BULGARIAN ACADEMY OF SCIENCES

INSTITUTE OF ROBOTICS

Section "Robotics in Energy"

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INCREASING ENERGY EFFICIENCY IN POWER SUPPLY SYSTEMS

DISSERTATION ABSTRACT

of a dissertation for the award of the educational and scientific degree "Doctor"

5.2. Electrical Engineering, Electronics and Automation

Scientific supervisor:

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The dissertation has been discussed and scheduled for defense by an extended seminar of the "Robotic Systems in Energy" laboratory at the Institute of Robotics, BAS

The defense of the dissertation will take place in Hall 427, Block 2, at the Institute of Robotics, BAS.

The materials for the dissertation are available in the office of the Institute of Robotics, BAS.

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A. INTRODUCTION

In the past 25 years, the Republic of Bulgaria has been in a severe economic crisis, manifested by a sharp decline in production or complete destruction of some types of industries, as well as fundamental technical, structural, production, and organizational changes in industrial sites (IS) and the communal sector (CS), which led to a significant decrease in electricity consumption. The electricity supply systems (ESS) of IS were built under different conditions and with different requirements for their operation. The load on the capacities of IS, the duration of their operation, and their reliability were well thought out, designed, and implemented under a different regulatory framework, technical standards, and technological characteristics.

External factors have also changed significantly, such as the relationships with energy resource suppliers, the emergence of a new market for electrical equipment and electrical services, changes in the ownership of electricity distribution companies (EDCs), and the change in the philosophy of forming and implementing the price of electrical energy (EE). All these factors have had a negative impact on the proper functioning of ESS in IS and the communal sector (CS) during the transition years.

Electric energy, as a material substance, has both a quantitative and qualitative aspect. The qualitative aspect has a quantitative expression and is characterized by the so-called quality indicators of electrical energy (QIEE). These are usually equated with the specific characteristics of the supply voltage regulated by national and international standards.

In principle, the quality of EE represents a set of requirements describing the characteristics of the process of transmitting EE for its continuous use with specific, normatively defined parameters of the supply voltage. As a result of the bidirectional process of generation and consumption, occurring simultaneously in real time, EE and its quality relate to both suppliers and consumers of EE. In this regard, the main task of this process is to achieve maximum consumer satisfaction with the conditions of electricity supply, as well as to regulate the requirements and responsibilities of electrical equipment manufacturers and electrical energy consumers for the production and operation of technical devices without creating electrical disturbances on their part.

Innovative modern technologies require electrification, the introduction of adjustable semiconductor drives, and the management of electrical processes in large consumers such as electric arc furnaces, welding units, electrolytic devices, electric excavators, cranes, electric locomotives and trolleybuses, industrial lighting, and many others. These consumers and their electronic systems for control, registration, and management cause serious disturbances such as voltage and current deviations and fluctuations, asymmetry and non-sinusoidal behavior of voltage and current, as well as an increased likelihood of power supply interruptions of various kinds. The deterioration of the quality of electrical energy (QEE) by the consumers of EE has a serious negative economic impact, resulting in increased power and EE losses.

The creation of electromagnetic disturbances by some consumers can lead to the degradation of the normal operation of other consumers, as well as deteriorate the parameters of the network, reducing its throughput capacity and the quality of the electrical energy (EE) passing through this network. In this regard, electromagnetic compatibility (EMC) is understood as the ability of electrical equipment and its components to operate normally in the electromagnetic environment of an existing ESS in industrial sites (IS) and not create unacceptable disturbances that disrupt the normal operation of other consumers, as well as the ESS as a whole. There is a direct relationship between QEE and characteristics that allow for a quantitative assessment of EMC. As a result of experimental studies, probabilistic-statistical dependencies can be established between individual QEE parameters and between one or more QEE parameters and EMC, quantitatively determined by them.

Objectives and Tasks of the Dissertation

The objective of this dissertation is as follows:

To study and develop current theoretical concepts for minimizing power losses in electricity supply systems (ESS), which can be applied in the processes of researching and optimizing the power balance in industrial sites and sectors, while performing a techno-economic evaluation of the operating regimes based on a defined optimization criterion.

To achieve this objective, the following tasks need to be formulated and solved:

1. To investigate ways of optimizing the management of power at industrial enterprises to enhance the efficiency of their electricity consumption. For the optimal operation of machines and equipment in industrial enterprises, it is essential to understand their parameters and the interactions between them. The optimization of technological processes and operating regimes is inextricably linked to the search for optimal solutions. These are made based on in-depth research and analysis.
2. To summarize the current theoretical concepts for the study and analysis of up-to-date theoretical approaches for minimizing power losses in electrical energy, methods with practically applicable integral characteristics;
3. To conduct a practical applied study of the power balance in the electricity supply systems (ESS) of industrial sites and sectors, and to synthesize a theoretical framework for the research process applied to a suitable research object.;
4. To investigate the possibilities for optimal techno-economic operating regimes of ESS based on the criterion $\Delta P < 0$ for optimizing the power balance equation.

Research Methods

The dissertation is based on a large volume of experimental studies, with all data and measured quantities processed and analyzed using methods of mathematical statistics, experimental design theory, and other tools.

Approval of the Work

A significant portion of the results of the work are presented in the dissertation and the author's publications.

Structure and Volume of the Dissertation

The dissertation has a volume of 173 pages, structured into 4 chapters, containing numerous formulas 235, 112 figures, 43 tables, and 116 references, of which 75 are in Cyrillic and 41 in Latin.

Throughout the dissertation, the main terms and definitions are presented with their abbreviations and symbols. For convenience of reading, they are listed on a separate page at the beginning of the dissertation.

B. SHORT SUMMARY OF THE DISSERTATION

CHAPTER ONE

LITERATURE REVIEW ON A WIDE RANGE OF ISSUES RELATED TO THE TOPIC OF THE DISSERTATION

1.1 Numerical Characteristics

To study a given phenomenon or process, it is not necessary to fully understand it, but it is sufficient to know some of its characteristics, called numerical characteristics (N.C.). They are divided into the following groups:

a) N.C. defining the position of the random variable (r.v.); b) N.C. defining the dispersion of the r.v.; c) N.C. related to the symmetry and the degree of skewness of the distribution (p) of the r.v.

The first group of N.C. includes the mathematical expectation (M.E.), mode, and median. M[x] of any r.v. x represents the sum of the products of all its values x_i and their probabilities P_i

$$\mathbf{M[x]=x_1P_1+ x_2P_2+\ldots+ x_nP_n=\sum_{i=1}^{n}x_iP_i}\ ; \qquad (1.1)$$

The M.E. is the center around which the possible values of the given r.v. are grouped to a greater or lesser degree, and with sufficient probabilistic accuracy, it can be assumed to be equal to the arithmetic mean of the observed values of the r.v. The M.E. possesses the following properties:

A) The M.E. of a constant value is the value itself **M[C]=C;** **b**) The constant multiplier can be taken outside the M.E. operator – **M[C.x]=C.M[x];** c) The M.E. of the product of two independent r.v.s is equal to the product of their M.E.s. - **M[xy] =M[x].M[y];** d) The M.E. of the sum of two r.v.s is equal to the sum of the M.E.s of the addends – **M[x+y]=M[x]+M[y];** The M.E. of a given r.v. coincides with its first moment. The mode of the r.v. x is called the value at which it corresponds to the highest probability (P), i.e., for which the probability distribution (P.D.) has a maximum (Fig. 1, item M). The median is called the value **x** The median is called the value of the r.v. for which the condition is fulfilled (Fig. 1, item **x½**); **P(x<x½) = P(x>x½)** , where **P(x<x½)** represents the probability that the random variable **x** takes values smaller than **x½**.

The second group of N.C. includes the range, variance (V), standard deviation (S.D.), and the coefficient of variation.

