

Торайғыров университетінің хабаршысы
ҒЫЛЫМИ ЖУРНАЛЫ

НАУЧНЫЙ ЖУРНАЛ
Вестник Торайғыров университета

Торайғыров университетінің ХАБАРШЫСЫ

Энергетикалық сериясы
1997 жылдан бастап шығады



ВЕСТНИК Торайғыров университета

Энергетическая серия
Издается с 1997 года

ISSN 2710-3420

№3 (2026)

ПАВЛОДАР

НАУЧНЫЙ ЖУРНАЛ
Вестник Торайгыров университета

Энергетическая серия
выходит 4 раза в год

СВИДЕТЕЛЬСТВО

о постановке на переучет периодического печатного издания,
информационного агентства и сетевого издания

№ 14310-Ж

выдано

Министерство информации и общественного развития
Республики Казахстан

Тематическая направленность

публикация материалов в области электроэнергетики,
электротехнологии, автоматизации, автоматизированных и
информационных систем, электромеханики и теплоэнергетики

Подписной индекс – 76136

<https://doi.org/10.48081/BTOUEn3.2026/2710-3420>

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OPTIMISATION OF 110 kV NETWORK OPERATING MODES USING REACTIVE POWER FLOW CONTROL

This research paper examines the optimisation of steady-state operating conditions in 110 kV high-voltage power networks, using the Astana power hub as a case study. The subject of the study is a section of the 110 kV network comprising 12 key substations equipped with various types of power transformers. The study calculates steady-state conditions for winter and summer peak load periods using the 'moment rule' method for closed loop circuits, which enabled the power distribution across network sections to be determined with sufficient accuracy. Based on these calculations, active and reactive power flows were determined, and transmission losses and voltage levels at load nodes were estimated. The most heavily loaded sections of the network, characterised by a drop in voltage levels during peak load periods, were identified. The data obtained provided a basis for demonstrating the need for local reactive power control to normalise system operation. The feasibility of controlling reactive power flows was established as an optimisation method. It is proposed to install compensation devices with a capacity of 4–6 Mvar at nodes with the highest reactive power consumption. Simulation results showed that the use of compensation devices allows voltage levels to be stabilised and active power losses in the network to be reduced.

Keywords: optimisation, control, electrical network, losses, operating modes, methods, reactive power, compensation.

Introduction

110 kV high-voltage power networks play a major and crucial role in the distribution of electrical energy. Optimising their operation is essential for improving the reliability of the power supply, enhancing power quality and reducing losses [1].

In the energy sector, the optimisation of operating modes refers to the process of selecting operating parameters for the power system that ensure the best possible value for a given efficiency criterion, whilst strictly adhering to technical and technological constraints; in simpler terms, it involves finding the 'happy medium' between the reliability of the power supply and the lowest possible costs [2].

In the modern energy sector, the tasks involved in optimising operating modes can be divided into technical, economic and technological categories, but they are all aimed at managing the modes of the power system, which is based on controlling its components via separate control systems:

1. Minimising active power losses is one of the priority tasks, as reducing losses directly affects the energy efficiency of the system;
2. Voltage level control, i.e. maintaining the voltage within the limits specified by GOST;
3. Optimisation of the reactive power balance;
4. Ensuring static and dynamic stability;
5. Economic load distribution [3].

Given the complex nature of the tasks outlined above, the most cost-effective and efficient tool for urban distribution networks is the regulation of reactive power flows. This is because reactive power regulation stabilises voltage levels at load nodes and reduces losses without the need for costly line upgrades or equipment replacement. The aim of this work is to analyse the steady-state conditions of the Astana power node and to justify measures for their optimisation using compensation devices. To achieve this aim, numerical modelling methods and analytical calculations of power flow distribution parameters in closed networks based on the rule of moments are employed. A detailed description of the methods used is provided in the following section.

