УДК 621.620.09 DOI:10.30724/1998-9903-2023-25-3-65-80

INFLUENCE OF THE TYPE OF LOAD GRAPHS ON THE SERVICE LIFE TRANSFORMERS 33/11 KV AT SUBSTATION "KABUN-1" (SYRIAN ARAB REPUBLIC)

E.Yu. Abdullazyanov[1], E.I. Gracheva[2], A. Alzakkar[3], S. Valtchev[4], N. Mestnikov[5]

[1,2,3]Kazan State Power Engineering University, Kazan, Russia
[4]UNINOVA−CTS, Faculty of Sciences and Technology University NOVA of Lisbon 2829-516 Campus Caparica, Portugal
[5]North-Eastern Federal University named M.K. Ammosov, Yakutsk, Russia
[2]https://orcid.org/0000-0002-8355-189X, Ahmadalzakkar86@gmail.com

Abstract: *Power transformers are one of the main components of power supply systems needed to reliably supply electricity to consumers. As we know, the value of the allowable load of transformers is determined by the value of the allowable heating of structural elements, on which the service life of transformer period depends. Reliable data on the technical condition of the structural elements of transformers is the decisive information for making decisions on the replacement and maintenance of transformers. METHODS. To assess the service life of transformers, methods were used to evaluate the statistical parameters of consumer load graphs, load factors and the heating temperature of the windings of transformers with a capacity of $S_{n.T}$ = 20 MVA, a voltage of 33/11 kV at substation Kabun-1. THE AIM. The aim of the work is to evaluate the service life of the transformers at substation Kabun-1 (Syrian Arab Republic) with various options for the type of load power consumption graph (first; second; third). THE RESULTS. The main statistical parameters of the characteristics of the original and proposed options of load power graphs (active, reactive and apparent) per day of transformers, the main electrical consumer of which is the spinning and weaving factory, are determined. Approximating functions of daily graphs of power loads of transformers, from which the spinning and weaving factory receives power (first and second approximations), have been developed. It is proved that with the considered options for shifting the time of the start of work of electrical consumers - with the third option -the maximum load power is reduced by 12.8%, load variation is reduced from 0.33 to 0.17 in relation to the second option for the subdivisions of the spinning and weaving factory. It has been established that for all the considered options, the average value of the load power of the transformers at substation Kabun-1 is constant. The laws of change in the relative value of the service life of transformers during the implementation of various technical measures are determined.*

Key words: *power consumer, power transformer, load graph, transformer load factor, winding heating, service life.*

For citation: EYu. Abdullazyanov, EI. Gracheva, A. Alzakkar, S. Valtchev, N. Mestnikov. Influence of the type of load graphs on the service life transformers 33/11 Kv at substation "Kabun-1" (Syrian Arab Republic). *Power engineering: research, equipment, technology*. 2023; 25 (3): 65-80. doi:10.30724/1998-9903-2023-25-3-65-80.

ВЛИЯНИЕ ВИДА ГРАФИКОВ НАГРУЗОК НА СРОК ЭКСПЛУАТАЦИИ ТРАНСФОРМАТОРОВ НАПРЯЖЕНИЕМ 33/11 КВ ПОДСТАНЦИИ «КАБУН-1» (СИРИЙСКАЯ АРАБСКАЯ РЕСПУБЛИКА)

Абдуллазянов Э.Ю.[1], Грачева Е.И.[2], Альзаккар А.[3], Valtchev S.[4], Местников Н. П.[5]

[1,2,3]Казанский государственный энергетический университет, г. Казань, Россия
[4]UNINOVA−CTS, Faculty of Sciences and Technology University NOVA of Lisbon 2829-516 Campus Caparica, Portugal
[5]Северо-Восточный федеральный университет им. М.К. Аммосова г. Якутск, Россия

[2]*https://orcid.org/0000-0002-8355-189X, Ahmadalzakkar86@gmail.com*

Резюме: *Силовые трансформаторы являются одними из основных элементов систем электроснабжения, необходимых для надёжного обеспечения потребителей электроэнергией. Как известно, величина допустимой нагрузки трансформаторов определяется значением допустимого нагрева элементов конструкции, от которого зависит период срока службы. Достоверные данные о техническом состоянии элементов конструкции трансформаторов являются определяющей информацией для принятия решений по замене и обслуживанию трансформаторов. ЦЕЛЬ. Целью работы является оценка срока службы трансформаторов подстанции «Кабун-1» (Сирийская Арабская Республика) при различных вариантах вида графика потребляемой мощности нагрузки (исходный; первой; второй; третий). МЕТОДЫ. Для оценки срока службы трансформаторов использованы методы оценки статистических параметров графиков нагрузок потребителей, коэффициентов загрузки и температуры нагрева обмоток трансформаторов мощностью Sном.тр= 20 мВА, напряжением 33/11 кВ подстанции «Кабун-1». РЕЗУЛЬТАТЫ. Определены основные статистические параметры характеристик исходных и предлагаемых вариантов графиков мощности нагрузки (активной, реактивной и полной) за сутки трансформаторов, основным электропотребителем которых является Прядильно-ткацкая фабрика. Разработаны аппроксимирующие функции суточных графиков мощностей нагрузок трансформаторов, от которых получает питание Прядильно- ткацкая фабрика (первое и второе приближение). Доказано, что при рассматриваемых вариантах сдвига времени начала работы электропотребителей -при третьем- наибольшая мощность нагрузки снижается на 12,8%, вариация нагрузок снижается с 0,33 до 0,17 по отношению ко второму варианту для подразделений Прядильно-ткацкой фабрики. Установлено, что для всех рассматриваемых вариантов среднее значение мощности нагрузок трансформаторов подстанции «Кабун-1» постоянно. Определены законы изменения относительного значения срока службы трансформаторов при внедрении различных технических мероприятий.*

Ключевые слова: *электропотребитель, силовой трансформатор, график нагрузки, коэффициент загрузки трансформатора, нагревание обмоток, срок службы.*

Для цитирования: Абдуллазянов Э.Ю., Грачева Е.И., Альзаккар А., Valtchev S., Местников Н.П. Влияние вида графиков нагрузок на срок эксплуатации трансформаторов напряжением 33/11 Кв подстанции «Кабун-1» (Сирийская Арабская Республика) // Известия высших учебных заведений. ПРОБЛЕМЫ ЭНЕРГЕТИКИ. 2023. Т.25. № 3. С. 65-80. doi:10.30724/1998-9903-2023-25-3-65-80.

Introduction (Введение)

In the current conditions of development of the Syrian Arab Republic, special attention is paid to improving the quality of power supply to the industrial city Adra, which is one of the largest in the Republic. In 2022, new industrial enterprises were put into operation in the city Adra, where there are 31 enterprises, including food factory, engineering and chemical enterprises, whose products on the local market account for more than 60%. At present, considerable attention is paid to the regulation of electricity consumption modes due to the increase in the cost of electricity. Below is an analysis of some of the scientific works of scientists conducting research in this field.

The authors E. Yu. Abdullazyanov, E. I. Gracheva, A. Alzakkar [1] presented a study that makes it possible to increase the reliability of predicting the magnitude of power consumption and power losses at industrial enterprises. At the same time, it is proposed to use the dynamics of changes in the value of the equivalent resistance of intra-factory power supply networks, which will make it possible to control the modes of electricity consumption and make adjustments to the forecasting processes.