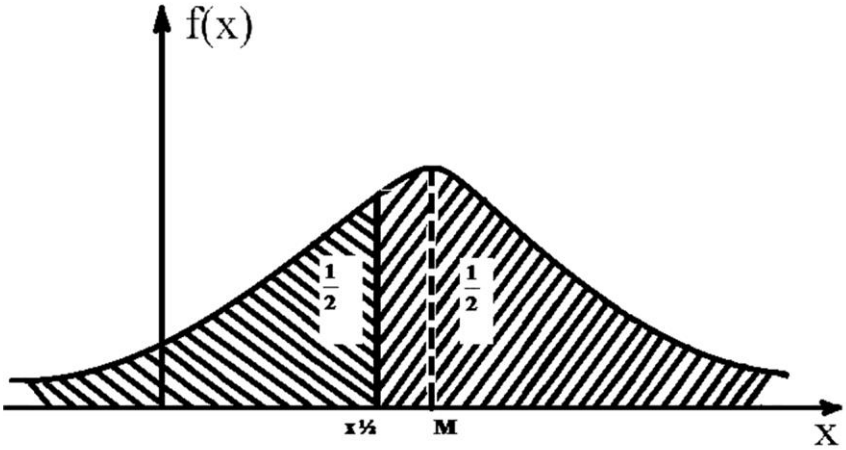

Fig. 1

The use of the third central moment to determine the degree of skewness is due to the following: as already explained, even central moments are always greater than zero. Odd central moments of third and higher orders are equal to zero only for symmetric distributions and are different from zero for asymmetric distributions. To assess the degree of skewness, it is natural to choose the simplest of them, i.e., the third central moment.

1.1 Normal distribution law

Very often, the distribution of a r.v. is judged by the density of the distribution, which represents the first derivative of the distribution function F(x):

$$F(x)= F'(x) \tag{1.2}$$

The normal distribution (N.D.), also known as the Gaussian distribution, has widespread application in engineering, particularly in the study of ESS. R.v.s that are influenced by a large number of independent and equally impactful factors follow the N.D. The effects of the factors are summed. In ESS, such r.v.s include voltages, currents, various loads, and others. In practice, it is considered that a distribution of 10 to 20 equally distributed values of the r.v. is sufficiently close to the N.D. In specific cases, even with n=6, an acceptable approximation to the N.D. is obtained. The probability density function of the N.D. and the integral function of the distribution are given by the following expressions:

$$f(x) = \frac{1}{b\sqrt{2\pi}} e^{\frac{(x-a)^2}{-2b^2}}; F(x) = \frac{1}{b\sqrt{2\pi}} \int_{-\infty}^{x} e^{\frac{(x-a)^2}{-2b^2}} dx; \qquad (1.3)$$

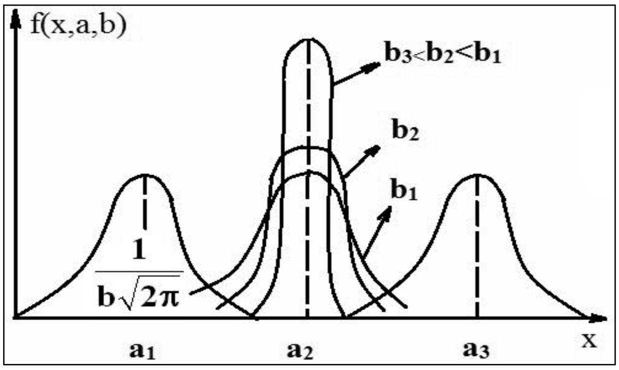

Fig. 1.2

It can be seen that the normal distribution is determined by two parameters: **a** and **b**. It can be proven that: **M[x]=a;** i.e., the M.E. of the N.D. is equal to the parameter **a**, **σ[x]=b**, , i.e., the standard deviation of the N.D. is equal to the parameter **b.**

The influence of the parameters of the normal distribution on the shape of the normal curve is as follows: when the parameter a changes, the shape of the normal curve does not change, but this only leads to a shift along the axis **0x**- To the right if **a** increases, and to the left if **a** decreases (Fig. 1.2). The influence of the parameter **b** on the N.D. is more specific. As **b** increases (Fig. 1.2), the maximum ordinate of the N.D. decreases, the curve becomes more flattened, i.e., it moves closer to the x-axis; when **b** decreases, the curve becomes more peaked and stretches in the positive direction along the y0-axis**.**

MAIN CONCLUSIONS AND RESULTS TO CHAPTER ONE

1. *The theoretical foundations for determining the computational loads at the design and operation stages of ESS have been developed. The analysis aims to provide guidelines for applying the developed methodologies in determining the different types of power and the losses occurring during their transfer, which are an integral part of the power balance equation during its optimization. The formulations have a probabilistic-statistical character, which is the most appropriate approach when studying processes in ESS of industrial sites (IS). Detailed guidelines have been formulated for determining the maximum continuous load under various scenarios, and a practical application*

environment for calculating the load characteristics in cases of asymmetrical power distribution in a three-phase system is also presented..

2. *A conceptual critical approach has been developed for studying the powers in the ESS of industrial sites (IS), aimed at providing guidelines and marking the main directions for composing the power balance during the operation of energy facilities. The characteristics and specifics of the electrical energy infrastructure and the electrical energy transferred through it as material substances of a unified system have been considered. The reactive connections between different electrical energy categories have been analyzed, presenting the trends and directions of their manifestation and realization, and some quantitative relationships in this regard have also been provided. Specific methodological guidelines have been marked for implementing and creating rational approaches for composing the power balance in both theoretical and practical aspects..*

CHAPTER TWO
STUDY AND ANALYSIS OF CURRENT THEORETICAL APPROACHES FOR MINIMIZING POWER LOSSES IN ELECTRICAL ENERGY.

1.1. Characteristics and Quantitative Features of Power and Electrical Energy Losses in Different Segments of the National Electricity Supply System (ESS).

The trends in the changes of power and electrical energy losses ΔP and ΔW in the ESS of developed countries are diverse – for some, there is an increase, for others stabilization, and for some, a decrease. For example, in the USA and Russia, at the beginning of the 21st century, a growth in ΔP is recorded compared to the period of 1970-1980, unlike in Sweden, the Czech Republic, Germany, and Japan, where a decrease is observed. In France, the UK, and Canada, no significant changes are noticed. The reasons for the dynamics of the losses are varied. Countries with lower losses managed to timely increase the transmission capacity of HV networks, compared to the growth in consumption, and also organized and implemented more efficient compensation of reactive loads. At the same time, the longer distances from substations to the end user, typical for larger countries, have a negative impact on ΔP, and this is a major reason for the increase in losses in these countries.

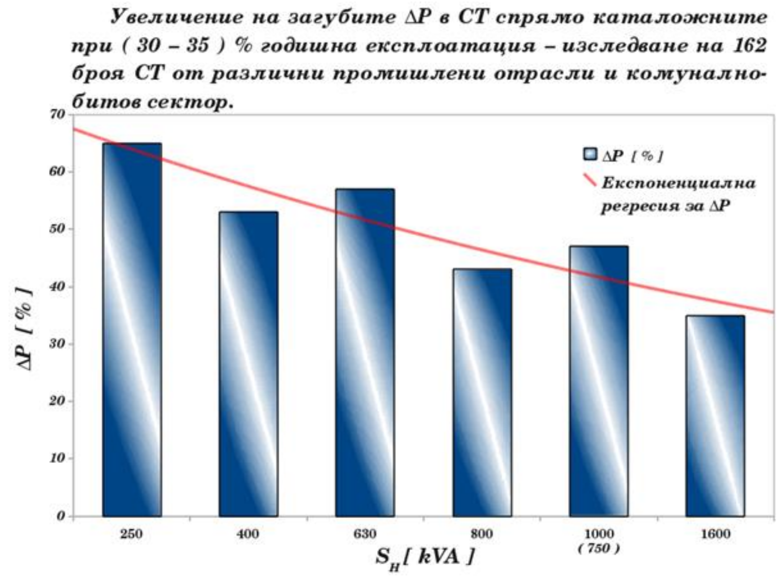

Fig. 2.1

The prolonged operation period significantly deteriorates the energy parameters of the transformers (T) and reduces their efficiency by (1-3.5)%. As seen in Figure (2.1), the increase in ΔP is more noticeable for low-power transformers, as well as for the most commonly used power ranges of 630 and 1,000 kVA.

