use of a few large-scale generating stations located far from load centers--the approach used in the traditional electric power paradigm--DG systems employ numerous, but small plants and can provide power onsite with little reliance on the distribution and transmission grid. DG technologies yield power in capacities that range from a fraction of a kilowatt [kW] to about 100 megawatts [MW]. Utility-scale generation units generate power in capacities that often reach beyond 1,000 MW.

4) Renewable energy sources:

Renewable energy (sources) or RES capture their energy from existing flows of energy, from on-going natural processes, such as sunshine, wind, flowing water, biological processes, and geothermal heat flows. The most common definition is that renewable energy is from an energy resource that is replaced rapidly by a natural process such as power generated from the sun or from the wind. Most renewable forms of energy, other than geothermal and tidal power, ultimately come from the Sun. Some forms are stored solar energy such as rainfall and wind power which are considered short-term solar-energy storage, whereas the energy in biomass is accumulated over a period of months, as in straw, or through many years as in wood. Capturing renewable energy by plants, animals and humans does not permanently deplete the resource. Fossil fuels, while theoretically renewable on a very long time-scale, are exploited at rates that may deplete these resources in the near future. Renewable energy resources may be used directly, or used to create other more convenient forms of energy. Examples of direct use are solar ovens, geothermal heating, and water- and windmills.

Annexes B. Renewable energy situation in Algeria

Solar Energy:

Algeria first introduced solar energy, in 1988, into the Southern project. Algeria started preparing larger cities, like Skikda and Oran, with the adequate equipment to improve the potential of solar energy as all. Solar energy can be generated either through the installation of CSP (Concentrated Solar power Plant) system, or the PV(Photovoltaic) system.