Materials and methods

In any system, there are constant changes in parameters such as frequency, voltage, the phase angle between the voltages at different points in the system, active and reactive power, and so on. The state of the power system, characterised by technical parameters and the condition of equipment during the generation, transmission and consumption of electrical energy, whilst maintaining a balance between generation and load, is referred to as the power system operating mode [3; 4].

The components of the operating mode control system are: the active power and frequency control system (P, f), the reactive power and voltage control system (Q, U), and the ES emergency control system (Figure 1) [4]. These three subsystems interact with one another to carry out overall control of the system's operation based on real-time information received from the information system (IS). This is a set of organisational and technical measures aimed at ensuring a reliable, high-quality and cost-effective power supply to consumers. It includes operational control, dispatching, voltage regulation, active and reactive power regulation, as well as the automation of protection and restoration of operating modes.

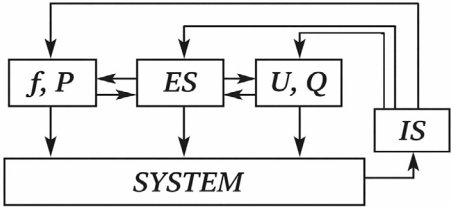


Figure 1 – General control of power supply system modes

Controlling a system's operating modes is a complex, multifaceted task that must be addressed under dynamically changing load conditions and relies on the use of computing technology in conjunction with economic and mathematical models. For the purposes of analysis, with a view to determining the best methods for optimising operating modes, we shall consider the single-line diagram of the Astana power substation, shown in Figure 2 [5; 6].

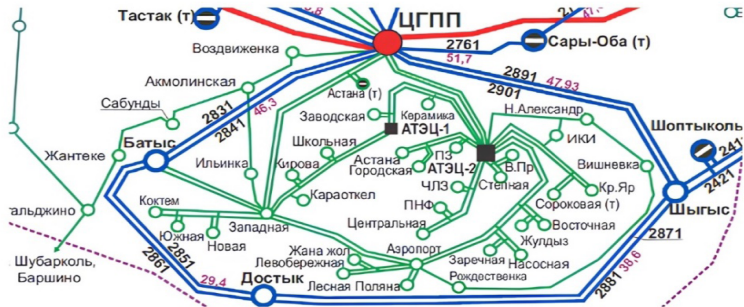


Figure 2 – Schematic diagram of the single-line diagram for the city of Astana, showing the --- 110 kV and --- 220 kV overhead lines

Astana's power system comprises more than 30 key substations equipped with power transformers of the two-winding and three-winding types. Twelve substations were selected for the optimisation calculations (Table 1), along with actual summer and winter electricity loads.

Table 1 – List of 110 kV substations and information on the load (automatic) of transformers at the Astana power hub (Data from Astana Regional Power Grid Company)

Substation name	Voltage	names of trans-formers	Rated power of transformers		Transformer loading	Transformer loading
	kV		MVA	MWt	MWt	%
«Zhuldiz» substations	110/10	T-1	40	36	17.3	48.18
		T-2	40	36	15.4	42.65
«Vostochnaya» substations	110/35/10	T-1	40	36	10.9	23.06
		T-2	40	36	13.3	23.89
«Baiterek» substations	110/20	T-1	63	56.7	2.0	3.57
		T-2	63	56.7	1.6	2.87
«Nasosnaya» substations	110/20/10	T-1	25	22.5	3.2	14.44
		T-2	25	22.5	2.9	12.84
«Zarechnaya» substations	110/10	T-1	63	56.7	10.4	18.32
		T-2	63	56.7	16.8	29.56
«Aeroport» substations	110/20/10	T-1	63	56.7	11.8	20.78
		T-2	63	56.7	11.8	20.78
		T-3	16	14.4	4.6	32.13
		T-4	16	14.4	4.0	28.00
«Zhana Zhol» substations	110/10	T-1	80	72	24.7	34.25
		T-2	80	72	17.3	23.99
«Levoberezhnaya» substations	110/10	T-1	63	56.7	6.1	10.83
		T-2	63	56.7	16.9	29.78
«Zapadnaya» substations	110/10/6	T-1	10	9	4.2	46.90
		T-2	10	9	3.6	39.60
		T-3	40	36	1.4	3.93
		T-4	40	36	1.2	3.43

