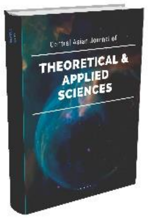

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Calculation of Power Losses in Electrical Networks Taking into Account Non-Sinusoidal Voltage

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Annotation: *The article considers the non-sinusoidal voltage, which is one of the indicators of the quality of electricity. The main sources of propagation of high voltage harmonics and their influence on the electrical network are given. Taking into account the non-sinusoidal voltage, an algorithm for calculating power losses has been developed and the results are presented. The program used data from the Malika-01 device, which measures the quality of electricity in low-voltage electrical networks, to perform calculations.*

Keywords: *Power, Electrical, Networks.*

Introduction. In our time of high technology, nonlinear loads (frequency converters, inverters, uninterruptible power supply systems, switching power supplies, fluorescent and LED lamps, etc.) are becoming more and more common. Due to such changes in the load structure, the main topic in this decade has been the quality of electricity and the reduction of harmonics. Problems caused by harmonics, such as overheating of transformers and rotating machines, overload of neutral conductors, failure of capacitor banks, etc., lead to increased operating costs and can also lead to a decrease in product quality and labor productivity. In addition, changes in the structure of electricity generation towards the use of wind energy and solar panels, which also generate harmonics, also lead to the fact that the use of harmonic filters is becoming increasingly important to ensure a stable energy supply with acceptable electricity quality [1-3].

Methods. In the past, most loads were linear (asynchronous motors, heaters, incandescent lamps), which means that the current of these devices when connected to a sinusoidal voltage will be sinusoidal. Now most loads are nonlinear, which means that the current through these devices when connected to a sinusoidal voltage will be non-sinusoidal (Fig. 1). Such currents, in addition to the main frequency current, contain currents with higher frequencies that distort the shape of the sinusoid. Voltage harmonics are mainly caused by current harmonics. A nonlinear load does not directly cause the appearance of voltage harmonics if it does not consume energy [1-5].

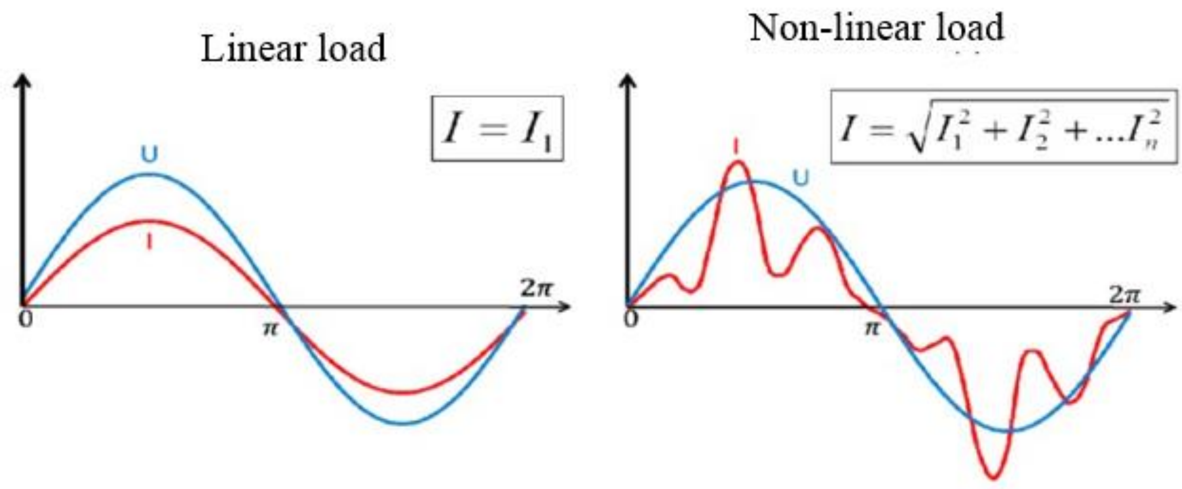

Fig.1. Comparison of linear and nonlinear load time diagrams

However, the source voltage will be distorted by the harmonics of the current due to the presence of the source impedance. If the impedance of the voltage source is small, harmonic currents will create small harmonic voltage distortions. The measure is the nonlinear distortion coefficient (THD), which is defined as the ratio of the sum of all harmonic components to the value of the signal at the fundamental frequency. Equality (1) shows this relation for current (when considering power systems). For voltage, power and other parameters, the formulas are similar [6], [11].

$$THD_i = \frac{I_{\text{harmonic}}}{I_{on\,osn.frequency}} \cdot 100 . \qquad (1)$$

Expression (1) can be rewritten as [6]:

$$THD_i = \frac{\sqrt{\sum_{j=2}^{\infty} I_j^2}}{I_1} = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + . . . + I_n^2}}{I_1} \qquad (2)$$

In (2) I_n is the effective value of the current of the nth harmonic, j=1 implies the fundamental frequency. Therefore, THD can be reduced by decreasing I harmonics or increasing I at the fundamental frequency [12], [13].