A. Naderian, P. Pattabi, L. Lamarre [2] presented an updated estimate of the residual life of transformers based on the results of an improved dynamic model.

K. Chitnavis, N. R. Bhasme [3] developed a power transformer life evaluation method, i.e. a method for calculating the actual serviceability index, including additional factors such as preload, bushing condition, aging, physical measurements of DGA, oil quality, power factor.

K.T. Muthanna, A. Sarkar; K. Das, K. Waldner [4] presented new methods for assessing the life of the insulation of high-power generator units in power plants. This paper shows modeling methods for estimating load factors and ambient temperature, taking into account preliminary operating conditions.

A. Alzakkar, E. Gracheva, Y. Samofalov [5, 6] conducted a study of the calculated power loads of communal electrical consumers and compared with the experimental power consumption in Adra city. Parameters and graphs of loads of electricity consumers at the facilities of the city of Adra were determined by methods of statistical data processing.

D.K. Yakubova [7] considers the effect of load modes on the wear of the insulation of power transformers using the example TNTS-000/220 1000-UHL.

V. A. Anishchenko, V. V. Ivanov [8] developed a method for determining the permissible duration of a systematic non-emergency overload of a distribution oil transformer, taking into account changes in the overload coefficient over the time interval of its operation and, accordingly, changes in the thermal state of the transformer structural elements.

A. Chatterjee, N. K. Roy [9] presented an analysis and simulation of the characteristics of dissolved gases in transformer oil in order to develop an oil change and filtration graph, which in turn regulates the quality of the oil when a failure occurs.

E.I. Gracheva, O.V. Naumov, E.A. Fedotov [10] calculated the operating mode of power transformers to determine the optimal load at which the efficiency of the transformer reaches its maximum value, and also proposed options for increasing the efficiency of power transformers of industrial enterprises.

D. S. Serebrennikov, V. G. Goldshtein [11] explore topical issues of assessing the actual state of power transformers with a significant service life using thermal imaging diagnostics.

The scientific and practical significance of the proposed article is the results of the studies that show that in conditions of high temperatures in the summer in Syria, which can reach 48 ° C, it is necessary to control the change in the load factors of transformers and the heating temperature of the windings, which are the determining factors in changing the relative service life of power transformers. This is especially important at the present time in connection with the imposition of economic sanctions by unfriendly states against the Syrian Arab Republic.

The difference between the presented work and the results of other studies is that for the first time the operating conditions of transformers with a voltage 33/11 kV (substation "Kabun-1", Syria) were studied on the basis of statistical data on power consumption by industrial and non-industrial facilities. The dependences of the change in load factors and the heating temperature of the windings are determined, and recommendations are made for technical solutions aimed at increasing the relative service life of transformers.

Materials and methods (Материалы и методы).

To select the type of approximating function for daily graphs of active power loads of transformers of a spinning and weaving factory we perform a two-stage approximation

A - First approximation.

To study the characteristics of the load graphs under consideration and the choice of approximating functions, we use the results of estimating the parameters of electrical consumers of the spinning and weaving factory, which is powered by substation Kabun-1, given in [5, 6]. The average value of the approximating function must be equal to the average value of the original graph. The maximum value of the approximating function should approach the maximum value of the original graph and approximately coincide in time. Therefore, the form of the function approximating the graph of the active load in the first approximation can be represented as [12, 13]:

$$\left.\begin{aligned} &\Phi^{[1]}(t)=B_P^{[1]}-A_P^{[1]}\cos(\omega^{[1]}t)=B_P^{[1]}-A_P^{[1]}\cos\left(\frac{2\pi t}{T^{[1]}}\right)\\ &B_P^{[1]}\approx M_P^{[1]}(+)\approx M_P^{[1]}(-)\\ &\omega^{[1]}=\frac{2\pi}{T^{[1]}}=\frac{6}{24}\approx 0{,}25\left[1/\mathrm{h}\right] \end{aligned}\right\} \quad (1)$$

$\mathbf{M_P=P_{av}}$ — is the average value per day of the original active load graph, obtained from statistical data;

$\mathbf{M_P^{[1]}}$ — is the daily average value of the active load approximation graph in the first approximation;

$\mathbf{A_P^{[1]}}$ — is the amplitude of the cosine can be approximately determined by the expression:

$$\left.\begin{aligned} A_P^{[1]} &\approx A_P \\ A_P &= 0{,}5\left(P_{макс} - P_{мин}\right) \end{aligned}\right\} \qquad (2)$$

$\mathbf{P_{max}}$ и $\mathbf{P_{min}}$ — respectively, are the maximum and minimum value of the daily graph of the active load;

Table 1 shows the total and average values of the original daily graphs of active power loads for 36 transformers of the spinning and weaving factory.

Table 1

Statistical values of the original daily graphs of active power loads of transformers

	$\mathbf{M_P}$, kW	$\mathbf{P_{max}}$, kW	$\mathbf{P_{min}}$, kW	$\mathbf{0{,}5(P_{max} - P_{min})}$; kW	**Φ, kW**	**(**	$\mathbf{K_{max}}$
Sum	14517	26730	4634	11048	7279	18,17	66.45
Average	403	743	129	307	202	0.51	1.85

**Источник: составлено автором. Source compiled by the author*

Table 2 shows:

1. Arguments of approximating functions of daily active loads of transformers in the first approximation with a period $T^{[1]}$ = 24 h and frequency T≃0.25 1/h.

$$\Phi^{[1]}(t) = B_P^{[1]} - A_P^{[1]} \cos\left(0.25\, t\right) \qquad (3)$$

2. Mean values of differences:

$$\left.\begin{aligned} M_R^{[1]} &\left[f_{orig}(t) - \Phi^{[1]}(t) \right] \\ M_R^{[1]}\% &= \frac{M_R^{[1]}}{M_P^{[1]}} \end{aligned}\right\} \qquad (4)$$

3. The value of the standard deviation of the differences:

$$\left.\begin{aligned} \delta_R^{[1]} &= \sqrt{\frac{\sum_{i=1}^{24}\left(\left(M_R^{[1]}\right)_i - \left(M_R^{[1]}\right)_{av}\right)^2}{24}} \\ \delta_R^{[1]}\% &= \frac{\delta_R}{M_P^{[1]}} \end{aligned}\right\} \qquad (5)$$

Table 2

Arguments and estimation of the error of the approximation function (first approximation) $B_P^{[1]} - A_P^{[1]}$ cos(0.25t) of daily graphs of active power of loads of 36 transformers

	Arguments function $N^{[1]}(t)$ approximations in the first approximation		$\mathbf{M_R^{[1]}}$	$\mathbf{*_R^{[1]}}$
	$\mathbf{B_P^{[1]}}$	$\mathbf{A_P^{[1]}}$		
Sum (kW)	14090	10480	62	4362

**Источник: составлено автором. Source compiled by the author*

The data in table 2 show that the average values of the differences between the original graph and the approximating function are fractions of a percent of the average value of the active load per day for all transformers. Fig.1 shows the original graph of the active load of the transformer 25 (with the highest value of the load factor K_L = 0.98) and their function approximation.