«Novaya» substations	110/10	T-1	40	36	23.5	65.33
		T-2	40	36	22.1	61.25
«Yuzhnaya» substations	110/10	T-1	25	22.5	2.5	11.32
		T-2	25	22.5	2.5	11.32
«Koktem» substations	110/10	T-1	63	56.7	13.5	17.28
		T-2	63	56.7	16.4	21.16

Let us perform the network calculations for winter load conditions. As the selected facilities have a closed power supply circuit with a single source (220 V central heating substation), we will use the closed-circuit calculation method; however, we will first model the circuit diagram shown in Figure 3.

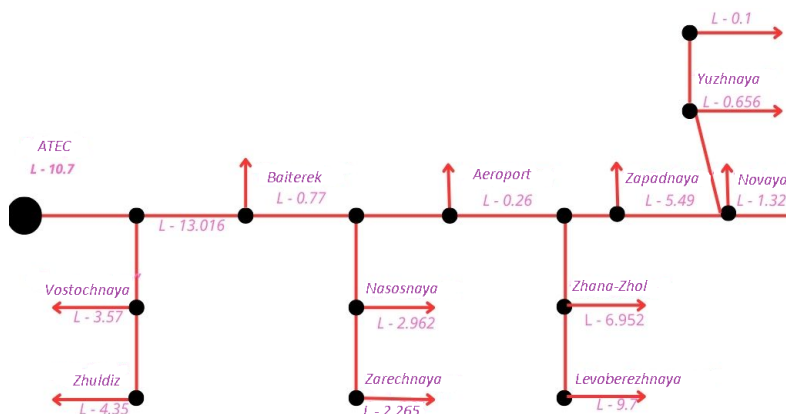


Figure 3 – Schematic diagram of the 110 kV power grid in Astana

In order to determine the power of each section of the circuit, we first calculate the power of the sections closest to the sources (САТӘІІ2 and СИҚПІІ). We determine these terminal powers in accordance with the rules for the moment, using the formula [7; 8]:

$$S_{ATEC2-Bait} = ((S_{Vost} + S_{Zhul}) \times L_1 + (S_{Bait} \times L_{1 \div 2}) + (S_{Nas} + S_{Zar}) \times L_{1 \div 3} + (S_{Aer} \times L_{1 \div 4}) + (S_{ZhZh} + S_{Lev}) \times L_{1 \div 5} + (S_{Zap} \times L_{1 \div 6}) + (S_{Nov} + S_{Yuzh} + S_{Kok}) \times L_{1 \div 7}) / \sum L_{1 \div 8}; \text{ MBA}$$

$$S_{ATEC2-Nov} = ((S_{Nov} + S_{Yuzh} + S_{Kok}) \times L_8 + (S_{Zap} \times L_{8 \div 7}) + (S_{ZhZh} + S_{Lev}) \times L_{8 \div 6} + (S_{Aer} \times L_{8 \div 5}) + (S_{Nas} + S_{Zar}) \times L_{8 \div 4} + (S_{Bait} \times L_{8 \div 3}) + (S_{Vost} + S_{Zhul}) \times L_{8 \div 2}) / \sum L_{1 \div 8}, \quad (1)$$