Problems arising from harmonics are, for example, overheating of transformers (K-factor) and rotating machines, overload of the neutral, increased voltage between neutral and ground, failure of capacitor banks, triggering of circuit breakers and fuses, improper operation of electronic equipment and generators, loss of energy and loss of network capacity (inefficient energy transfer). These problems lead to additional costs, such as higher electricity consumption, costs due to faster aging of equipment, equipment downtime, increased maintenance and repair costs, as well as losses due to lower product quality and productivity (for example, with an increase in defects in the production of semiconductors) [1-5].

Currently, research is relevant in the electric power industry, the purpose of which is to calculate and analyze power and energy losses in electric networks taking into account higher harmonics [7]. Therefore, the purpose of this article was to create an algorithm that would allow creating a program for calculating power losses based on data obtained from the electric energy quality meter "Malika-01" of the electric network [8], [9].

The analysis of electricity quality indicators (PCE) is carried out by specialized measuring instruments – analyzers of electricity quality at time intervals from 24 hours (minimum value) to 7 days (recommended value). The initial information for calculations is the instantaneous values of linear (phase) voltages at the point of common connection of electricity consumers [6], [10].

A domestic specialized measuring device "Malika-01" was developed jointly by the Department of "Electric Power Stations, Networks and Systems" of the Tashkent State Technical University and "Electric Power Engineering" of the Fergana Polytechnic Institute [9, 10]. The device is designed to register additional technological losses and conduct PCE measurements in electrical networks with a voltage of 220 – 380 V. This device is used when conducting surveys and evaluating the CE using statistical methods, including with a limited range of indicators in accordance with the requirements of GOST [6].

The analog part provides connection of up to three phases of alternating current at the same time, the switching circuit and the general view of the device are shown in Fig. 2 [14], [15].

Fig.2. General view of the device "Malika-01"

Results. When developing the program, data from 6 transformer substations (TP) connected to one feeder were used. The program is aimed at determining the power dissipated in power lines when additional currents of higher harmonics flow through them. Data were obtained on the power consumption during the day, by each substation. The data was analyzed and approximated for each hour. The daily load schedule of each substation is shown in Fig. 3.

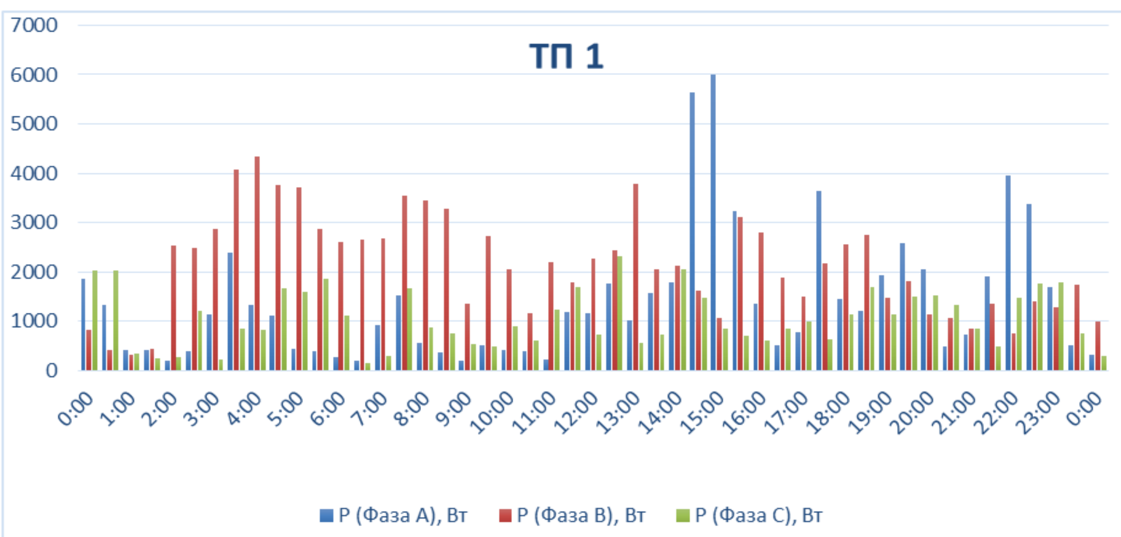

Fig.3. Power consumed by TP 1

The non-sinusoidal voltage coefficients at these substations are within acceptable limits according to [6]. The total coefficient of non-sinusoidal voltage is shown in Fig. 4.