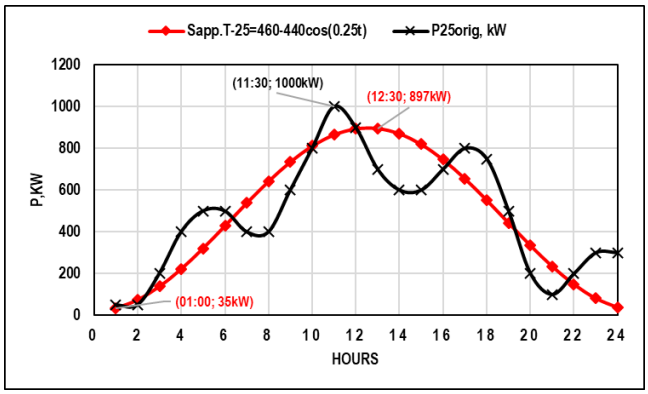

Fig.1. The original graph of the active load T-25 and its function approximation 460-440cos(0.25t)

**Источник: составлено автором. Source compiled by the author*

Fig.1 shows that the maximum time of the original graph is 11:30 am and the maximum time of the function approximation is 12:30 pm. Values of root mean square error for loads (28) of transformers exceed 20%, which indicates the need for a more accurate approximation. Table 3 shows the statistical characteristics of the approximated graphs of the active load of 36 transformers.

Table 3

The values of the statistical data of the daily graphs and approximation functions of the active power of the loads of transformers with a voltage of 11/0.4 kV of the spinning and weaving factory (first approximation)

	M_P [1], kW	P_{max}, kW	P_{min}, kW	Φ, kW	(	K_{max}
Sum	14579	24310	4126	7232	17,85	59,98
Average	405	675	115	201	0,49	1,67

**Источник: составлено автором. Source compiled by the author*

Table 4 presents the characteristics of the original total graphs of the active load of the spinning and weaving factory and the sum of the approximating functions of the transformers.

Table 4

Statistical parameters of the original graphs and approximated (first approximation 14090-10480cos(0.25t) total daily graphs of the active power of the loads of the spinning and weaving factory.

Graph	ΣM_P, kW	ΣP_{max}, kW	ΣP_{min}, kW	ΣΦ, kW	$(_{av}$	$(K_{max})_{av}$
Original	14517	26730	4634	7279	0,51	1,85
Approximate	14579	24310	4126	7232	0,49	1,67

**Источник: составлено автором. Source compiled by the author*

Expression (2) determines the function of approximation of the total load graph of the factory.

$$B_{P\ \Sigma}^{[1]} - A_{P\ \Sigma}^{[1]} \cos(0{,}25\,t) = 14090 - 10480\cos(0{,}25\,t) \quad (6)$$

Fig.2 shows the total graphs of the active power of the loads of the spinning and weaving factory of the original and approximated ones.

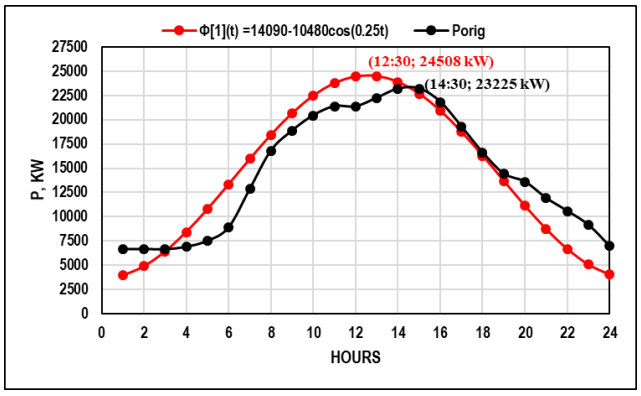

Fig.2. The total active power graphs of the loads of the spinning and weaving factory of the original and approximated $\Phi^{[1](}t) =14090-10480\cos(0.25t)$.

**Источник: составлено автором. Source compiled by the author*

The data in table 4 and Fig. 2 show that with the practical coincidence of the average values of the load power graphs, there is a significant difference in the minimum and maximum values. The maximum load of the original graph is observed at 14:30, and the approximated one - at 12:30, so the approximation needs to be refined.

B- Second approximation.

To approximate the daily graphs of the active load of transformers in the second approximation, the sum of harmonic functions was used:

1. The first one with the period $T_1^{[2]}$=20 ч или 24 ч ($_1^{[2]}$=0.25 и 0.33);

2. The second one with the period $T_2^{[2]}$≈6ч ($_2^{[2]}$=1).

For a more accurate approximation of the maximum load time in the original graph to the time of the maximum of the approximation function, various initial phases were selected.

$$j_0^{[2]}=2\pi.t_0\omega^{[2]} \quad (5)$$

Therefore, the form of the function approximating the graph of the active load in the second approximation.

$$\left.\begin{aligned}\Phi^{[2]}(t)&=B_{P1}^{[2]}-A_{P1}^{[2]}\cos\left(\omega_1^{[2]}t+j_{01}^{[2]}\right)\pm A_{P2}^{[2]}\cos\left(\omega_2^{[2]}t+j_{02}^{[2]}\right)\\ \Phi^{[2]}(t)&=\underbrace{B_{P1}^{[2]}-A_{P1}^{[2]}\cos\left(\frac{2\pi t}{T_1^{[2]}}+j_{01}^{[2]}\right)}_{First\ Function}\pm\underbrace{A_{P2}^{[2]}\cos\left(\frac{2\pi t}{T_2^{[2]}}+j_{02}^{[2]}\right)}_{Second\ Function}\end{aligned}\right\} \quad (7)$$

Let's find the approximation of the function in the second approximation for the transformer 25 using (8):

1. First function $\left(B_{P1}^{[2]}-A_{P1}^{[2]}\cos\left(\omega_1^{[2]}t+j_{01}^{[2]}\right)\right)$:

$$\left.\begin{aligned}\left(B_{P1}^{[2]}\right)_{T-25}&\approx\left(M_{P,1}^{[2]}\right)_{T-25}=480\ kW\\ \left(A_{P1}^{[2]}\right)_{T-25}&=\frac{P_{max.1}^{[2]}-P_{min.1}^{[2]}}{2}=\frac{800-200}{2}=300\ kW\end{aligned}\right\} \quad (8)$$

2. Second function $\left(A_{P2}^{[2]}\cos\left(\omega_2^{[2]}t+j_{02}^{[2]}\right)\right)$:

$$\left(A_{P2}^{[2]}\right)_{T-25}=\left(P_{min}^{[2]}\right)_{T-25}=235\ kW \quad (9)$$

3. The total approximation of the function in the second approximation for the transformer T-25:

$$\left.\begin{aligned}\left[\Phi^{[2]}(t)\right]_{T-25}&=\underbrace{480-300\cos\left(\frac{2\pi t}{24}+0\right)}_{First\ Function}-\underbrace{235\cos\left(\frac{2\pi t}{6}-8\right)}_{Second\ Function}\\ \left[\Phi^{[2]}(t)\right]_{T-25}&=480-300\cos(0.25t)-235\cos(t-8)\end{aligned}\right\} \quad (10)$$

Fig.3 shows 4 graphs, first, second, total approximation of the function and the original for the transformerT-25:

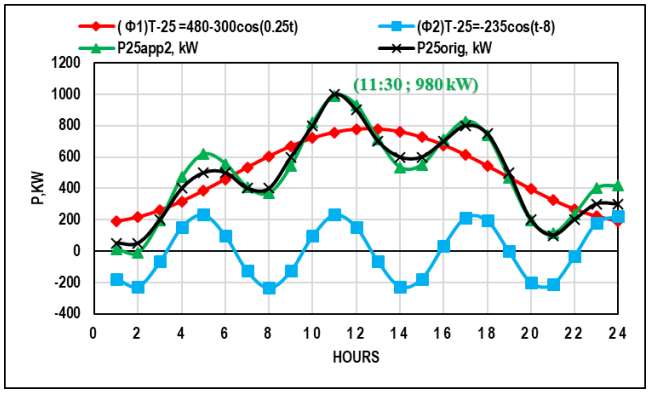

Fig.3. Graphs of the original and functions of the refined approximation of the active load T-25.