We shall determine the power in the remaining sections of the closed circuit using Kirchhoff's first law [7, 8]:

$$\begin{aligned}
 S_{\text{Nov-Zap}} &= S_{\text{ATEC2-Nov}} - S_{\text{Nov}}; \text{ MBA.} \\
 S_{\text{Zap-ZhZh}} &= S_{\text{Nov-Zap}} - S_{\text{Zap}}; \text{ MBA.} \\
 S_{\text{ZhZh-Aer}} &= S_{\text{Zap-ZhZh}} - S_{\text{ZhZh}}; \text{ MBA.} \\
 S_{\text{Aer-Nas}} &= S_{\text{ZhZh-Aer}} - S_{\text{Aer}}; \text{ MBA.} \\
 S_{\text{Nas-Bait}} &= S_{\text{Aer-Nas}} - S_{\text{Nas}}; \text{ MBA.} \\
 S_{\text{Bait-Vost}} &= S_{\text{Nas-Bait}} - S_{\text{Bait}}; \text{ MBA.}
 \end{aligned} \tag{2}$$

We calculate the power of the sections not included in the ring using the summation method; after calculating all the powers, we determine the line losses, which can be divided into active power losses (ΔP ; MWt) and reactive power losses (ΔQ ; MVar), charging power (ΔQC ; MVar) and voltage drop (ΔU ; kV) [7, 8].

Active power losses are defined as:

$$\Delta P_i = \left(\frac{S_{pi}}{U_n} \right)^2 \times \frac{R_l}{n}, \tag{3}$$

where U_n – rated line voltage, kV;

R_l – active line resistance, Ohms;

n – the number of circuits in a power line.

Reactive power losses are defined as:

$$\Delta Q_i = \left(\frac{S_{pi}}{U_n} \right)^2 \times \frac{X_l}{n}, \tag{4}$$

where X_l is the reactive resistance of the line, in Ohms.

The power-carrying capacity of a power line is defined as:

$$Q_c = \left(\frac{Boi \times Li \times n \times Un^2}{2} \right), \tag{5}$$

where Bo is the specific insulation capacity of the overhead power line, sm/km;

L – line length, km.

All the calculation results are summarised in Table 2.

Table 2 – Results of the calculation of the line's electrical parameters under winter load conditions

Power allocation by section		Losses under winter load conditions					
plot	S, MVA	I, A	Short-circuit lines	ΔP ; MWt	ΔQ ; MVA _r	ΔU ; кV	ΔQ_c ; MVA _r
«ATEC 2-Baiterek»	72,3	190	52706	0.053	0.145	0.68	3.25
«Vostochnaya-Zhuldiz»	51,6	136	9432	0.0094	0.026	0.16	1.13
«Zhuldiz-Baiterek»	67,7	178	77625	0.0775	0.2126	1.14	5.44
«Baiterek-Nasosnaya»	61.3	161	10368	0.0114	0.03128	0.17	0.98
«Nasosnaya-Zarechnaya»	61.3	161	6843	0.00688	0.01887	0.11	0.59
«Nasosnaya-Aeroport»	61.3	161	29109	0.009	0.02467	0.14	0.77
«Aeroport-Zhana Zhol»	92.2	243	66312	0.0661	0.1812	0.71	2.5
«Zhana Zhol-Levoberezhnaya»	92.2	243	85916	0.08562	0.2348	0.92	3.24
«Zhana Zhol-Zapadnaya»	73	192	82833	0.08295	0.2275	1.11	5.0
«Zapadnaya-Novaya»	37	97	4808	0.00484	0.01328	0.12	1.14
«Novaya-Yuzhnaya»	42.5	112	2420	0.00241	0.00662	0.06	0.43
«Yuzhnaya-Koktem»	61.3	161	3188	0.0032	0.00877	0.05	0.27
Total losses:	$\Sigma \Delta U$; %	$\Sigma \Delta P$; %	$\Sigma \Delta Q$; %				
	1.42	0.07	0.24				