2.2. Relative Relationship of Power Losses and the Parameters of Electrical Networks

The reduction of current density, and consequently the increase in the transmission capacity, can be achieved by constructing cable and overhead lines with larger cross-sections. This can be done during the construction phase or when reconstructing existing ESS. In recent years, this measure has been widely implemented through certain mandatory requirements from the electricity supplier during the construction of transformer substations, supply panels, and cable routes. For example, for urban and industrial networks, EDCs (Electricity Distribution Companies) require the minimum cross-sections of low-voltage cable lines to be 185 mm^2. This is not always financially advantageous for investors, but in most cases, it is economically justified. In fact, this measure involves the creation of methodological rules aimed at achieving standardization in the use of cables with different cross-sections. This approach seeks a compromise between two conflicting trends:

- **Reducing electrical energy losses by applying larger cross-sections, which in practice leads to a reduction in operating costs C by ΔC;**

- **Additional cost of non-ferrous metals as a result of resizing the power supply networks, meaning that capital investments K will increase by ΔK.**

Based on the above considerations, two options can be considered:

I. Option – without standardization of the cable network cross-sections, where the number of cross-sections used is unlimited;

II. Option – Optimal standardization of the cross-sections, where their number can be reduced to one.

The comparison of the two options is performed based on the criterion of minimizing the total cost. For the first option, the following can be written:

$$З_{\boldsymbol{I}} = \boldsymbol{\alpha}_{\text{H}}\boldsymbol{K} + \qquad (2.1)$$

For the second option, as mentioned, the capital investments K and the operating costs C will change by ΔK and ΔC, respectively:

$$З_{\boldsymbol{II}} = \boldsymbol{\alpha}_{\text{H}}(\boldsymbol{K} + \boldsymbol{\Delta K}) + (\boldsymbol{C} - \boldsymbol{\Delta C}) \qquad (2.2)$$

For deep standardization to be effective, the following condition must be met: $З_{\boldsymbol{II}} < З_{\boldsymbol{I}}$ или $\boldsymbol{\alpha}_{\text{H}}(\boldsymbol{K} + \boldsymbol{\Delta K}) + (\boldsymbol{C} - \boldsymbol{\Delta C}) < \boldsymbol{\alpha}_{\text{H}}\boldsymbol{K} + \boldsymbol{C}$

If we denote the difference $З_{II} - З_{I}$ с μ the result is:

$$\boldsymbol{\mu} = \boldsymbol{\alpha}_{\text{H}}(\boldsymbol{K} + \boldsymbol{\Delta K}) + (\boldsymbol{C} - \boldsymbol{\Delta C}) - \boldsymbol{\alpha}_{\text{H}}\boldsymbol{K} - \boldsymbol{C} = \boldsymbol{\alpha}_{\text{H}}.\boldsymbol{\Delta K} - \boldsymbol{\Delta C} \qquad (2.3)$$

Therefore, the conditions can be written as:

$\mu < 0$ - Economically feasible standardization of the cable network cross-sections;
$\mu > 0$ - Economically inefficient standardization.

The expression (2.66), satisfying the first condition, will be: $\boldsymbol{\alpha}_{\text{Н}}.\boldsymbol{\Delta K} - \boldsymbol{\Delta C} < 0$ следователно $\boldsymbol{\alpha}_{\text{Н}}.\boldsymbol{\Delta K} < \boldsymbol{\Delta}$

With the commonly accepted payback period $T_{отк}$ = 10 г.; $\alpha_{Н}$ = 0,1 and therefore:

$$\boldsymbol{\Delta K} < 10.\boldsymbol{\Delta C} \tag{2.4}$$

It can be concluded that for deep standardization to be effective, the reduction in operating costs resulting from decreased power losses must be one order of magnitude greater than the increase in capital investments caused by the use of cable networks with larger cross-sections. Based on (2.3), averaged graphical dependencies in kWh are determined and presented on a logarithmic scale for urban networks of 0.4, 10, and 20 kV (Fig. 2.1), with the calculations showing that ΔP is reduced to values of ΔP = (7 ÷ 8.5)%.

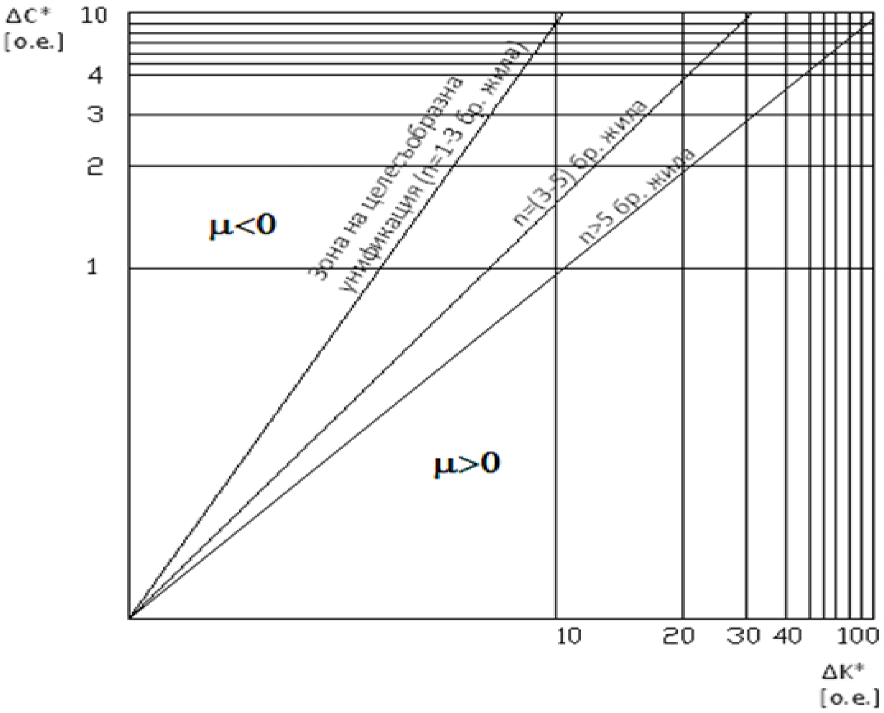

Fig.2.1 Averaged graphical dependencies fo ΔK* in relative units

Urban distribution networks, both low-voltage and medium-voltage, have a number of specific characteristics: uniformity of the used elements, possibilities for the application of modern industrial technologies for installation and operation, relatively short lengths, development potential, and more. These characteristics are a strong basis for developing fundamental concepts for standardizing the cross-sections of cable and overhead lines, even creating conditions for "deep" standardization with a cross-section count of n=1.

Using the above-mentioned methodological framework, calculations have been performed to determine the optimal number of cross-sections for urban cable networks. The object of the study is the ESS of Varna city, with medium voltage 10 and 20 kV and low voltage 0.4 kV. The number of studied transformer substations is 57, some of which are at 20 kV, while others are at 10 kV. In most of the analyzed cases, the power transformers are 2x1000 kVA and 2x630 kVA. The specific load density ω is related to their specific locations in the neighborhoods of "Chaika", "Levski", "Asparuhovo", and "Vladislavovo" and varies within quite wide limits: ω = (2 ÷ 13) [MVA/km²]. The average load density for the city as a whole is around (7.5 ÷ 8) MVA/km². This is determined by the average installed power of all the substations (S_avg = 1540 ÷ 1640 MVA) and the built-up area of the city F ≈ 205 km².

In Tables 2.1 and 2.2, the recommended number of cross-sections is shown in a summarized form.

Table 2.1		
μ<0 – Feasible standardization of the number of cross-sections		
Cable network	ω<6 [MVA/km^2]	ω≥6 [MVA/km^2]
0,4 kV 2x1000 kVA; 2x630 kVA	3÷4 Cross-sections 50, 70, 90, 120 мм^2 Aluminum	1÷2 Cross-sections 90 и 120 мм^2 Aluminum
10 kV 2x1000 kVA; 2x630 kVA	2÷3 сечения 120, 150, 185 мм^2 Aluminum	1÷2 Cross-sections 120 и 150 мм^2 Aluminum
20 kV 2x1000kVA; 2x630 kVA	1÷2 сечения 150 и 185 мм^2 Aluminum	1 Cross-section 185 мм^2 Aluminum

Табл. 2.2		
μ>0 – Economically inefficient standardization of the number of cross-sections		
Cable network	ω<6 [MVA/km^2]	ω≥6 [MVA/km^2]
0,4 kV 2x1000 kVA; 2x630 kVA	4÷8 Cross-sections 25, 35 50, 90, 120, 150, 185 мм^2	3÷5 Cross-sections 50, 90, 120, 150 и 185 мм^2
10 kV 2x1000 kVA; 2x630 kVA	3÷5 Cross-sections 35, 50, 90, 120, 150 мм^2	3÷4 Cross-sections 50, 90, 120 и 150 мм^2
20 kV 2x1000kVA; 2x630 kVA	3÷4 Cross-sections 90, 120, 150 и 185 мм^2	3 Cross-sections 120, 150 и 185 мм^2