**Источник: составлено автором. Source compiled by the author*

Fig.3 shows the agreement between the original and approximated graphs, especially during the maximum (11:30; 980 kW).

Table 5 and 6 show the statistical indicators of the original graphs (average and total) of the active load and approximation functions in the second approximation.

Table 5

Statistical indicators of the original graphs of active load and approximation functions in the second approximation (part-1)

	M_P, kW		**P_{max}, kW**		**Φ, kW**	
	Original	**Second approximation**	**Original**	**Second approximation**	**Original**	**Second approximation**
Average	403	403	743	743	202	201
Sum	14517	14513	26730	26754	7279	7227

**Источник: составлено автором. Source compiled by the author*

Table 6

Statistical indicators of the original active load graphs and approximation functions in the second approximation (part-2)

	P_{min}, кВт		(		K_{max}	
	Original	**Second Approximation**	**Original**	**Second Approximation**	**Original**	**Second Approximation**
Average	128	61	0.51	0.51	1.84	1.86
Sum	4634	2162	18.17	18.13	66.45	66.60

**Источник: составлено автором. Source compiled by the author*

Let's calculate the errors for the second approximation of the graphs of the active power of the loads of the spinning and weaving factory (for transformer 25):

1. Approximation function.

$$\Phi^{[2]}(t) = 480 - 300\cos(0.25t) - 235\cos(t-8) \qquad (11)$$

2. Average values of differences (Fig. 3).

$$\left.\begin{aligned} M_R^{[2]}\left[f_{orig}(t) - \Phi^{[2]}(t)\right] &= \frac{16}{24} \approx 0.66 \\ M_R^{[2]}\% &= \frac{0.66}{483}\times 100 = 0.14\% \end{aligned}\right\} \qquad (12)$$

3. The value of the standard deviation of the differences.

$$\left.\begin{aligned} \delta_R^{[2]} &= \sqrt{\frac{65599}{24}} = 52.28 \\ \delta_R^{[2]}\% &= \frac{52.28}{483}\times 100 = 11\% \end{aligned}\right\} \qquad (13)$$

Table 7 presents comparisons of the error for the first and second approximation of the graphs of the active power of the loads of the spinning and weaving factory.

Table 7

Approximation error values (first and second approximation) on average for transformers of the spinning and weaving factory

Graph type	**Average difference**		**Average difference**		**Root mean square error**		**Root mean square error**	
	$M_R^{[2]}$кВт	$M_R^{[1]}$кВт	$M_R^{[2]}$%	$M_R^{[1]}$%	$*_R^{[2]}$кВт	$*_R^{[1]}$кВт	$*_R^{[2]}$%	$*_R^{[1]}$%
Average	-0.13	2	-0.03	0.418	67.67	121	17.18	30

**Источник: составлено автором. Source compiled by the author*

Table 8 presents a comparison of the values of the original and (first, second) approximation daily graphs of the active power of the loads of the spinning and weaving factory.

Table 8

Statistical parameters of the original graphs and approximation functions, the first approximation (14090-10480cos(0.25t)) and the second approximation of the daily graphs of the active power of the loads of the spinning and weaving factory

Graph	**ΣM_P, kW**	**ΣP_{min}, kW**	**Time maximum**	**$\Sigma P_{мmin}$, kW**	**$\Sigma\Phi$, kW**	**$(_{av}$**	**$(K_{max})_{av}$**
Original	14517	26730	14:30	4634	7279	0.51	1.85
Approximate (1)	14579	24310	12:30	4126	7232	0.49	1.67
Approximate (2)	14513	26754	14:30	2712	7227	0.51	1.86

**Источник: составлено автором. Source compiled by the author*

It is noted that for second approximation a fairly accurate degree of coincidence of the graphs is shown by the statistical data in tables 5 and 6; time error estimates and maximum values are shown in tables 7 and 8 (14h:30min; 26750 kW).

The discussion and results (Обсуждение и результаты).

The possible ways to align the load graphs [14, 15] of the spinning and weaving factory

1. The shift in the start time of the weaving production from 5:30 to 12:30, the rest of the production works in the original modes (first option).

2. The shift in the start time of the weaving production from 5:30 to 12:30 and the spinning production from 5:30 to 22:30, the rest of the consumers work in their original modes (second option).

A. First and second options.

In tables 9, 10 and 11 show the calculations of the parameters of the approximate graphs of the total power of the loads for the original, first and second options.

Table 9

Approximate values of the total power of the loads of electrical consumers at substation Kabun-1, taking into account reactive power compensation at the spinning and weaving factory.

	S_{com}: 15-7cos(0.5t+5)	S_{weav}: 5.7-3.5cos(0.25t)	S_{spin}: 6.6-3.8cos(0.25t)	S_{other}: 2.1-1.9cos(0.25t)	$S_{sum.app}$	$S_{sum.Kabun-1.orig.comp}$
S_{av}, MVA	14.99	5.86	6.77	2.18	29.81	28.93
S_{max}, MVA	22	9.19	10.39	3.99	42.69	42
K_{fill}	0.68	0.64	0.65	0.55	0.70	0.69
S_{eff}, MVA	22.36	8.96	7.28	2.57	30.88	30.46
Φ_S, MVA	7.13	3.41	2.69	1.34	8.41	9.53
(S	0.48	0.58	0.40	0.61	0.28	0.33

**Источник: составлено автором. Source compiled by the author*

Table 10

Approximate values of the loads of electrical consumers at substation "Kabun-1" (Option 1), the start time of the weaving production is 12:30

	S_{com}: 15-7cos(0.5t+5)	S_{weav}: 5.7-3.5cos(0.25t-8)	S_{spin}: 6.6-3.8cos(0.25t)	S_{other}: 2.1-1.9cos(0.25t)	$S_{sum.app.opt.1}$
S_{av}, MVA	14.99	5.65	6.77	2.18	29.6
S_{max}, MVA	22	9.18	10.39	3.99	37.4
K_{fill}	0.68	0.62	0.65	0.55	0.79
S_{eff}, MVA	22.36	6.19	7.28	2.57	30.29
Φ_S, MVA	7.13	2.56	2.69	1.34	6.92
(S	0.48	0.46	0.40	0.61	0.23