Data on the coefficients of the higher harmonics of the current were also obtained. The spectra of harmonic currents (coefficients of the nth harmonic component of the current Ij) are shown in Fig. 5.

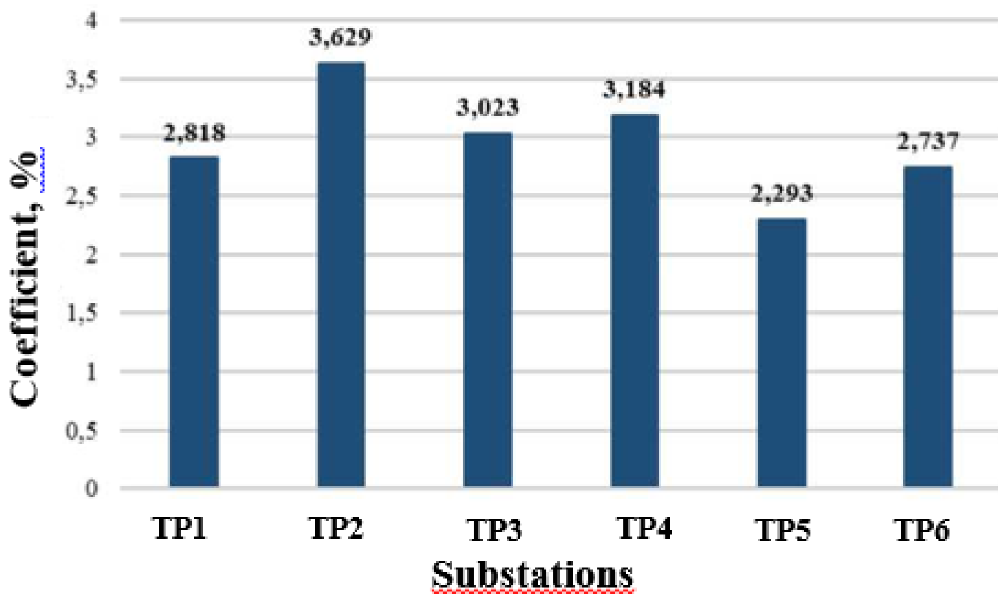

Fig. 4. The total coefficient of non-sinusoidal voltage of transformer substations

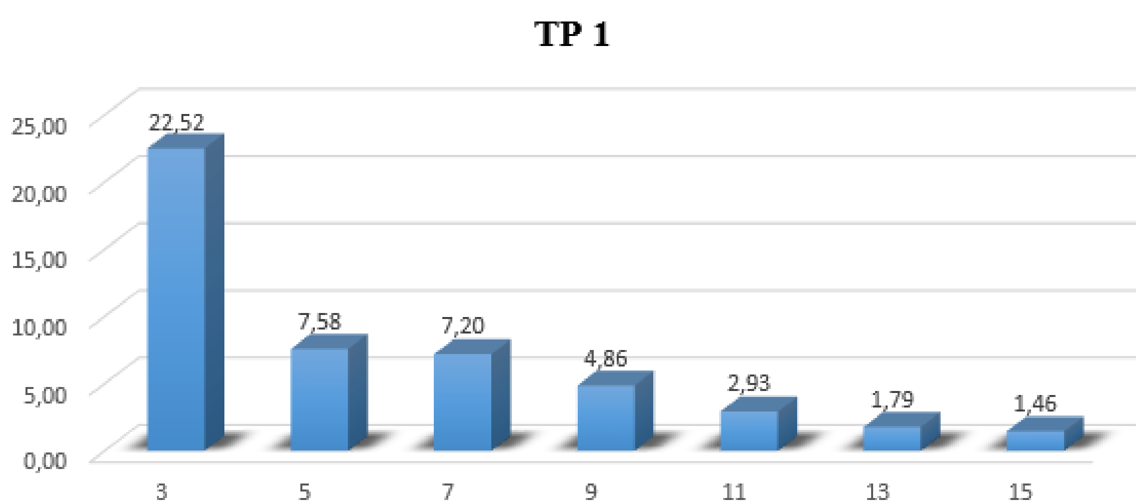

Fig. 5. Spectrum of harmonic currents TP 1

The busbar of the 110/6 kV step-down substation is taken as the base node, taking into account that the voltage on its tires is unchanged.