Based on the conducted studies, the following summary can be made:

1. *Regardless of the value of the parameter μ, for $\omega \geq 6$ MVA/km^2, the optimal number of cross-sections is up to n = 3. For $\omega < 6$ MVA/km^2 this number can reach n = 6 or more.*
2. *For medium voltage (MV) networks, the standardization of the number of cable cross-sections is much stricter compared to low voltage (LV) networks. While the maximum number of cross-sections for MV cables is 1-5, for LV cables it is 1-8.*
3. *With deep standardization of the cable line cross-sections, a significant reduction in active power losses can be achieved, and the economic benefit from this far exceeds the additional investments required for the construction of the reinforced cable network.*

MAIN CONCLUSIONS AND RESULTS TO CHAPTER TWO

1. In connection with the objectives of the study, an investigation of the methods for determining conventional power and electrical energy losses has been conducted. The comparative analysis of the different methods shows the high adequacy, reliability, significance, justification, and consistency of the probabilistic-statistical approaches for determining conventional losses. In this regard, it is advisable to recommend that when developing comprehensive methodologies for assessing EE efficiency in the ESS of industry and the communal sector, this significant parameter for the power industry should be included with the appropriate weight.

2. A comprehensive multifactorial approach has been developed based on the Theory of Experimental Design, and multifactorial mathematical models have been obtained for five industrial sectors in the country. Using these models, the management and optimization of conventional power losses are achieved through appropriate influence from the system's factors. This approach has high practical value and has been tested in dozens of industrial sites in industry and the communal sector (CS).

3. The conducted studies over a 20-year period (1994–2013) in the sectoral structure of the country show that for the majority of the analyzed industrial sites and sectors, the averaged conventional power losses over time are around 10%, with a tendency to increase, currently reaching approximately 14%. The operation of industrial sites, characterized by a low-load regime, creates conditions for deterioration of technical and economic indicators and the generation of new trends for increasing conventional power and electrical energy losses. Urgent restructuring, renovation, and modernization of energy facilities and ESS in industry and households are necessary, as well as optimizing the operating modes of ESS to halt this negative trend. The economic grounds and advantages for this are the acceptable payback periods for invested capital and investments, which are lower than the normatively defined ones.

4. A method has been proposed, based on solving an optimization problem with the criterion of minimizing total cost, through deep standardization of cable line cross-sections for low-voltage (LV) and medium-voltage (MV) networks. Depending on the specific load density ω [MVA/km²], the feasibility of such standardization has been determined with the goal of achieving reduced power and electrical energy losses. The methodology has been tested for the cable network of Varna city, where the optimal number of cross-sections for voltages 0.4kV, 10kV, and 20kV has been determined. The effect of increasing the transmission capacity of the networks through standardization of the cable line cross-sections is determined by the reduced power and electrical energy losses, which reach levels of ΔP = (7 ÷ 8.5)%. The realized savings are greater than the investments made for reinforcing the cable network..

5. Conventional power and electrical energy losses are a key energy indicator that characterizes processes in the ESS from a technical and economic perspective. In this regard, this indicator can be defined and established as the main criterion for the rational operation of ESS and used in the creation of a methodological framework for assessing Electrical Energy Efficiency. The conducted studies in the sectoral structure of the country using the Experimental Design Method provide a solid methodological basis, and the obtained adequate, significant, reliable, and trustworthy results can serve as a starting point for developing concepts for standardization, norming, and forecasting the parameters and characteristics of electrical energy efficiency related to power and electrical energy losses.

CHAPTER THREE

PRACTICAL-APPLIED STUDY OF THE POWER BALANCE IN THE ESS OF INDUSTRIAL SITES AND SECTORS

3.1. SYNTHESIS OF THE THEORETICAL FRAMEWORK OF THE RESEARCH PROCESS

ESS are a symbiosis of schematic setups and operational components, where the main parameters are the network characteristics, power and electrical energy losses, reactive power processes (KRT), voltage variations, and the power balance.

The processes of reactive power (KRT) and voltage regulation in the ESS of industrial sites (Fig. 3.1) directly impact power losses, and consequently, the electrical energy balance. The active power losses in item 2 of (Fig. 3.1), when the voltage regime is changed, can be represented as:

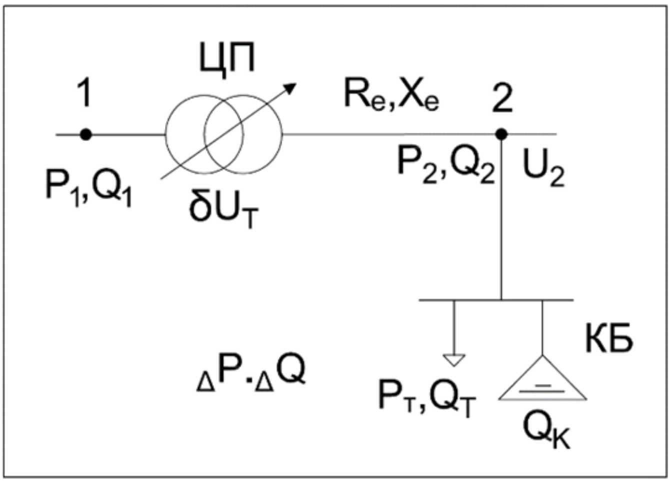

Fig. 3.1

$$\Delta P(U)=\Delta P_a(U)+P_r(U)=\frac{R_e}{U_{2H}^2}.U_{2*}^{-2}.\left[P_2^2(U)+Q_2^2(U)\right] \qquad (3.1)$$

where: $U_{2*}=U_2/U_{2H}$.

When the voltage U_2 within the limits $\pm$ **10%**U_H the static characteristics can be represented as:

$$P_2(U)=P_2.U_{2*}^p \qquad Q_2(U)=Q_2.U_{2*}^p \qquad (3.2)$$

where: **p** and **q** are characteristic coefficients, specific to different consumers; P_2 and Q_2 – active and reactive power in item 2 at $U_2=U_{2H}$.

If several electrical consumers (EC) with active and inductive powers P_i and Q_i, are connected at node 2, the expressions for **p** and **q** are:

$$p=\sum_{i=1}^{n} p_i \cdot \frac{P_i}{P_\Sigma} \qquad q=\sum_{i=1}^{n} q_i \cdot \frac{Q_i}{Q_\Sigma} \tag{3.3}$$

Taking into account (3.2), the expression (3.1) is written as:

$$\Delta P(U)=\frac{R_e}{U_{2H}^2}\cdot\left[P_2^2.U_{2*}^{(p-1)}+Q_2^2.U_{2*}^{2(q-1)}\right] \tag{3.4}$$

In the case of transverse reactive power (RPC) in item 2, as a result of an increase in voltage, a positive regulation effect is observed on the active and reactive load, i.e., their increase, and a negative regulation effect on the active power losses. Accordingly, two opposing trends affect the power balance, and in order to achieve a reduction in electricity consumption, it is necessary to change the voltage in the control point (CP). Therefore, optimizing such an operating mode can be achieved by simultaneously performing reactive power compensation (RPC) and managing the voltage regime.