**Источник: составлено автором. Source compiled by the author*

Table 11

Approximate values of loads of electrical consumers of substation "Kabun-1" (Option 2), start time of weaving production 12:30 and spinning production 22:30

	S_{com}: 15-7cos(0.5t+5)	S_{weav}: 5.7-3.5cos(0.25t-8)	S_{spin}: 6.6-3.8cos(0.25t+2)	S_{other}: 2.1-1.9cos(0.25t)	$S_{sum.app.opt.2}$
S_{av}, MVA	14.99	5.65	6.55	2.18	29.38
S_{max}, MVA	22	9.18	10.39	3.99	36.36
K_{fill}	0.68	0.62	0.63	0.55	0.81
S_{eff}, MVA	22.36	6.19	7.15	2.57	29.74
Φ_S, MVA	7.13	2.56	2.81	1.34	5.15
(S	0.48	0.46	0.43	0.61	0.18

**Источник: составлено автором. Source compiled by the author*

Using table 6, the total capacity of the spinning and weaving factory at the substation "Kabun-1" for the second option:

$$S_{sum.Kabun-1.fact.opt.2} = S_{sum.fact} + S_{com.orig} \qquad (14)$$

All calculated values are presented in table 12.

Table 12

The values of the total power of loads of electrical consumers of transformers 33/11 kV at substation "Kabun-1", a spinning and weaving factory, with a shift in the start time (option 2) and compensation of reactive power of domestic consumers.

	$S_{sum.Kabun-1.orig.comp}$	$S_{sum.fact}$	$S_{com.orig}$	$S_{sum.Kabun-1.fact.opt.2}$
S_{av}, MVA	28.93	14.39	14.46	28.85
S_{max}, MVA	42	14.59	23	37.47
K_{fill}	0.69	0.99	0.63	0.77
S_{eff}, MVA	30.46	14.39	21.90	29.46
Φ_S, MVA	9.53	0.13	7.85	5.62
(S	0.33	0.01	0.54	0.19

Fig.4, 5, and 6 show the graphs of the loads of transformers with a voltage 33/11 kV at substation Kabun-1 and their terms - in real and approximate form - for various cases of the time when the production of the spinning and weaving factory began to work.

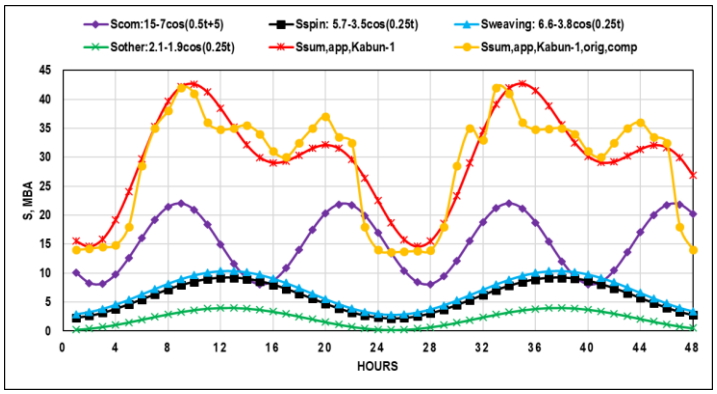

Fig. 4. Approximate graphs of the total power loads of electrical consumers at substation Kabun-1, taking into account reactive power compensation at the spinning and weaving factory.

**Источник: составлено автором. Source compiled by the author*

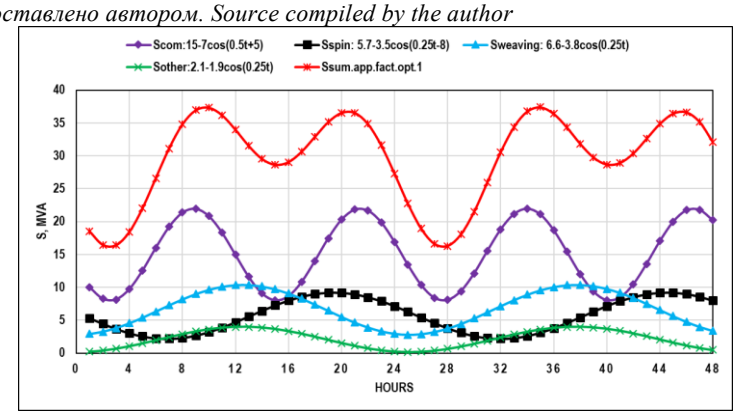

Fig.5. Approximate graphs of loads of electrical consumers at substation "Kabun-1" (Option 1), the start time of the weaving production is 12:30.

**Источник: составлено автором. Source compiled by the author*

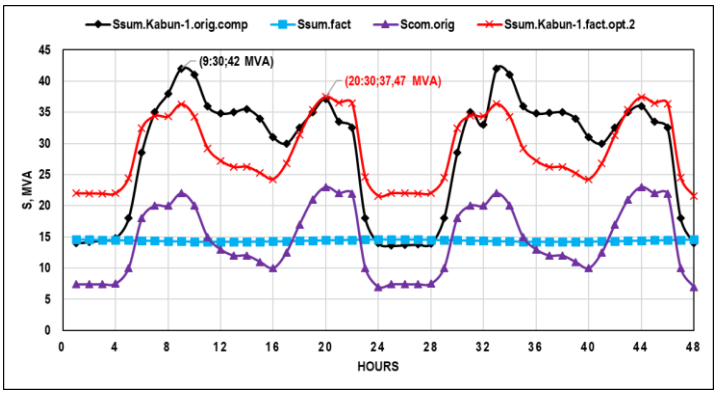

Fig.6. Actual load graphs of electrical consumers of transformers 33/11 kV at substation Kabun-1, spinning and weaving factory, with a shift in the start time (option 2) and reactive power compensation of domestic consumers.

**Источник: составлено автором. Source compiled by the author*

Table 13 shows the statistical characteristics of the conducted studies.

Table 13 shows that in the second option of shifting the start time, the maximum load is reduced by 4.5 MVA (42–37.47), and its onset time is shifted from 9:30 in the original option to 20:30 in the second option (Fig. 6). The value of the load variation decreases from 0.33 in the original case to 0.19 in the second case, i.e. the graph is compressed. To assess the service life of transformers [16], it is required to determine the graphical changes in the dependence and load factors of transformers and the corresponding winding heating temperatures, and then the value of the relative service lives.

Table 13

Statistical characteristics of the actual and approximate load graphs of transformers with a voltage 33/11 kV at substation Kabun-1 with various options for shifting the start time of the spinning and weaving factory divisions.