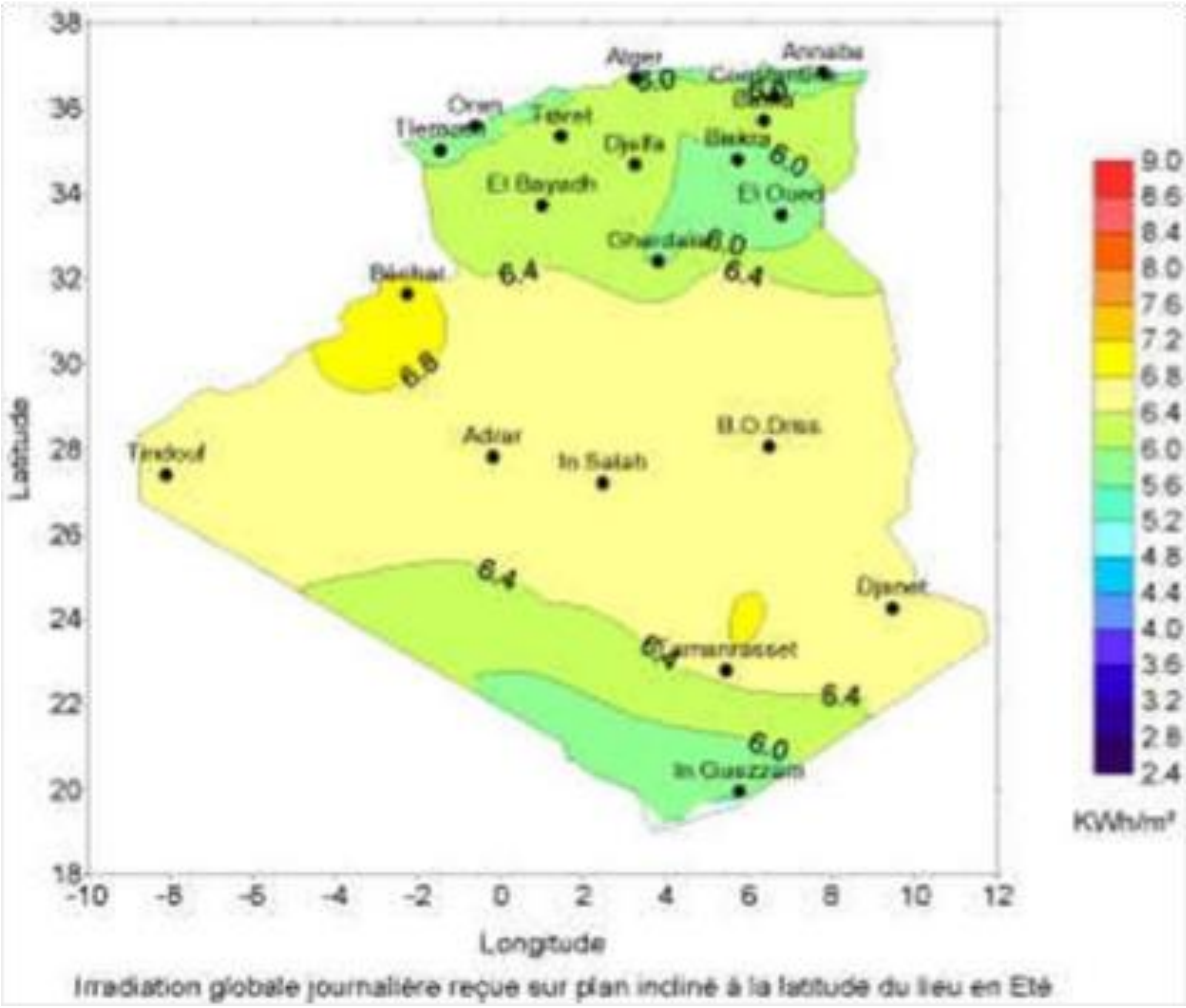


Figure B.1 – Algeria’s daily global irradiation on inclined plane received in summer (Source: Renewable Energy Development Center Algeria)

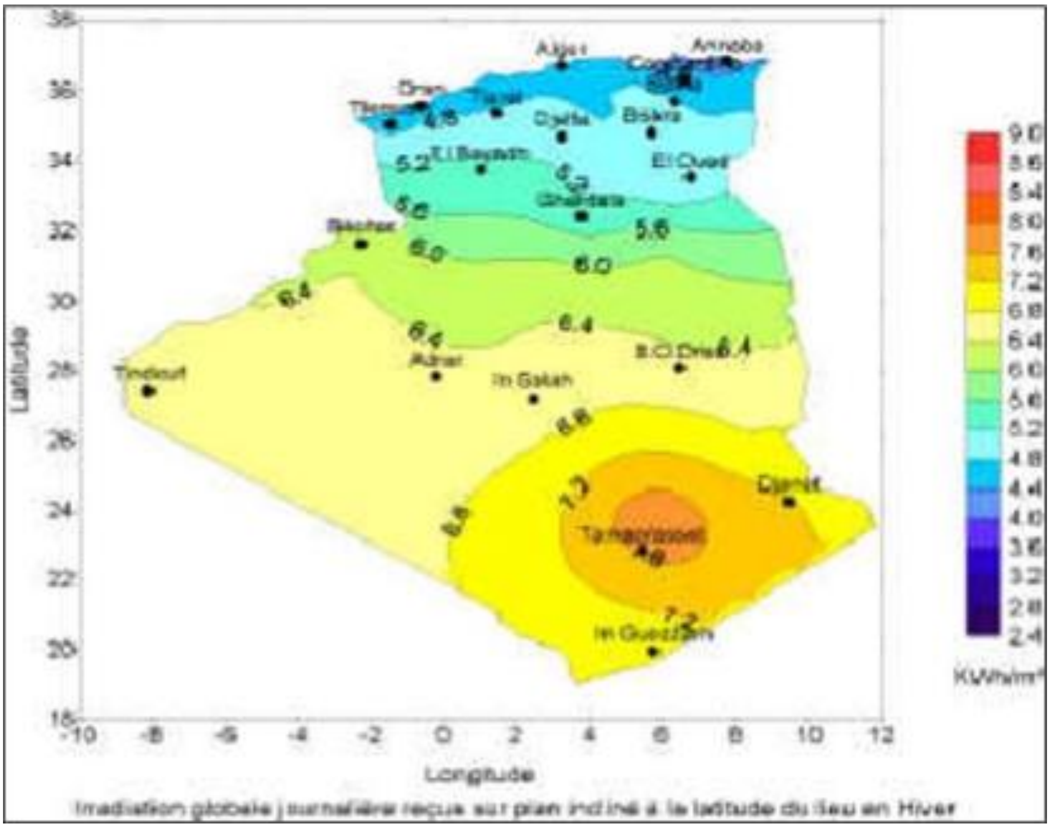


Figure B2 – Algeria’s daily global irradiation on inclined plane received in winter (Source: Renewable Energy Development Center Algeria)

Biomass Fuel

To generate fuel through biological processes may require a couple of restrictions. To succeed in generating biofuel, you have to have vast areas of Greenland and not just that, but also to be ready to use them in your generation process. Luckily, Algeria has plenty of agricultural lands and a high quality of unpolluted soil fully rich with minerals, making it a good call to plant soybeans, corn and wheat.etc. for energy purposes. “To each his own biofuel feedstock” - that is what Nakheel, an Algerian biotech company must have thought when it took decision to research and invest in bioethanol production using dates from the abundantly growing palm trees in North Africa and the Near East as a raw material.