In the case of RPC, at node 2, the reactive power will be:

$$Q_2^{'}=Q_2-Q_k=Q_2-k.Q_2=Q_2.(1-k),\ \text{i.e.} \frac{Q_2^{'}}{Q_2}.1-k \tag{3.5}$$

where: $k=Q_k/Q_2$. Then, in accordance with (3.5), the expression for q is obtained:

$$q^{'}=q\frac{Q_2}{Q_2^{'}}-q_k\frac{Q_k}{Q_2^{'}}=q\frac{1}{1-k}-q_k\frac{1}{1-k} \tag{3.6}$$

where: **q'** – the new value of the characteristic coefficient, accounting for KRT; q_k – the characteristic coefficient for the CS. The studies show that $q_k =$, and then (3.6) is written as:

$$q^{'}=q\frac{1}{1-k}-2\frac{1}{1-k} \tag{3.7}$$

When the CS is connected at node 2, the voltage $\mathbf{U_2}$ increases by the value $\mathbf{U_k=k.Q_2.X_e/U_{2H}}$, and taking into account the voltage increase from the transformer $\boldsymbol{\delta}$ $\mathbf{U_{T*}}$, the relative change in voltage at node 2 will be determined by:

$$\mathbf{U_{2**}=U_{2*}+\frac{X_e.k.Q_2}{U_{2H}^2}m\delta U_{T*}} \tag{3.8}$$

Taking into account (3.1, 3.8), the expression (3.4) is written as:

$$\mathbf{\Delta P(U)=\frac{R_e}{U_{2H}^2}.\left[P_2^2.U_{2*}^{(p\text{-}1)}+Q_2^2\left(1\text{-}k\right)^2.U_{2*}^{2(q\text{-}1)}\right]} \tag{3.9}$$

The application of probabilistic-statistical methods based on Experimental Design (ED) for determining power and electrical energy losses are approaches with high reliability and adequacy. Determining the key factors (KFs) in this process is of utmost importance for achieving accurate and reliable results. Here, an assessment of the technical characteristics of the factors influencing the losses is made.

2.2. Relative deviation of the voltage ($\mathbf{U_*}$)

The voltage regime directly affects the power losses through the static characteristics $(\boldsymbol{U}) = \boldsymbol{P}.\boldsymbol{U}^{\boldsymbol{p}}; \boldsymbol{Q}(\boldsymbol{U}) = \boldsymbol{Q}.\boldsymbol{U}^{\boldsymbol{q}}$;

$$\Delta \boldsymbol{P} = \boldsymbol{R}_{\text{екв}}.\boldsymbol{U}_{\text{H}}^{-2}[\boldsymbol{P}^2\boldsymbol{U}^{2(\boldsymbol{p}-1)} + \boldsymbol{Q}^2\boldsymbol{U}^{2(\boldsymbol{q}-1)}] \tag{3.10}$$

where: p and q – characteristic coefficients for active and reactive load;

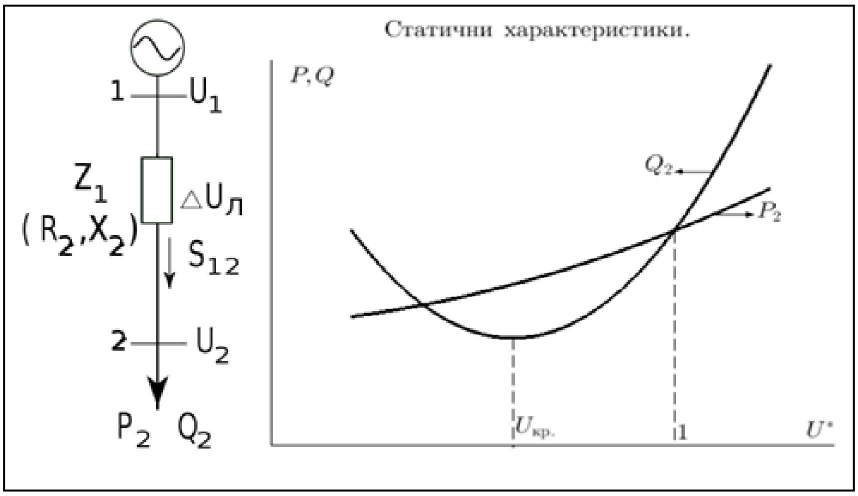

Fig.3.4 Static characteristics in the ESS

The change in voltage is carried out by regulating devices – Jansen regulators, volt-addition transformers, synchronous compensators, cross-sectional and longitudinally connected CS, and others. The loads also have a regulating effect, as shown in (Fig. 3.4).. The voltage at the end of the line is $\boldsymbol{U_2 \approx U_1 - \Delta U_{Л} = U_1 - \frac{P_2.r_2+Q_2.x_2}{U_2}}$. If, for some reason, the voltage at point 2- $\boldsymbol{U_2}$ decreases, in accordance with the static characteristics (Fig. 2.7), the values of P_2 and Q_2 will decrease, the voltage losses $\boldsymbol{\Delta U_{Л}}$, will also decrease, and therefore the value of $\boldsymbol{U_2}$ will increase. This is the so-called regulating effect, valid if the condition is met $\boldsymbol{U > U_{kp.} \approx (0,7 \div 0,8)U_H}$. For $\boldsymbol{U < U_{kp.}}$ the decrease in $\boldsymbol{U_2}$ causes an increase in $\boldsymbol{Q_2}$ (Fig.2.7), an increase in $\boldsymbol{\Delta U_{Л}}$, and further reduction in $\boldsymbol{U_2}$. After that $\boldsymbol{Q_2}$ increases again, an avalanche process is created, and a voltage collapse of $\boldsymbol{U_2}$ occurs, which is an emergency situation. The prevention of the failure can be achieved by activating the automatic voltage regulation system or disconnecting the load.

MAIN CONCLUSIONS AND RESULTS TO CHAPTER THREE

1. The theoretical foundations have been formulated, and the possibility of using the Experimental Design Method (EDM) for determining the characteristic operating parameters (COPT) has been justified. The conducted long-term active-passive experiments for 6 sectors in industry and the communal sector (CS) in the country, at two load levels β1 and β2, provide the basis to determine the COPT R(U) and Q*(U). As a result of the probabilistic-statistical processing of data using EDM, multifactorial models (MM) have been obtained, theoretical comparative analyses have been made, and the impact of the load β on the behavior of R*(U) and Q*(U) has been determined, as well as on the characteristic coefficients p¯ and q¯ and the regulating effects Sr and Sq. Through the analysis of literary sources and the results of the studies, the impact of COPT on the electrical energy efficiency of various types of consumers, as well as on the ESS as a whole, has been established.*

CHAPTER FOUR

OPTIMAL TECHNICAL-ECONOMIC OPERATING REGIMES OF THE ESS BASED ON THE CRITERION ΔP<0

4.1. Influence of voltage quality on the technical-economic indicators of the electrolytic process

The quality of the voltage, composed of a constant and variable part, plays a significant role in the electrolytic process regime and electrical energy consumption. In this regard, it is necessary to establish an optimal voltage regime that determines optimal performance, as the electrical energy portion reaches up to 40% of the cost of production. In a twelve-phase rectifier circuit, the secondary winding of the power transformer typically consists of 4 parts, two of which are in a star configuration and two in a delta (Δ), with the secondary voltage vectors being phase-shifted by 30˚. The voltage is regulated under load using step regulators or smoothly, by adjusting the inductance of saturated chokes. When two rectifiers operate together, compensation for the 5th and 7th current harmonics is ensured, whereas, with separate operation, this effect does not occur. As a result, the power losses due to the presence of higher harmonics are significant. Optimizing the voltage regime of the electrolytic process can be done based on the criterion of minimizing the annual equivalent costs. The main significant factors influencing the total annual cost (TAC) are the volume of produced goods, the specific electrical energy consumption per unit of production, and the active and reactive power losses in the transformers (T). The first two factors are dominant, while the third can be neglected. Experimental studies can be used to create the functions **З(U)** and **З(I)**, representing the dependencies of TAC on the voltage and current of the electrolyzers (Fig. 4.1).

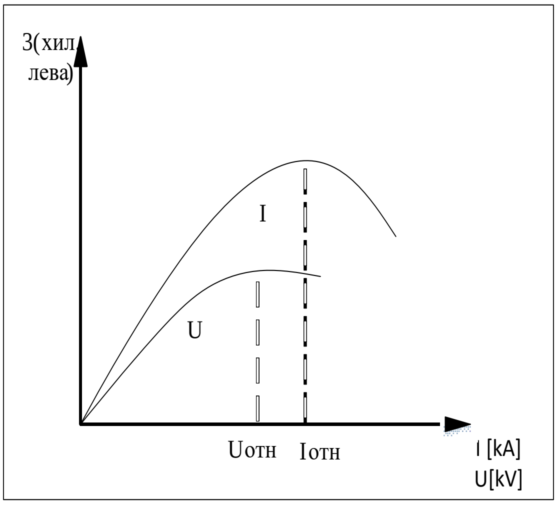

Fig. 4.1. Optimal values U_{OTH} and I_{OTH}

$$З(U) = a + cU2; \; З(I) = d + f.I2 \qquad (4.1)$$

The optimal values **Uопт** and **Iопт** are determined by differentiating the expressions and setting the derivatives equal to zero:

$$\partial З / \partial U = 0 \rightarrow U_{опт}; \; \partial З / \partial U = 0 \rightarrow U_{опт} \qquad (4.2)$$

Uопт and **Iопт** may correspond to the same or different maximum values of TAC. In the latter case, it is recommended that the optimization of the electrolytic system's regime be carried out by automatically regulating the current value.