Index	Original with compensation		Option-1	Option-2	
	Approx	Real	Approx	Approx	Real
S_{av}, MVA	29.81	28.93	29.60	29.38	28.85
S_{max}, MVA	42.69	42.00	37.40	36.36	37.47
K_{fill}	0.70	0.69	0.79	0.81	0.77
S_{eff}, MVA	30.88	30.46	30.29	29.74	29.46
Φ_S, MVA	8.41	9.53	6.92	5.15	5.62
($_S$	0.28	0.33	0.23	0.18	0.19

**Источник: составлено автором. Source compiled by the author*

The load factor of the second option is calculated by the expression

$$t=1h \Rightarrow \left\{ \begin{array}{l} K_{L.opt.2} = \dfrac{S_{sum.Kabun\text{-}1.fact.opt.2}}{S_{n.T}} \\ K_{L.opt.2} = \dfrac{21.99}{40} = 0.55 \end{array} \right\} \quad (15)$$

Using [6], we calculate the value of the relative service life, the second option

$$t=1h \Rightarrow \left\{ \begin{array}{l} T_{ser.life.opt.2} = -1.46K^2_{L.opt.2} - 0.5K_{L.opt.2} + 1.83 \\ T_{ser.life.opt.2} = -1.46(0{,}55)^2 - 0.5(0.55) + 1.83 \\ T_{ser.life.opt.2} = 1.35 \end{array} \right\} \quad (16)$$

All calculated values are presented in table 14

Table 14

Calculations of the value of the load factor of the transformers at substation "Kabun-1" of the second option

	$S_{sum.Kabun\text{-}1.fact.opt.2}$; MVA	$S_{n.T}$, MVA	$K_{L.opt.2}$	$T_{ser.life.opt.2}$
Average	28.85	40	0.75	0.9
Sum	37.47	40	0.94	1.35

**Источник: составлено автором. Source compiled by the author*

Fig.7 and 8 show the results of calculations of the load factor and the relative service life of transformers, the second option.

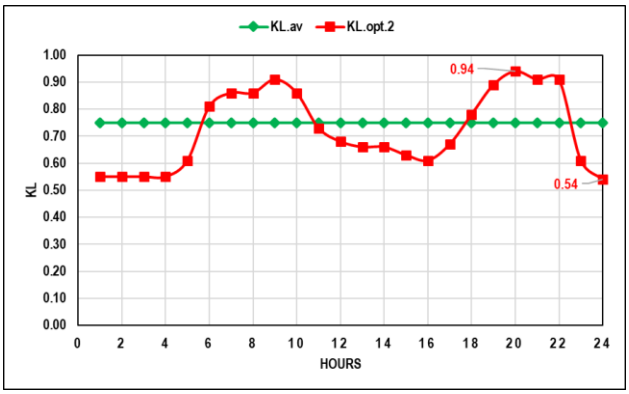

Fig.7. Graphical dependences of the daily values of the load factor of the transformers at substation "Kabun-1" (the second option for shifting the start time of electrical consumers).

**Источник: составлено автором. Source compiled by the author*

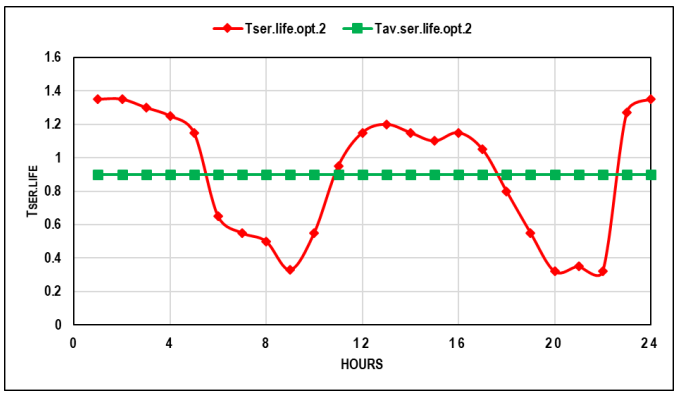

Fig.8. Graphical dependences of the relative service life of the transformers at substation Kabun-1 (the second option for shifting the start time of work)

*Источник: составлено автором. Source compiled by the author

From Fig. 7 it is shown that the value of the average load factors of transformers (the second option for the start time of the spinning and weaving factory) is 0.75, the limit values are 0.54 -0.94.

It can be seen from Fig. 8 that the value of the average relative service life of transformers (second option) is 0.9.

From [6], we consider the values of the heating temperature of the transformer windings of the second option

$$t=1h \Rightarrow \begin{cases} T_{ser.life.opt.2} = -0.125\, t_{winding.opt.2} + 11.792 \\ t_{winding.opt.2} = \dfrac{11.79 - T_{ser.life.opt.2}}{0.125} \\ t_{winding.opt.2} = \dfrac{11.79 - 1.35}{0.125} = 83.52\ ^{\circ}C \end{cases} \qquad (17)$$

Table 15 shows the values of the heating temperature of the transformer windings at substation Kabun-1 of the second option.

Table 15

Calculation of the heating temperature of the transformer windings at substation Kabun-1 of the second option

	$t_{winding.orig}$ (°C)	$T_{ser.life.opt.2}$	$t_{winding.opt.2}$
Average	90.3	0.9	87
Max	97.5	1.35	91.76
Min	83.5	0.32	83.52

*Источник: составлено автором. Source compiled by the author

Fig.9 shows graphs of the calculation results from table 15 for various load options.

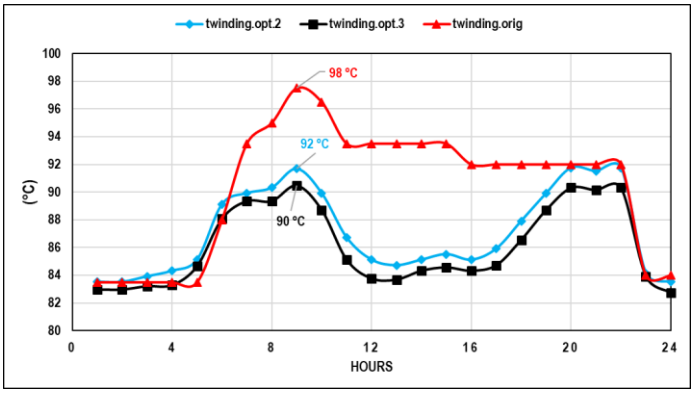

Fig.9. Graphical dependences of the daily values of the heating temperature of the winding of the transformers at substation Kabun-1 for various load options.

*Источник: составлено автором. Source compiled by the author

From Fig. 9, it is noticed that it is less than desired, since the period of the greatest loads, the value of the heating temperature of the windings is higher than the permissible 85°C.

Table 16 presents a comparison between the original, second and third option.

Table 16

The values of the winding heating temperature and the service life of the transformers at substation Kabun-1 for various options for load graphs

Load characteristic	**Coefficient transformer loading**		**Winding heating temperature, °C**		**Relative service life $T_{ser.life}$**
	$K_{L.max}$	$K_{L.av}$	$t_{winding.max}$	$t_{winding.av}$	
Original graph for reactive power compensation	1.05	0.75	98	90	0.63
Graph according to option 2 when approximating reactive power compensation	0.94	0.72	92	87	0.9
Graph according to option 3 when approximating reactive power compensation	0.9	0.72	90	84	1.05

**Источник: составлено автором. Source compiled by the author*

From table 16, it is noted that the value of the service life of transformers for the load graph for the second equalization option is significantly greater (about one and a half times) (0.63→0.9) than for the original load graph, taking into account reactive power compensation.

B. Third option.

It is possible to analyze additional measures to equalize the load graphs of transformers when changing the start time for some small industrial power consumers in the new sector of Adra.

The results of studies of the characteristics of the load graphs of communal, administrative and public electrical consumers, a mechanical workshop and a juice factory plant in the city of Adra, powered by transformers with a voltage 33/11 kV at substation Kabun-1, are presented in [1, 5, 6].