Similarly, based on the circuit diagram (Figure 3) and the above formulas, it is possible to calculate the electrical parameters of the line under summer load conditions. Let us plot the graphs of electrical loads and power losses under winter load conditions (Figure 4). Analysis of the calculation data presented in the graph has enabled us to identify the sections of the network with the highest load and to determine the nodes characterised by a local reactive power deficit. Although the total technical power losses in transmission lines do not exceed the standard

values, a tendency towards a drop in voltage levels is observed at a number of remote nodes during periods of peak load. This justifies the need to implement measures to regulate reactive power flows in order to ensure the required stability margin and power supply quality in accordance with standards [9]. From this, it can be concluded that there is a voltage imbalance in the network. To address this issue, the reactive power flow control method can be applied. Of course, there are other optimization methods, such as changing the number of circuits or the cross-section of transmission line conductors, which would require replacing all supporting structures. From an economic point of view, this is considered costly. Similarly, the method of increasing the nominal voltage of the network implies replacing all substation transformers, which is practically unfeasible. Compared to these methods, the reactive power flow control method is less labor-intensive, yet it addresses the critically important task of maintaining voltage levels at network nodes and minimizing power losses. Based on these control methods, systems can be categorised according to the equipment used and the specific problem to be solved [10]:

1. The use of compensating devices, the most common method, based on the generation or absorption of reactive power at the point of consumption (capacitor banks, reactors, static thyristor compensators and synchronous compensators);

2. Regulation using synchronous machines, whose generators and motors are the most flexible sources of reactive power (synchronous generators, synchronous compensators);

3. Adjustment of transformation ratios: a method that does not generate new power but redistributes power flows between networks of different classes (transformers with on-load tap changers, voltage-boosting transformers);

4. influencing network parameters – FACTS, which are modern control methods that allow the resistance of lines affecting power flow distribution to be altered (longitudinal compensation devices, controllable shunt reactors, SVC, STATCOM) [11].

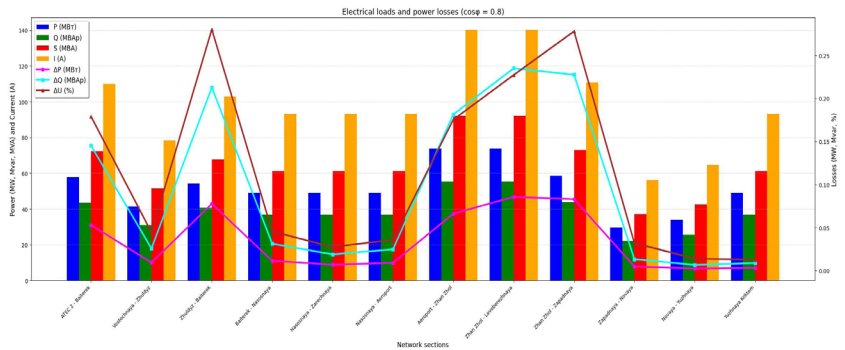


Figure 4 – Graphs showing electrical loads and power losses under winter load conditions

A comparative analysis of the methods considered shows that, within the context of the 110 kV grid of the Astana power hub, the most rational approach is to install static reactive power sources at load centers. This method is effective for local voltage stabilization and allows lines to be relieved of excessive power flows without the need for large-scale grid reconstruction. Based on the results of steady-state calculations (see Table 2), the nodes where the installation of additional reactive power generation sources is required have been identified. Thus, further optimization of the network’s operation can be achieved by installing compensating devices at these critical nodes [11, 12].

As an example, let us install reactive power compensation units for transverse reactive power compensation in power grid substations where reactive power consumption is higher. We select the capacity of the compensation units so as to avoid over-compensation of reactive power.

Table 3 – Capacity of compensation equipment at individual substations

Substation name	Reactive power of the substation Qs; MVar	Reactive power of the compensation device Qcd; MVar
Zhana Zhol	8	6
Aeroport	6,3	6
Novaya	4,25	4

Figure 5 shows the graph of electrical loads and power losses following optimisation using the method of adjusting reactive power flows under winter load conditions. Following optimisation using the reactive power compensation

method, the graphs show that the voltage drop has decreased and is now within the optimal permissible range.