The Deglet Nour date originally comes from Algeria, which is still the world's largest producer of Deglet Nour dates. It is grown predominantly in the Biskra province of Algeria, in the oases of Tolga and M'Chouneche. Biofuel also is based on animals' waste, as their waste usually is responsible for many pollution problems, but can be solved through the generation of renewable energy out of it. Animal or plants waste eventually can be turned into high-calorie energy source.

Figure B3 – palm trees crop waste, mostly seen in southeastern region (Source: Renewable Energy Development Center Algeria)

Wind Energy

Wind power usually ranges from a topographic area to another, also it depends on the climate too. Algeria's climate ranges greatly between the northern and the southern halves of Algeria. Northern half, is unique because it acquires an ideal location on the Mediterranean, it has the Atlas Mountains and other high plains. But the northern winds aren't as strong as the southern ones. The southern winds speeds range from 4m/s - 6m/s, but most southern lands are lower in latitude than the northern region, whereas desert represents more the 70% of the total Algerian surface area. Adrar is considered to be the most suitable place as it's famous for operating, and providing strong winds. Having strong winds around a high hill or ridge can provide a good power plant.

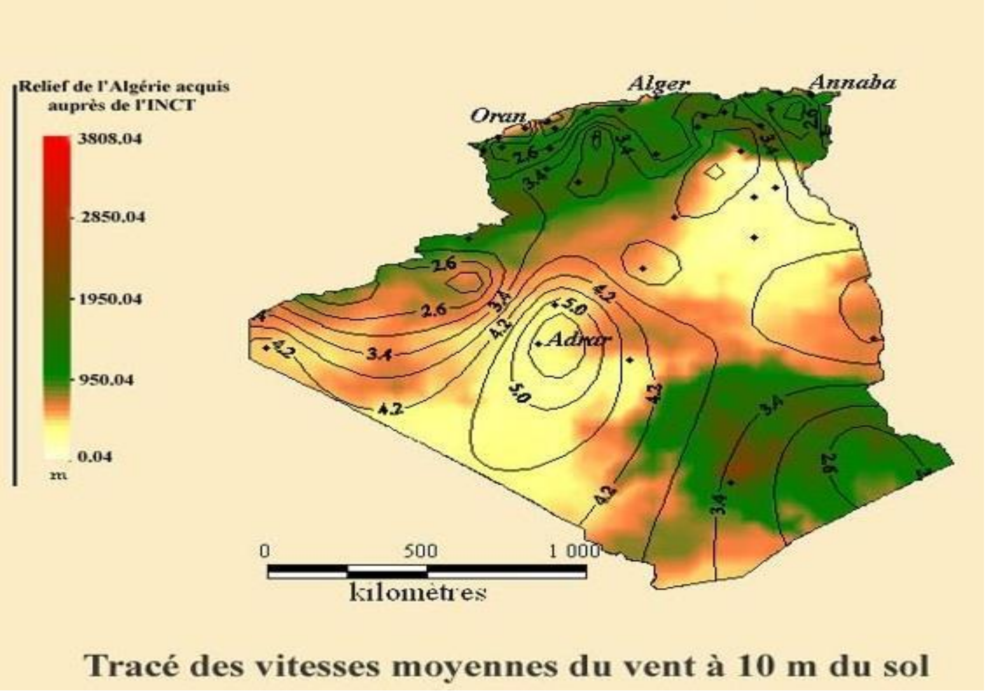


Figure B4 – Algeria's average wind speeds to 10 m above ground (Source: Renewable Energy Development Center Algeria)