The third option for reducing power consumption and leveling the load graph of transformers with a voltage 33/11 kV at substation Kabun-1 includes the following measures:

1. Installation of a capacitor bank on the low voltage side of transformers in a spinning and weaving factory.
2. Shift in the start time of the weaving production from 5:30 to 12:30.
3. Shift in the start time of the spinning production from 5:30 to 22:30.
4. Shift in the start time of the mechanical workshop from 7:30 to 23:30.
5. Shift the start time of the juice factory from 8:30 to 0:30.

The total power at substation "Kabun-1" of the third option:

$$\left.\begin{aligned} S_{\text{Kabun-1.opt.3}} &= S_{\text{Com.opt.3}} + S_{\text{Spin\&weaving.opt.3}} \\ S_{\text{Com.opt.3}} &= S_{\text{ad\&pub}} + S_{\text{Juice.opt.3}} + S_{\text{Mec.opt.3}} \end{aligned}\right\} \qquad (17)$$

Table 17

Calculations of the total power at substation "Kabun-1" of the third option

	Administrative &public	Mechanical workshop	Juice factory	Communal	Spin & weaving factory	«Kabun-1» opt.3
Average (MVA)	13.05	0.46	0.90	14.41	14.51	28.92

**Источник: составлено автором. Source compiled by the author*

Fig.10 shows the graphs of the total power loads of transformers of the third option.

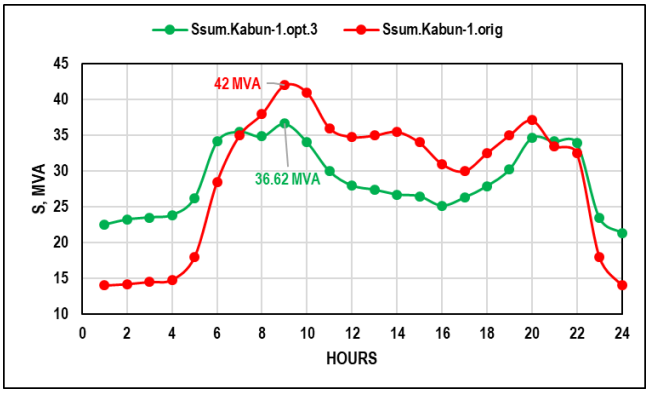

Fig.10. Graphs of the total power loads of transformers with a voltage 33/11 kV for the original and for the third shift option

*Источник: составлено автором. Source compiled by the author

For the third option of shifting the start time of work, the largest load power is reduced by 5.38 MVA (42.0 - 36.62), the load variation is reduced from 0.33 to 0.17 in relation to the second option only for divisions of the spinning and weaving factory, the largest value decreased by another 0.85 MVA (42.0 - 37.47), while in all options the average value of the load power of transformers with a voltage 33/11 kV at substation "Kabun-1" is constantly equal to 28.9 (table 18).

Table 18

Statistical parameters of the actual load graphs of transformers with a voltage 33/11 kV at substation "Kabun-1" for the third option of shifting the start time of electrical consumers

Parameter	Administrative & public	Mechanical workshop	Juice factory	Communal	Spin & weaving factory	«Kabun-1» opt.3	«Kabun-1» original
S_{av}, MVA	13.05	0.46	0.90	14.41	14.51	28.92	28.93
S_{max}, MVA	21.40	1.10	1.80	21.70	15.94	36.62	42.00
K_{fill}	0.61	0.42	0.50	0.66	0.91	0.80	0.69
S_{eff}, MVA	14.12	0.64	1.06	15.22	14.54	29.33	30.46
Φ_S, MVA	5.39	0.45	0.57	4.90	0.99	4.89	9.53
($_S$	0.41	0.98	0.63	0.34	0.07	0.17	0.33

*Источник: составлено автором. Source compiled by the author

Also, as the second option, you can evaluate the service life of the transformer of the third option (we use (15), (16) and (17)) and the results in the tables 19 and 20.

Table 19

Calculations of the value of the load factor of transformers and the relative service life at substation "Kabun-1" of the third option

	$S_{n.T}$	$S_{sum.Kabun-1.opt.3}$	$K_{L.opt.3}$	$T_{ser.life.opt.3}$
Average (MVA)	40	28.75	0.72	1.45
Max (MVA)	40	36.21	0.90	1.02

*Источник: составлено автором. Source compiled by the author

Table 20

Calculations of the heating temperature of the transformer windings at substation Kabun-1 of the third option

	$t_{winding.orig}$	$T_{ser.life.opt.3}$	$t_{winding.opt.3}$
Average (°C)	90.3	1.45	84
Max (°C)	97.5	1.02	90

*Источник: составлено автором. Source compiled by the author

Fig.11 and 12 show the results of calculations of the load factor and the relative service life of transformers of the third option.

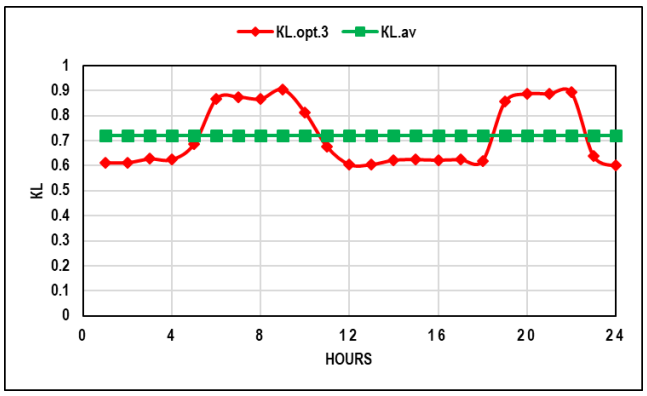

Fig.11. Graphical dependences of the daily change in the load factor of the transformers at substation "Kabun-1" (the third option for shifting the start time of electrical consumers)

**Источник: составлено автором. Source compiled by the author*

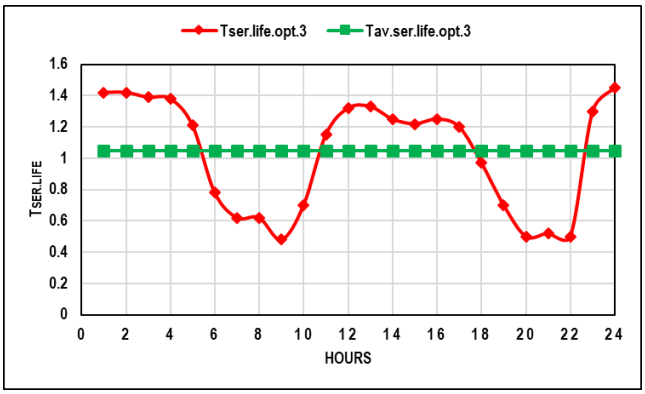

Fig.12. Graphical dependences of the relative service life of transformers "Kabun-1" (the third option for the start of operation of electrical consumers)

**Источник: составлено автором. Source compiled by the author*

Table 16 compares the original and second options with the third option. The research results showed the following:

1. The value of the average load factor of transformers (the third option of the shift in the start time of the operation of electrical consumers at substation Kabun-1) is 0.72, the limit values are 0.61–0.91.