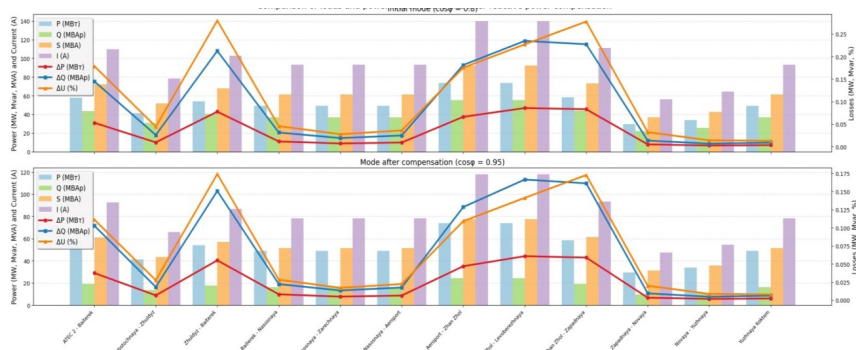


Figure 5 – Graphs showing electrical loads and power losses before and after optimisation under winter electrical load conditions

Results and discussion

Based on an analysis of the electrical load and power loss graphs (Figure 5), key findings have been identified that demonstrate the impact of reactive power compensation on the operating mode of the 110 kV network:

1 Stabilisation of voltage levels: reactive power compensation led to a reduction in voltage drops at load nodes, bringing them into line with regulatory values.

2 Reduction of network current load: an increase in the power factor at the «Zhana Zhol», «Aeroport» and «Novaya» nodes reduced the operating current in the feeder lines.

3 Reduction in transmission losses: the reduction in reactive power flows from the source to the load has led to a minimisation of active power losses, thereby improving the energy efficiency of the network.

Thus, the use of compensation devices in the 110 kV network under study ensures effective regulation of voltage levels and a reduction in operating current, confirming the advisability of using this method to optimise the network's operating modes [12].

Conclusion

As part of a study of steady-state operating conditions in the 110 kV network of the Astana power hub, a comprehensive assessment of the system's condition was carried out and sections requiring optimisation of electricity parameters were identified. Modelling of winter and summer peak operating conditions confirmed

that technical losses in the system comply with regulatory requirements; however, a need for local voltage support was identified in nodes furthest from power sources. It was established that the most rational way to normalise the operating conditions is to install compensating devices, which would eliminate reactive power deficits at the points of consumption and improve the overall energy efficiency of the distribution network.

The analysis carried out has shown that regulating reactive power flows is a rational and technically sound method of optimising grid operating conditions. The installation of 4–6 MVar compensation units at the «Zhana Zhol», «Aeroport» and «Novaya» substations has enabled the normalization of voltage levels and a reduction in current loads on the lines.

The results obtained confirm the effectiveness of using compensation devices to improve power quality and reduce power losses in 110 kV networks. The proposed solutions can be utilised in the planning and optimization of operating modes for distribution networks.

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Received 04.04.26.

Received in revised form 27.04.26.

Accepted for publication 31.08.26.

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Поступило в редакцию 04.04.26.

Поступило с исправлениями 27.04.26.

Принято в печать 31.08.26.

РЕАКТИВТІ ҚУАТ АҒЫНЫН БАСҚАРУ ҚОЛДАНУ АРҚЫЛЫ 110 КВ ЖЕЛІЛІК ЖҰМЫС РЕЖИМІН ОҢТАЙЛАНДЫРУ

Бұл зерттеу мақаласы 110 кВ жоғары кернеулі электр желілеріндегі тұрақты жұмыс режимдерін оңтайландыру мәселелерін қарастырады және мысал ретінде Астана энергетикалық хабын пайдаланады. Зерттеу объектісі – әртүрлі типтегі қуат трансформаторларымен жабдықталған 12 негізгі қосалқы станциядан тұратын 110 кВ желінің бір бөлігі. Зерттеуде жабық