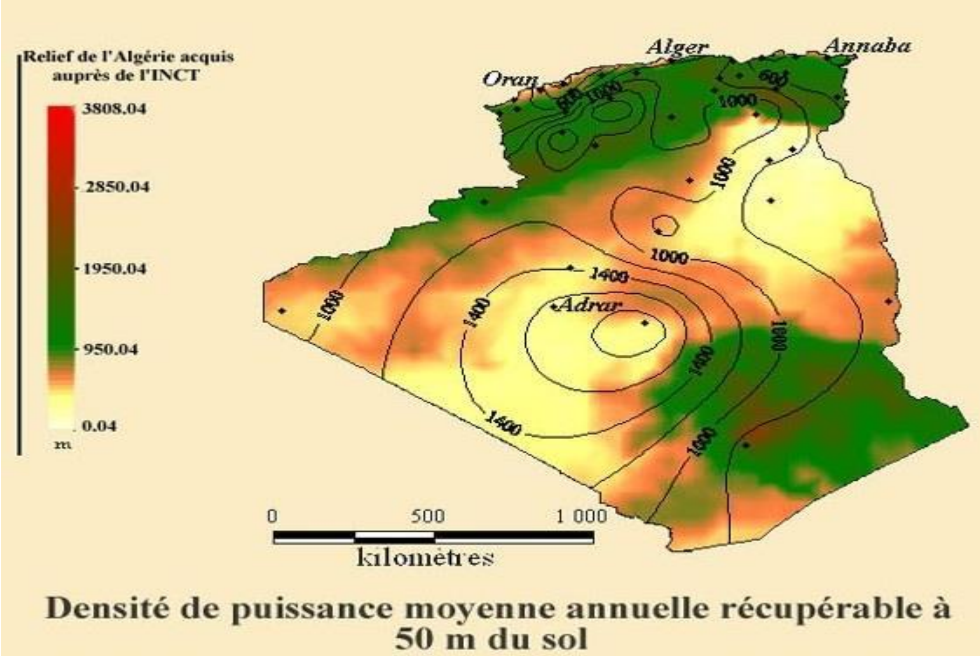


Figure B5 – Algeria's average wind speeds to 50 m above ground (Source: Renewable Energy Development Center Algeria)

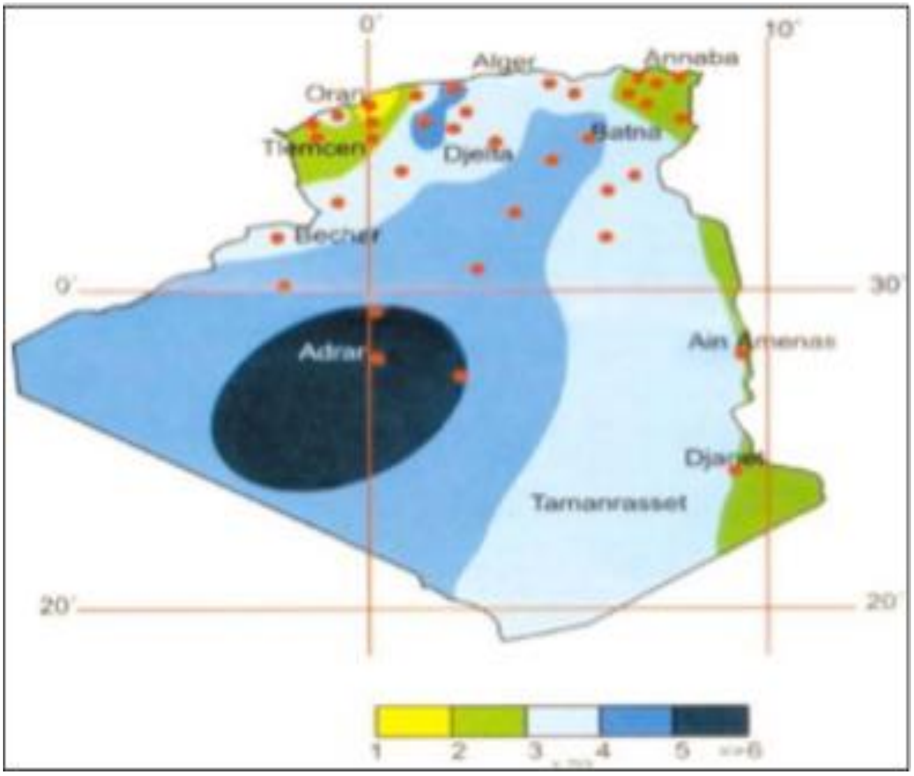


Figure B6 – Algeria's average wind speeds by area (Source: Renewable Energy Development Center Algeria)

Geothermal Energy

Algeria is famous for its cluster of hot springs, as there exists, more than 200 hot springs all around the country. They been used mostly for leisure and therapeutic purposes, widely recognized by locals. With such amount of hot springs in a country, it can be taken into consideration to take use of the pressurized heat and make useful work out of it.