4.2. Compensation of reactive loads - an effective method for saving electrical energy in electrolytic systems

The subject of this study is the ESS of a large chemical plant for PVC production. Its production units process the products of chlor-alkali electrolysis from the "Electrolysis" workshop (Fig. 4.2). The incoming sodium chloride solution, under the influence of direct current, decomposes into a brine solution (12-13% NaOH), wet chlorine, and hydrogen. The brine is fed to the "Caustic" workshop for concentration. The hydrogen and the dried and compressed chlorine are accepted in the "Liquefaction" workshop for further processing into commercial products – liquid chlorine and hydrochloric acid. In the "Caustic" workshop, the brine is concentrated to 50% diaphragm caustic, and in the "DHE" workshop, through direct synthesis of evaporated chlorine from the "Liquefaction and Hydrochloric Acid" workshop and the ethylene obtained via pipeline, dichloroethane is produced. The synthesis takes place in a reactor and scrubber in the presence of a catalyst. The "AV" workshop and the "PVC" workshop produce and supply the necessary nitrogen, compressed air, cooled circulating and fresh water, and thermal energy for the production processes.

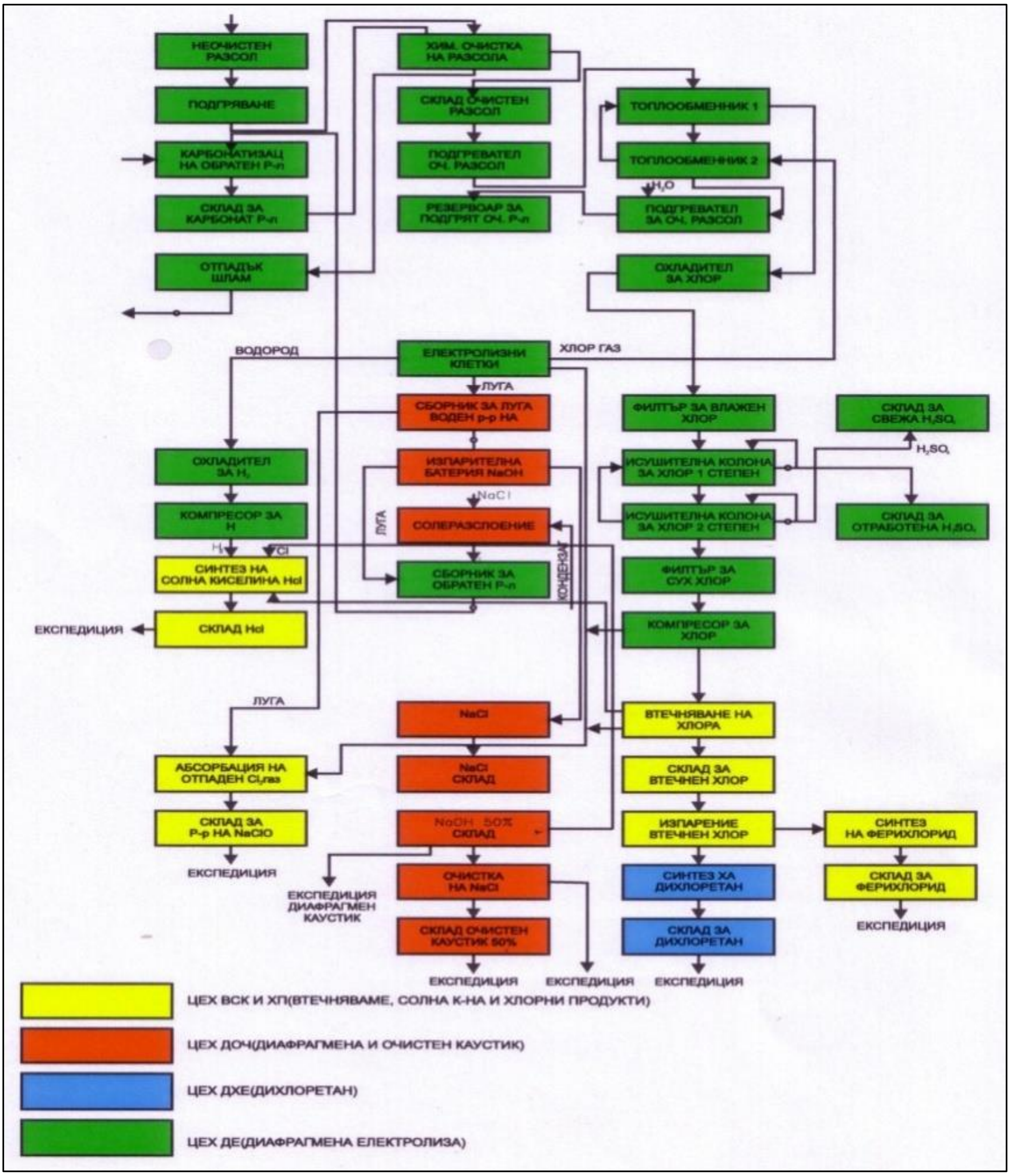

Fig. 4.2 Technological flow diagram of the chemical plant

The electrolytic process is carried out in NU 42 – 75 electrolyzers, with a total number of 168 cells. These are equipped with modified asbestos diaphragms and were manufactured in the USA, Italy, and Germany. The electrolysis is accompanied by complex processes on the surface of the electrodes. The electrode-solution boundary acts as a capacitor with active-capacitive conductivity, where higher current harmonics (HCH) are generated. In this way, alternating components are superimposed on the anode current, disrupting the steadiness of the electrolytic process. Experimental studies show that when there are pulsations in the rectified current, the technological process proceeds more intensively compared to their absence. With pulsations at frequencies up to 100 Hz, the capacitance of the "electrode-solution" capacitor is the largest, and the rate of the technological process increases sharply.

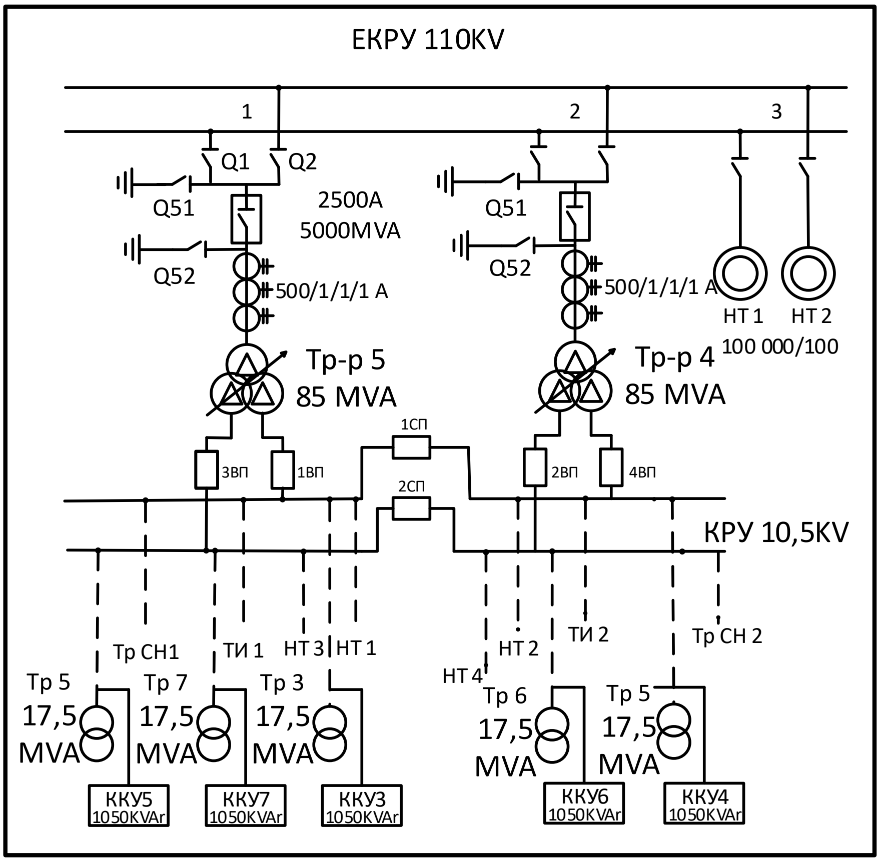

Fig. 4.3. Single-line diagram of the plant

The current pulsations also improve its uniform distribution across the surface of the electrodes, as well as the gas release from them. A significant influence on the current and voltage ($I_{ел}$, $U_{ел}$) of the electrolyzers is exerted by the deviation of the voltage in the supply network of the facility $U_{мр}$ (Fig. 4.3).