контурлы желілер үшін «момент ережесі» әдісі қолданылып, қысқы және жазғы ең жоғары жүктеме кезеңдеріне арналған тұрақты режим жағдайлары есептелді, бұл желі бөлімдері арасындағы қуат таралуын жеткілікті дәлдікпен анықтауға мүмкіндік берді. Есептеулер негізінде белсенді және реактивті қуат ағындары анықталып, беріліс шығындары мен жүктеме түйіндеріндегі кернеу деңгейлері бағаланды. Ең көп жүктелген, шыңдық жүктеме кезеңдерінде кернеу деңгейінің төмендеуімен сипатталатын желінің бөлімдері анықталды. Алынған деректер жұмыс жағдайларын қалыпқа келтіру үшін жергілікті реактивті қуатты басқару қажеттігін негіздеді. Реактивті қуат ағындарын басқарудың мүмкіндігі оңтайландыру әдісі ретінде көрсетілді. Ең жоғары реактивті қуат тұтыну көрсеткіші бар түйіндерге 4–6 МВар сыйымдылығы бар компенсациялық құрылғыларды орнату ұсынылады. Симуляция нәтижелері компенсациялық құрылғыларды қолдану кернеу деңгейін тұрақтандырып, желідегі белсенді қуат шығындарын азайтатынын көрсетті.

Кілтті сөздер: оңтайландыру, басқару, электр желісі, шығындар, жұмыс режимдері, әдістер, реактивті қуат, компенсация.

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Республика Казахстан, г. Астана.

04.04.26 ж. баспаға түсті.

27.04.26 ж. түзетулерімен түсті.

31.08.26 ж. басып шығаруға қабылданды.

ОПТИМИЗАЦИЯ РЕЖИМОВ РАБОТЫ СЕТИ 110 КВ С ИСПОЛЬЗОВАНИЕМ РЕГУЛИРОВАНИЯ ПОТОКОВ РЕАКТИВНОЙ МОЩНОСТИ

В данной научной статье рассматриваются вопросы оптимизации установившихся режимов работы высоковольтных электрических сетей напряжением 110 кВ на примере Астанинского энергоузла. Объектом исследования является фрагмент сети 110 кВ, включающий 12 ключевых подстанций с различными типами силовых трансформаторов. В работе выполнен расчет установившихся режимов для периодов зимнего и летнего максимумов нагрузок

с применением метода «правила моментов» для замкнутых кольцевых цепей, что позволило определить распределение мощностей по участкам сети с достаточной точностью. На основе расчетов определены потоки активной и реактивной мощностей, а также оценены технологические потери и уровни напряжения в узлах нагрузки. Были идентифицированы наиболее нагруженные участки сети, характеризующиеся снижением уровней напряжения в периоды максимумов нагрузки. Полученные данные позволили обосновать необходимость локального регулирования реактивной мощности для нормализации режима. В качестве метода оптимизации обоснована целесообразность регулирования потоков реактивной мощности. Предложена установка компенсирующих устройств мощностью 4–6 МВАр в узлах с наибольшим потреблением реактивной мощности. Результаты моделирования показали, что применение компенсирующих устройств позволяет стабилизировать уровни напряжения и снизить потери активной мощности в сети.

Ключевые слова: оптимизация, управление, электрическая сеть, потери, режимы работы, методы, реактивная мощность, компенсация.

Теруге 07.09.2026 ж. жіберілді. Басуға 30.09.2026 ж. қол қойылды.

Электронды баспа

19,0 Mb RAM

Шартты баспа табағы 34,4. Таралымы 300 дана. Бағасы келісім бойынша.

Компьютерде беттеген: Шукитова А. Б.

Корректор: А. Р. Омарова, Д. А. Кожас

Тапсырыс № 4601

Сдано в набор 07.09.2026 г. Подписано в печать 30.09.2026 г.

Электронное издание

19,0 Mb RAM

Усл. печ. л. 34,4. Тираж 300 экз. Цена договорная.

Компьютерная верстка: Шукитова А. Б.

Корректор: А. Р. Омарова, Д. А. Кожас

Заказ № 4601

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