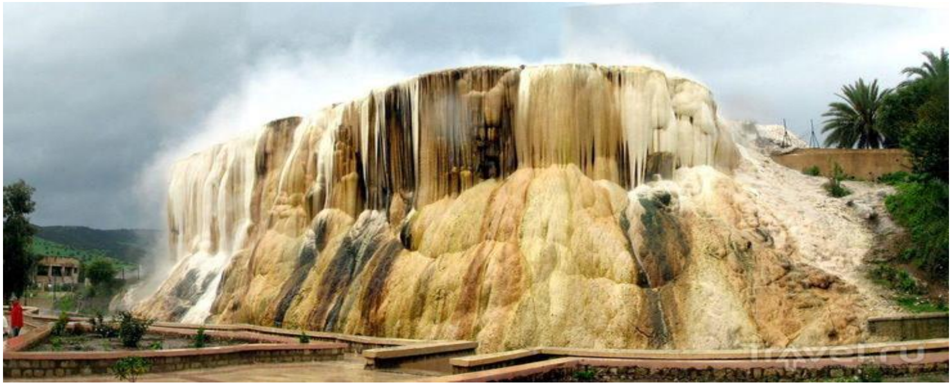


Figure B7 – Hammam Meskoutine hot springs, Guelma, Algeria (Source: Renewable Energy Development Center Algeria)

Hydroelectric Energy

One of the main forms of energy comes after oil and natural gas in terms of popularity and business in Algeria, by generating 5% of the total energy consumed. Ever since, Algeria has managed to generate itself a considerate amount of hydroelectric energy through the making of power plants.

Figure B8 – Ain Defla Dam, Algeria.

These are usually built into large bodies of water, such as lakes, rivers, etc. Hydro- electric is one of the most efficient sources of energy, at about 90% effectiveness. Algeria uses mostly the traditional hydropower method, which is suited only to large dams. While the new technology, is the concentrated reduced flow of water, but it's most effective in the generation process.

Annexes C. Renewable energies potentials in algeria

Algeria has broad reserves of power resources, mainly oil and solar power. There is respectable capacity to use renewable power sources, particularly regarding solar and wind energy.

Algeria has one of the largest solar potential in the world, as estimated 13.9 TWh per year. The country receives annual exhibition equivalent sun to 2500 kWh / m2.

Solar energy

The solar energy capacity is 7.26 kWh/m2 in the south and 4.66 kWh/m2 in the north of Algeria [8, 9]. The dead time on almost all the national territory exceeds 2000 hours and 3900 hours (highlands and the south region). The 10,000 square feet (2200 kWh/m2/year for the north and 2263 kWh/m2/year for the south of the country) is 10 kWh and it is over most of the national territory as shown in Table C1.

Table C1 – the solar potential by regions

Region	Coastal	Highlands	South
Areas (%)	4	10	86
Average duration of sunshine (Hours/ year)	2650	3100	3600
Received average energy (kWh/m2/year)	1700	1900	2650

Wind Energy

Wind energy is an important and effective renewable energy resource of Algeria. The southwest have strongest winds, as shown in Figure C1, particularly near Adrar. So the first wind farms were completed in 2013 that generates 10 MW with the installation of 12 Gamesa 850kW turbine.