These are transformers Tr 3, 4, 5, 6, 7, with $U_{мр} = 10{,}5$ kV, , where the voltage regulation is manually performed under load with a regulation range of 11x1.5%. The dependency $U_{ел} = f(I_{ел}, U_{мр})$ needs to be optimized not only concerning the technological parameters of the electrolyzer but also taking into account the significant factor $U_{мр}$. As shown, the total annual costs depend quadratically on $U_{мр}$ and $I_{ел}$ (фиг. 4.3) and optimal values $U_{мропт}$ и $I_{елопт}$ can be defined. The economic effect of introducing stabilization of $I_{ел}$ around the optimal value $I_{елопт}$ reaches values of (35 – 40) thousand BGN per year. The electrolytic systems are powered by constant voltage and current$U_{ел}$= 600 V; $I_{ел.}$ = 240 A, obtained from 12-phase uncontrolled rectifiers in a Laryonov configuration, with natural minimization of the higher harmonic levels n=12; k = ±1. Its main drawback is the generation of higher harmonics (HCH) and the consumption of reactive power from the network, which necessitates the corresponding compensation. The compensating system at 10.5 [kV], Qk = 5100 [kVAr], is primarily designed to improve the power factor of the "Electrolysis" workshop, which is the main energy consumer of the plant. The required compensating power is determined using the expression:

$$\mathbf{Q_K = k.P_{ср}.(tg\varphi_e - tg_{Ж})} \tag{4.3}$$

where: **$P_{ср.}$ [kW]** – Average monthly load for industrial sites; **$tg\varphi_e$** and **$tg_{Ж}$** - The natural and desired **tgφ**, corresponding to **$\cos\varphi_e$** and **$\cos\varphi_{ж}$**; **k** – a coefficient accounting for the unevenness of the load profile (**k = 1,05 – 1,25**). In Table 4.1, the above-mentioned quantities are presented as average values for the corresponding month.

The analysis of the results obtained in Table 4.1 shows that the highest reactive power occurs in December, with Q_k = 1247,26 kVAr. Based on this power, the capacitor banks have been selected, and their distribution into groups has been specified. The power of the capacitor banks is chosen in accordance with the formula:

$$\sum Q_{КБ} \approx Q \tag{4.4}$$

Tabl. 4.13 Energy indicators on an annual basis						
Month	k	$P_{ср.}$	$Q_{ср.}$	$Tg\varphi_{e}$	$Tg\varphi_{ж}$	Q_{k}
	[-]	[kW]	[kVAr]	[-]	[-]	[kVAr]
January	1,01	9 688,28	7 970,11	0,823	0,484	3 317,146
February	1,01	9 235,57	7 441,81	0,806	0,484	3 003,592
March	1,01	11 930,72	9 183,47	0,770	0,484	3 446,308
April	1,01	10 244,21	7 610,63	0,743	0,484	2 679,783
May	1,01	12 197,78	9 260,68	0,759	0,484	3 387,933
June	1,01	10 018,86	7 657,08	0,764	0,484	2 833,334
July	1,01	11 745,86	8 480,69	0,722	0,484	2 823,470
August	1,01	12 983,06	8 850,42	0,628	0,484	2 596,352
September	1,01	14 281,67	10 099,38	0,070	0,484	3 216,661
October	1,01	14 623,89	10 275,07	0,703	0,484	3 234,658
November	1,01	18 075,14	18 075,14	0,682	0,484	3 614,660
December	1,01	17 971,00	17 971,25	0,718	0,484	4 247,260

We adopt the principle of group compensation for reactive loads, where the number of groups corresponds to the number of rectifiers, and each group is connected to the respective rectifier (Fig. 4.42). The power and energy parameters of the individual rectifiers are identical, which justifies that the compensating powers of the individual groups are also identical. It is also taken into account that excessive fragmentation leads to a significant increase in switching and protective equipment and complicates the scheme. The power of the integrated capacitor devices, for medium voltage compensation (6-10 kV), is determined from Table 4.2.

Table 4.2						
Recommended power of the integrated capacitor units (CCUs) for $U_н = 6 – 10$ kV						
300	450	600	750	900	1050	1200

Based on the above considerations, as well as the standard range of power ratings of capacitor banks produced by different manufacturers, the capacitor power for each group (CCU) is chosen to be $Q_{КБг} = 805$ kVAr. Therefore, the total compensating power is obtained as:

$$\sum_{i=1}^{5} \mathbf{Q_{КБi}} = \mathbf{4025kVar} \qquad (4.5)$$

To improve the powers in each group, the statistical data on the dynamics of the required compensating power Q_k, presented in Table 1, are used. It can be seen that the difference between the highest and lowest value of Q_k is:

$$\mathbf{\Delta Q_{K\,max} = Q_{K\,max} - Q_{K\,min} \approx 2000kVAr}. \qquad (4.6)$$

The most practical approach is the method of distribution, proportional to each compensating group. This means that the scheme should provide the possibility for switching the compensating power on and off within the range of 350 – 400 kVAr. Currently, in accordance with European standards, most capacitor banks are produced for U н = 7,2 kV, 12 kV, 24 kV. This provides the basis for each group to consist of two capacitor banks with standard power ratings at U н = 7,2 kV, corresponding to: QКБ1 = 700 kVAr, QКБ2 = 350 kVAr. Those operating at a nominal voltage Uн = 10,5 kV, will have power ratings of: QКБ1 = 536 kVAr, QКБ2 = 268 kVAr. The result obtained so far is determined by the expression:

$$Q_{КБ} = Q_{КБН} \frac{U^2}{U_Н^2} \tag{4.7}$$

This three-step configuration of each group allows for the achievement of optimized reactive power regimes. As a result of this, five CCUs are selected, with the power of each being **$Q_{ККУ} = Q_{КБ1} + Q_{КБ2}$ = 700 + 350 = 1 050 kVAr**. Each of them is composed of two CCUs with the specified power and is built from two independent fields with the possibility of independent switching. The following three-phase capacitor banks have been selected:

$Q_{КБ1}$ – type CPEFS 23 – 12,5/700 production of ZEZ Silko ;

$Q_{КБ2}$ – type CPEFS 23 – 12,5/350 production of ZEZ Silko ;

$Q_{КБ21}$ – type CPAKS 11 – 12/100 production of ZEZ Silko ;

$Q_{КБ22}$ – type CPAKS 11 – 12/250 production of ZEZ Silko ;

$Q_{КБ21}$ and $Q_{КБ22}$ are connected in parallel, working as a single capacitor bank (CB) with a power of 350kVAr.

In the synthesis of the circuit design, the principle of achieving the most simplified scheme is adopted, while simultaneously ensuring the necessary reliability in the operation of the equipment. Furthermore, the circuit design must strongly emphasize the main function of the equipment, namely the effective compensation of reactive loads, and to a lesser extent, the other secondary functions, such as voltage regulation, current regulation, and others.

The higher harmonics of the voltage significantly affect the operating regime of the capacitor banks. The linear nature of the frequency characteristics of the network changes significantly, and resonance phenomena may arise in the L-C circuit of the network and capacitor banks (CB). The use of harmonic filters (HF) to reduce THD, by suppressing some of the higher harmonics, is not always effective, as, in addition to canonical harmonics, there are also abnormal ones that are difficult to predict and analyze. The simplest method for implementing an HF can be considered the use of capacitor banks connected directly to the busbar system without reactors, as is the case in the current scheme. Capacitor banks have the primary function of compensating reactive loads, but they also act as natural filters for the higher harmonics of the current, as their resistance decreases with the increase in frequency, thus shunting the corresponding current harmonic.

To determine the quality indicators of electrical energy and the effect of reactive load compensation, studies were conducted using a measurement system based on

ABB Power Plus, operating with the PPDS software developed by Power T&D. For the needs of the study, a special algorithm was developed in the Mathcad environment.