2. The value of the average relative service life of transformers in the third option is 1.05 - slightly more than desired. This is explained by the fact that the value of the average winding heating temperature [17, 18] is less than 84°C (allowable temperature of 85°C).

3. The value of the relative service life of transformers in the case of the load graph corresponding to the third option is significantly higher (almost twice) (0.63→1.05) than with the original graph with the installation of compensating devices.

Conclusion (Заключение).

1. Approximation functions have been developed for daily graphs of active power loads of transformers of the spinning and weaving factory (first and second approximations).

2. A sufficiently high degree of coincidence of the statistical parameters of the load graphs has been proved; estimates of the error of the approximation function for approximation 2.

3. It is proved that the numerical parameters of the sum of the approximated graphs and the original graph of the spinning and weaving factory approximately coincide. Therefore, to align the load graphs of the factory, the developed approximation functions were used, and then the obtained results of the load parameters were compared with the real charts.

4. As a result of the research, it was established that the service life of the transformers at substation Kabun-1 (the second option and the third option) depends on the start time of the spinning and weaving factory units. At the same time, it was revealed.

A. In the second option, the service life of transformers with an equalization load graph is significantly longer (about one and a half times) (0.63→0.9) than for the original load graph taking into account reactive power compensation and the average winding heating temperature decreased by 3 °C (90 → 87) °C.

B. In the third option, the service life of transformers is significantly higher (almost twice) (0.63→1.05) than with the original graph with the installation of compensating devices and the average winding heating temperature decreased by 6 °C (90 → 84) °C.

References

1. Abdullazyanov E.Y., Gracheva E.I., Alzakkar A., Nizamiev M.F., Shumikhina O.A., Valtchev S. Prediction and analysis of power consumption and power loss at industrial facilities. Power engineering: research, equipment, technology. 2022;24(6):3-12. (In Russ.) https://doi.org/10.30724/1998-9903-2022-24-6-3-12.

2. Naderian A., Pattabi P. and Lamarre L. Improving the Assessment of Remaining Life of Service Aged Power Transformers, IEEE Electrical Insulation Conference (EIC), Calgary, AB, Canada, 2019, pp. 330-334, doi: 10.1109/EIC43217.2019.9046610.

3. Chitnavis K. and Bhasme N. R. Review of critical analysis for life estimation of power transformer, 2017 4th International Conference on Power, Control & Embedded Systems (ICPCES), Allahabad, India, 2017, Pp. 1-6, DOI: 10.1109/ICPCES.2017.8117632.

4. Muthanna K. T., Sarkar A., Das K. and Waldner K. Transformer insulation life assessment, IEEE Transactions on Power Delivery, Vol. 21, №. 1, pp. 150-156, Jan. 2006, DOI: 10.1109/TPWRD.2005.855474.

5. Alzakkar A., Gracheva E. and Samofalov Y. An Analytical Study of the Electrical Power Consumption in the Industrial City (Adra – Syria), 2023 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM), Sochi, Russian Federation, 2023, pp. 410-415, doi: 10.1109/ICIEAM57311.2023.10139241.

6. Alzakkar A., Mestnikov N.P., Maksimov V.V., Valeev I.M. Assessment of the voltage stability index of electric networks supplying charging stations using a multilayer perceptron. Power engineering: research, equipment, technology. 2022;24(2):36-49. (In Russ.) https://doi.org/10.30724/1998-9903-2022-24-2-36-49.

7. Yakubova D. K., A study of the influence of load modes of the transformer TNTS-000/220 1000-UHL1 for worn insulation. Conference proceedings: Energy for resource tezhash muammolari, 2016. (In Russ.).

8. Anishchenko V.A., Ivanov V.V. Ascertainment of admissible systematic overloads in the distributive oil-transformers. Energetika. Proceedings of CIS higher education institutions and power engineering associations. 2015;(3):5-15. (In Russ.)

9. Chatterjee A. and Roy N. K. Mathematical model for predicting the state of health of transformers and service methodology for enhancing their life, 24th Canadian Conference on Electrical and Computer Engineering (CCECE), Niagara Falls, ON, Canada, 2011, Pp. 126-129, DOI: 10.1109/CCECE.2011.6030423.

10. Gracheva E.I., Naumov O.V., Fedotov E.A. Influence of a load capability of power transformers on their operational characteristics. Power engineering: research, equipment, technology. 2017;19(7-8):71-77. (In Russ.) https://doi.org/10.30724/1998-9903-2017-19-7-8-71-77.

11. Serebrennikov D.S., Goldstein V.G. Evaluation of the technical condition of power transformers with a long service life based on the results of external thermal vision diagnosis. News of Higher Educational Institutions. Electromechanics. 2014. - №. 3. - Pp. 100-102. (In Russ.).

12. Vakhrushev A. I., Aleksanyan G. A. Approximation of functions Applied questions of exact sciences– 2018. – Pp. 35-37. (In Russ.).

13. Zakharov V. S. Influence of 35 kV feeder parameters on the approximation functions of the criteria for default location2020. - №. 58-3. - Pp. 79-83. – DOI:10.18411/lj-02-2020-55. – EDN RIFPQA. (In Russ.).

14. Bazarov, A. A. The method of leveling the load graph of powerful induction installations. Technical Sciences Series Vestnik of Samara State Technical University. Technical Sciences Series. 2021. - Vol. 29, №. 4 (72). - S. 71-85. – (In Russ.) DOI 10.14498/tech.2021.4.6. – EDN KPVHQQ.

15. Titarenko, O. N. Analysis of methods for leveling daily load graph. Power installations and technologies. - 2018. - Vol. 4, No. 3. - Pp. 67-73. – EDN VAQFER. (In Russ.).

16. Mayorov A.V., Lvov M.Yu., Lvov Yu.N., Komarov V.B., Ershov B.G. Power transformers and autotransfrormers of electrical network life time prediction. Power engineer - 2018. - №. 11. - Pp. 17-20. – EDN YSEYDR. (In Russ.).

17. Abdullazyanov E.Yu., Gracheva E.I., Alzakkar A. Analysis and study of power consumption of objects in the industrial zone of Adra-Syria. Power engineering: research,

equipment, technology. 2023;25(1):118-129. (In Russ.) https://doi.org/10.30724/1998-9903-2023-25-1-118-129.

18. Daghrah M., Wang Z., Liu Q. Experimental Study of the Influence of Different Liquids on the Transformer Cooling Performance. IEEE Transactions on Power Delivery, Vol.34, Issue.2, 2019. DOI: 10.1109/TPWRD.2019.2895533.

Authors of the publication

Edward Y. Abdullazyanov – Rector of Kazan State Energy University.

Elena I. Gracheva – Doctor of Technical Sciences, Professor of the University of Electric Power Industry, Kazan State Power Engineering University.

Ahmad Alzakkar – Master of Technology and Technology, graduate student of the Institute of Electric Power Engineering of Kazan State Power Engineering University.

Stanimir Valtchev – Associate Professor of University NOVA of Lisbon, Portugal.

Nikolai P. Mestnikov – North-Eastern Federal University named M.K. Ammosov.

Получено 15.06.2023 г.

Отредактировано 20.06.2023 г.

Принято 06.07.2023 г.