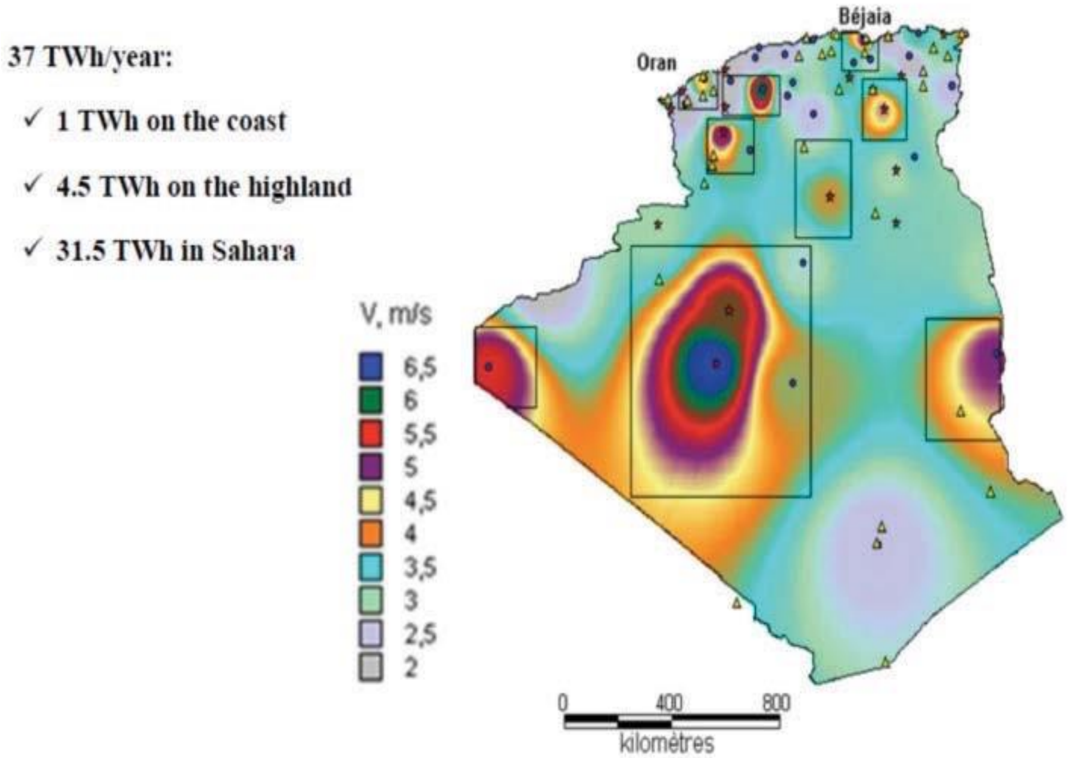


Figure C1 – Map of Algeria Wind

Geothermal Energy

There are more than 240 sites for inventory of the thermal springs at now in Algeria. The temperature of hot Algerian waters varies between 22 and 98 °C. The recorded temperatures of highest springs are 68 °C in the western area (Hammam Bouhnifia), 80 °C in the central area (Hammam El Biban) and 98 °C in the eastern area (Hammam Maskhoutine) in northern Algeria as shown in Figure C2. There are some hot springs in the south the average temperature is 50 °C.

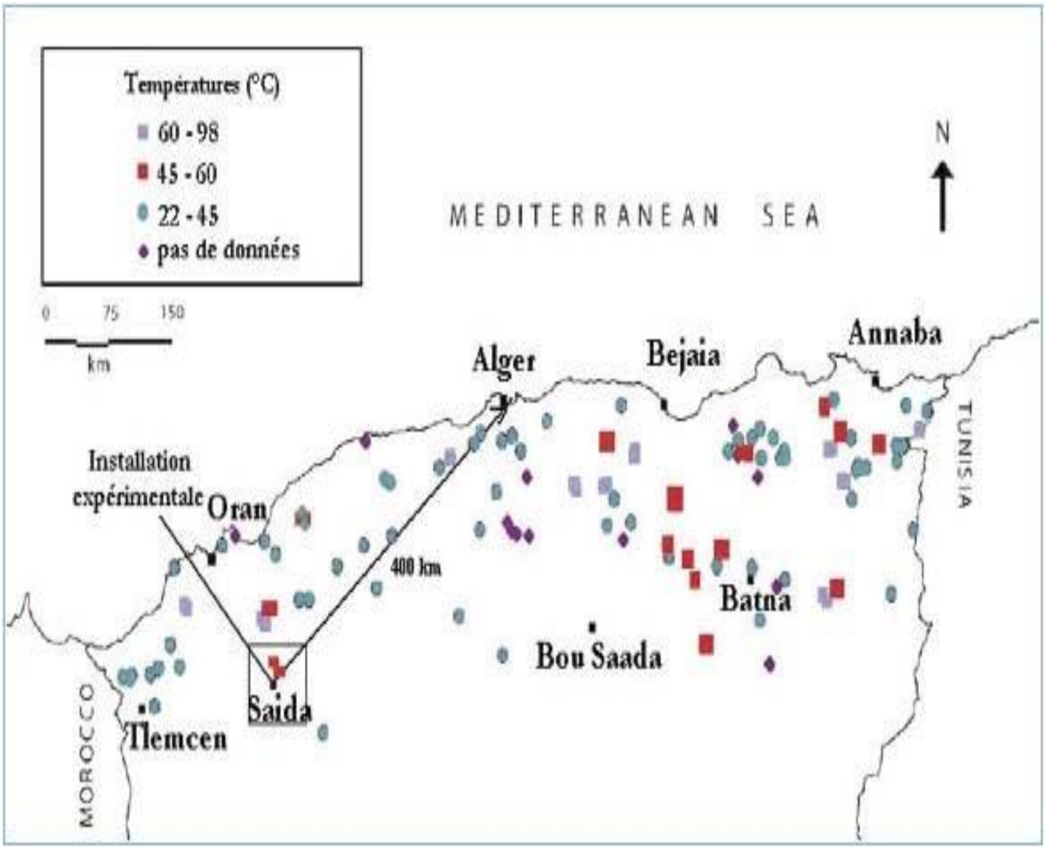


Figure C2 – Geothermal in algeria

Biomass energy

Another energy potential of Algeria is biomass energy. Annual municipal wastes generation is more than 10 million tones according to the report of national cadaster. Solid wastes are disposed in open or unpleasantly burned landfills. Wastewater effluent can be directed to sewage treatment plants. The appropriate green and solids are converted to biogas.