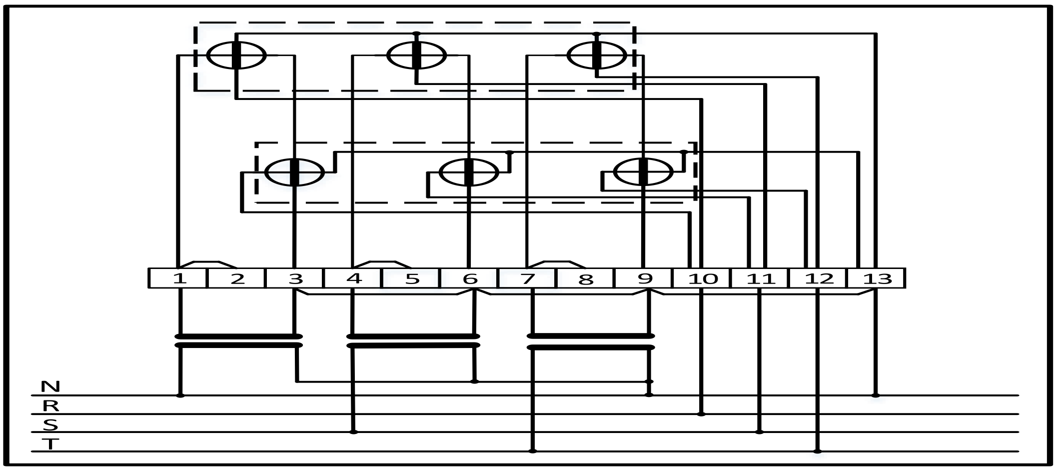

Fig. 4.4 Connection diagram of the measuring equipment

The system is connected to the existing measurement according to the schematic shown in Figure 4.4.

MAIN CONCLUSIONS AND RESULTS TO CHAPTER FOUR

1. Achieving electrical energy efficiency in industry and the communal sector (CS) is a multi-parameter task, and it must be solved based on a criterion defined by the inequality $\delta P^* < 0$. It has been experimentally proven that by reducing the voltage $U2^{**}$ within the limits of ±10% and increasing cosφ, the consumed power, and consequently δP^*, decrease and can take negative values. This reduction is more pronounced the smaller the load coefficient β is. The analytical expressions for δP^* obtained using the Experimental Design Method (EDM) allow for the minimization of the power balance equation by appropriately combining the influencing factors in such a way that the condition $\delta P^* < 0$ is satisfied. Over 60% of the studied industrial sites with reduced loading $\beta < 0.5$ satisfy this condition. As a result of the research, a methodology for the economic operation mode of the ESS based on the criterion $\delta P^* < 0$ has been proposed, and optimal areas and ranges for changes in the key factors (KFs) have been defined.

2. Analyses have been conducted, and guidelines and recommendations have been provided for achieving electrical energy efficiency (EEE) in the operation of various electrical installations. For electrolytic systems, the possibility of optimizing the operating regime by regulating the supply voltage has been confirmed. A number of appropriate measures for energy savings in arc furnaces and electric resistance furnaces have been identified. Several initiatives and technical possibilities for improving the electric welding technology have been outlined. The potential for achieving electrical energy efficiency in compressor and ventilation systems has been thoroughly analyzed. A study has been conducted to identify measures for

economical consumption in large single-phase consumers, with key principles and opportunities for reducing overall power and electrical energy losses highlighted.

GENERAL CONCLUSIONS AND RESULTS TO THE DISSERTATION WORK

The work thoroughly examines classical examples, such as modern drive systems, uninterruptible power supplies (UPS), soft starters for motors, and many others. In the future industrial development, this trend will increasingly prevail. As conversion technology becomes widespread in industrial enterprises, power supply systems are getting polluted, and ideal sinusoidal current and voltage are rarely encountered. On the other hand, these modern systems exacerbate problems, especially concerning power quality.

The analysis of the methods for determining the computational loads and their characteristics provides the opportunity for a more complete, reliable, and accurate determination of the different types of power and the losses associated with them. This, in turn, allows for the creation of more effective frameworks for composing optimal balances of these energy indicators and characteristics. When studying them, a comprehensive approach must be adopted, taking into account the influence of various essential factors arising at different levels of the ESS, and sometimes even triggered by natural phenomena. Disruptions in energy balances are most often caused by the irrational operation of electrical equipment at low, medium, or high voltage, phenomena occurring during emergency, pre-operational, and switching processes, as well as errors and improper management and handling of electrical equipment and the system as a whole. As noted earlier, natural energy sources and disturbances, such as lightning, the Earth's magnetic field, static electricity, and others, can also influence energy balances. Therefore, the electrical energy characteristics and power balance may be influenced, on one hand, by the electrical energy infrastructure, which represents a stationary material substance with electrical and technical-economic indicators, and on the other hand, by the electrical energy transferred through this infrastructure, which is also a specific material substance with its own parameters and characteristics.

The majority of industrial sites have not restructured their ESS in accordance with the new conditions of electricity consumption with reduced load, leading to worsened technical and economic indicators during operation. Urgent measures need to be taken to improve electrical energy efficiency in the ESS of industrial sites and the communal sector. The renovation and modernization of electrical equipment in the energy sector lead to a sharp reduction in power and electrical energy losses and have their technical-economic grounds and advantages, considering the relatively acceptable payback periods, which are lower than the normatively established ones.

A methodological framework has been developed, where calculations have been made to determine the optimal number of cross-sections for urban cable networks. The object of the study is the ESS of Varna city, with medium voltage 10 and 20 kV, and low voltage 0.4 kV.

Based on the conducted studies, the following conclusions can be made:

1. Regardless of the value of the parameter μ, for $\omega \geq 6$ MVA/km², the optimal number of cross-sections is up to n = 3. For $\omega < 6$ MVA/km², this number can reach n = 6 or more.

2. For medium voltage (MV) networks, the standardization of the number of cable cross-sections is much stricter compared to low voltage (LV) networks. While the maximum number of cross-sections for MV cables is 1-5, for LV cables it is 1-8.

3. With deep standardization of the cable line cross-sections, a significant reduction in active power losses can be achieved, and the economic benefit from this far exceeds the additional investments required for the construction of the reinforced cable network.

C. AUTHOR'S STATEMENT ON THE CONTRIBUTIONS OF THE WORK

SCIENTIFIC CONTRIBUTIONS

1. A method in a multifactor space for estimating active power losses depending on four main factors has been synthesized, allowing for the determination of optimal areas with a minimum value of the output parameter.

2. A scientifically based method and a probabilistic-statistical approach for analyzing the balance of capacities in industrial facilities and in the sectoral structure of the country are proposed, with the help of which a criterion for achieving high energy efficiency is substantiated in a global aspect.

SCIENTIFIC-APPLIED CONTRIBUTIONS

1. A setting is presented in a practically applied aspect for determining electrical loads in industrial facilities based on the application of a probabilistic-statistical approach in a research process, with the help of which power and electrical energy losses are most adequately and accurately determined.

2. A methodology for assessing electrical energy efficiency has been developed and analyzed with the aim of practical application in the real operation of various electrical equipment and systems.

Author's publications related to the dissertation work

1. Iliyan Iliev, Desislava Delcheva, Rosen Yordanov, Minimum losses of electrical energy in the process of operation of a power transformer, Yearbook of the Moscow State University "St. Ivan Rilski", 2023, pp. 233 – 236, ISSN 2738-8808.
2. Iliev I., Delcheva D., Synthesis of a technical solution for capacitive load compensation. Energy Forum 24-27 June 2025., Sofia. ISSN 1313-2962, p. 434-440
3. liev I., Delcheva D., Minimizing power losses by optimizing electrical schedules of industrial facilities. Energy Forum 24-27 June 2025., Sofia. ISSN 1313-2962, p. 419-433
4. liev I., Petrov P., Delcheva D., Optimal distribution and location of compensating capacities in an international aspect. Energy Forum 24-27 June 2025., Sofia. ISSN 1313-2962, p. 525-535

5.Iliev I., Delcheva D., Mathematical formulation for determining economic losses from deteriorated indicators in the quality of electrical energy. Energy Forum 27-30 June 2023., Sofia. ISSN 1313-2962, pp. 322-327