Annexes D. Optimal based formulation of DSM programs

In this section, the different DSM. programs will be briefly explained. This explanation will include the main objective of the program and the changes made on a typical load curve after applying this program. Firstly, a DSM. program is a program used to control the load profile indirectly in order to achieve the utility objectives. These objectives are:

- To have the load factor as close as possible to 1.0
- To have the peak load within the proper margin.

This classification can be used for comparing different DR systems, it can help in the definition of controller specifications, and it puts forward a point of view for controllers standardisation.

Direct Load Control (DLC). It is a technique based on issuing specific commands to controllable DSRs. The decision on each DSR operation is taken by an external controller that embeds the main intelligence and has a knowledge of the DSR status. A direct controller uses two-way or one-way communication to exchange information with a DSR. In case of one-way communication, a DSR is obliged to follow control commands. The only deviation from expected behavior can occur due to safety issues or unit failure. Vice versa, with bidirectional communication each DSR is obliged to acknowledge the received command. A DSR informs the external controller whether the control command can be executed or not, communicating also its status. Commands sent by the direct controller may vary depending on the DSR type and the communication protocol.

Indirect Load Control (ILC). It is a scheme for managing DSRs by issuing signals which may or may not affect the units operation. Indirect Load Control uses one-way communication, and the interested DSRs are not obliged to react to the control signal or send any feedback. Thanks to that, this scheme is easily scalable and cheap to deploy. However, an aggregated model of the response of the DSR population is needed in order to appropriately design the ILC control strategy. In fact, it has been shown that price-based indirect control can cause consumption kick- back effects.

Transactional Load Control (TLC). This scheme is also called market-based control, and it refers to a control strategy based on negotiations in a bid- based market. In transactional control DSRs are competing for one or more resources on an equilibrium market with the use of bids. After the end of the transaction DSRs can optimise their production or consumption with use of the equilibrium value determined by the market. The main goal of the transactional control is to distribute resources efficiently by taking into account correlated needs of different DSRs. A DER independently decides about the bidding amount and autonomously plan the control accordingly to the winning bid.

Autonomous Load Control (ALC). This scheme is based on measurements of frequency and/or voltage that are performed at unit level, in a way that each single unit can participate in frequency or voltage regulation independently. Due to the use of local measurements, this kind of control is characterised by a fast response and it does not need a communication infrastructure or higher-level control entities. DSR participating to DSM via Autonomous Load Control do not need any supervision, they work autonomously, and they can provide valuable services to the power system.

Demand Response allows reducing investments for grid reinforcements and peak generation by controlling the consumption as balancing resource for wind and solar generation, it reduces the need for spinning reserves (plants that are continuously running in order to supply power on short notice), bringing therefore financial and environmental benefits to the society.

Yet, benefits of DR are not limited to the system level. The Smart Energy Demand Coalition (SEDC) estimates that in 2013 business and private customers in USA earned over 2.2 billions of Dollars in direct revenues from trading flexibility in Demand Response programs. In the same report, SEDC concludes that comparable benefits could be achieved also in Europe, with consequent beneficial impact on local economies.

By achieving the previous objectives, the utility would get the maximum possible energy from the installed units, thus maximizing the total profit and minimizing the average cost per KWh. Reference has listed these programs as follows:

1) Valley Filling

In this program, the main objective is to increase the demand during the off peak periods while having the same load peak. This could be achieved by encouraging the consumers to increase their demand.

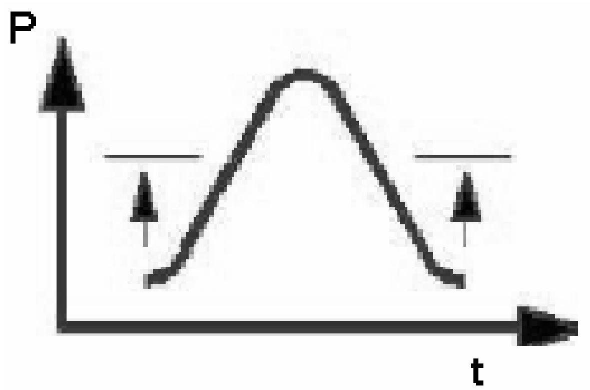
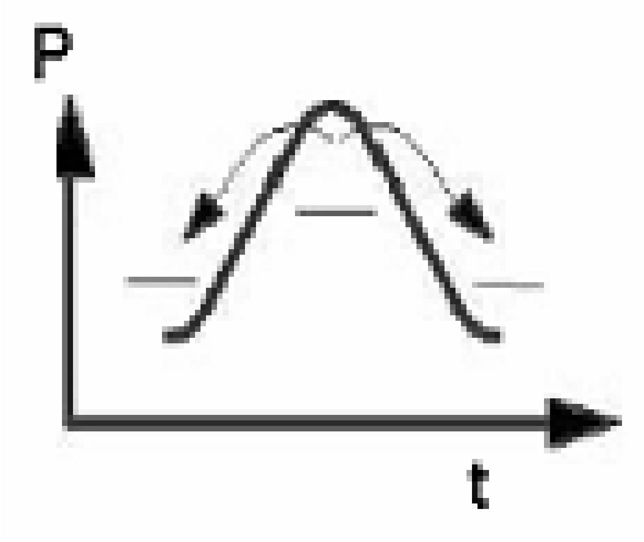


Figure D1 – Valley filling program effect

2) Load Shifting

In this program, it is required to shift part of the demand at the peak period to the off peak periods. This program could be used in case that the installed capacity is not enough during the peak load



Figbre D2 – Load shifting program effect

3) Peak Clipping

This program is used to decrease the demand during the peak load periods. Also, these loads can't be shifted to the off peak periods. This could due to lack of installed capacity be during these periods. This program could be achieved be indirectly forcing the consumers to decrease their loads by the use of miniatures on their supply points.

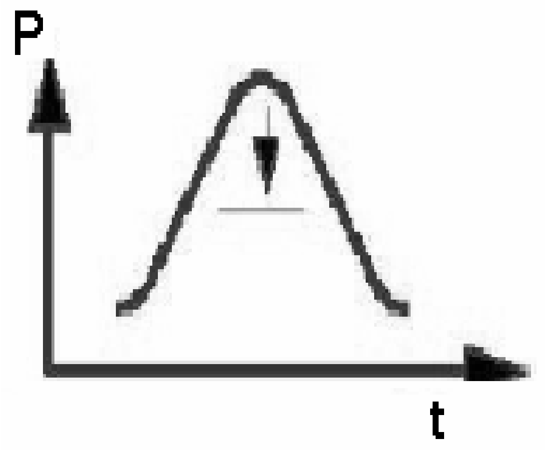


Figure D3 – Peak clipping program effect

4) Energy Conservation

This program is used when it is required to decrease the energy consumption all over the load period. This could be achieved by using high efficiency components

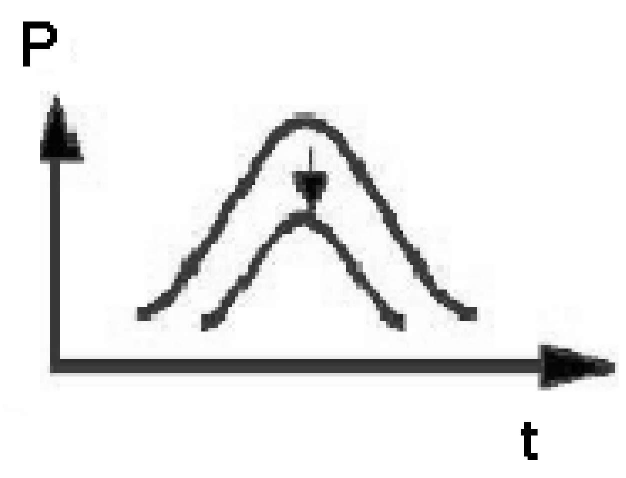


Figure D4 – Energy conservation program effect

5) Load Building

This program is used when it is required to increase the energy consumption. This could be very beneficial in case of surplus capacity. This is because the average cost per KWh will decrease.

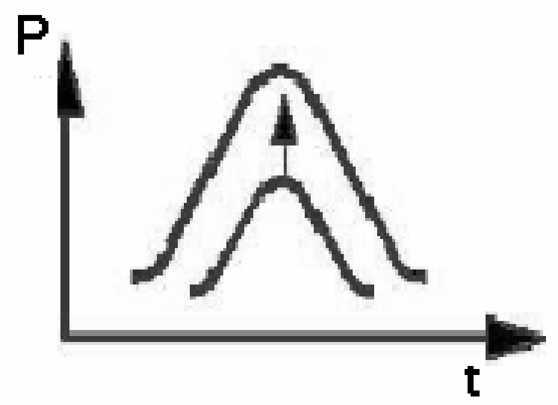


Figure D5 – Load building program effect