When developing a program, it is required to draw up a flowchart of the algorithm by which the program will be compiled. The block diagram of the algorithm of the program for calculating power losses taking into account the non-sinusoidal voltage is shown in Fig. 6.

To compile the program, you need to enter data on the configuration of the electrical network so that the program can process this information. The data describing the network configuration is presented below, an excerpt from the Mathcad program.

Table 1. Information about the lines connecting the transformer points

	1	2	3	4	5	6
1	2.75	1	0.251	0.4	2	1
2	2.23	1	0.251	0.4	3	2
3	1.97	1	0.251	0.4	4	3
4	1.32	1	0.251	0.4	4	5
5	1.22	1	0.251	0.4	6	4
6	0.72	1	0.251	0.4	7	6

In this table, the rows correspond to the power lines connecting transformer substations. The first column of the table indicates the lengths of the lines. The second column indicates the number of parallel lines (circuits of power lines). The third and fourth columns indicate the specific active and reactive resistance of the wires of this line. The fifth and sixth columns show which nodes (transformer substations) are connected by the corresponding line. Column 5 corresponds to the beginning of the power line, column 6 corresponds to the end of the power line [15].

The loads of these transformer substations are given in the form of currents. Harmonic currents are represented by a part of the canonical series (n=3, 5, 7, 11, 13). Since the weight of higher-order harmonics is minimal in relation to those presented, the currents of these harmonics are not taken into account. The higher harmonics of the current are usually represented as current sources, then they will be written with a "+" sign. The currents consumed by the load are represented with the sign "-". Load currents and currents of higher harmonics are presented in Table 2.

Table 2. Currents of the main and higher harmonics

	Harmonica	3	5	7	9	11	13	15
		A						
TP 1	1.	-25.4	8.45	9.1	6.345	4.41	2.35	1.6
	2.	-38.4	17.1	15.75	13.355	8.115	3.55	3.2
	3.	-35.35	15.05	13.9	11.625	6.995	2.85	2.6
	4.	-26.3	8.35	7.4	6.415	3.885	1.4	1.6
	5.	-20.2	5	6	3.34	2.025	0.7	0.85
	6.	-20.75	3.9	5.1	3.195	2.265	1.05	0.75
	7.	-21.75	4.85	5.4	4.13	2.985	1.35	0.9
	8.	-30.25	12.05	9.25	7.005	4.29	2.5	2.1
	9.	-16.6	2.4	2.75	2.735	1.69	1.15	0.45
	10.	-20.45	4.6	5.15	3.87	2.755	1.9	1.15
	11.	-17.9	4.45	4.7	2.86	1.89	1.8	1.2
	12.	-21.2	7.05	6.9	3.76	2.445	2.25	1.9
	13.	-18.6	5.75	5.2	2.75	1.715	1.7	1.35
	14.	-18.05	5.7	5.15	3.125	1.92	1.55	1.1
	15.	-17.8	4.8	4.9	2.975	1.705	1.4	0.95
	16.	-18.3	5.35	6.1	3.675	1.675	1.5	1.05
	17.	-19	6.5	5.7	3.965	2.36	1.95	1.35
	18.	-19.8	6.05	5.85	4.015	2.835	2.3	1.7

	19.	-16.05	4.1	4.3	2.37	1.03	1.05	1
	20.	-17	5.6	4.9	2.51	1.585	1.45	1.2
	21.	-20.9	7.9	6.7	3.935	2.425	1.65	1.45
	22.	-32.05	16.5	13.75	9.565	5.08	2.7	2.45
	23.	-26.37	11.77	10.43	6.42	3.22	1.77	1.67
	24.	-26.20	9.87	9.23	5.64	3.18	1.78	1.87

In accordance with the block diagram of the algorithm (part I, indicated in Fig. 6) the first matrix of incidents was obtained in the Mathcad program. Its definition and result are shown below.

$$M1 = \begin{pmatrix} -1 & 0 & 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & -1 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \qquad (3)$$

$$M1 := \left| \begin{array}{l} \textit{for } k \in 1..\text{пуст} \\ \quad \left| \begin{array}{l} n1 \leftarrow (lin^{\langle 5 \rangle})_k \\ n2 \leftarrow (lin^{\langle 6 \rangle})_k \\ X_{n1.k} \leftarrow 1 \\ X_{n2.k} \leftarrow -1 \end{array} \right. \\ \qquad\qquad X \end{array} \right.$$

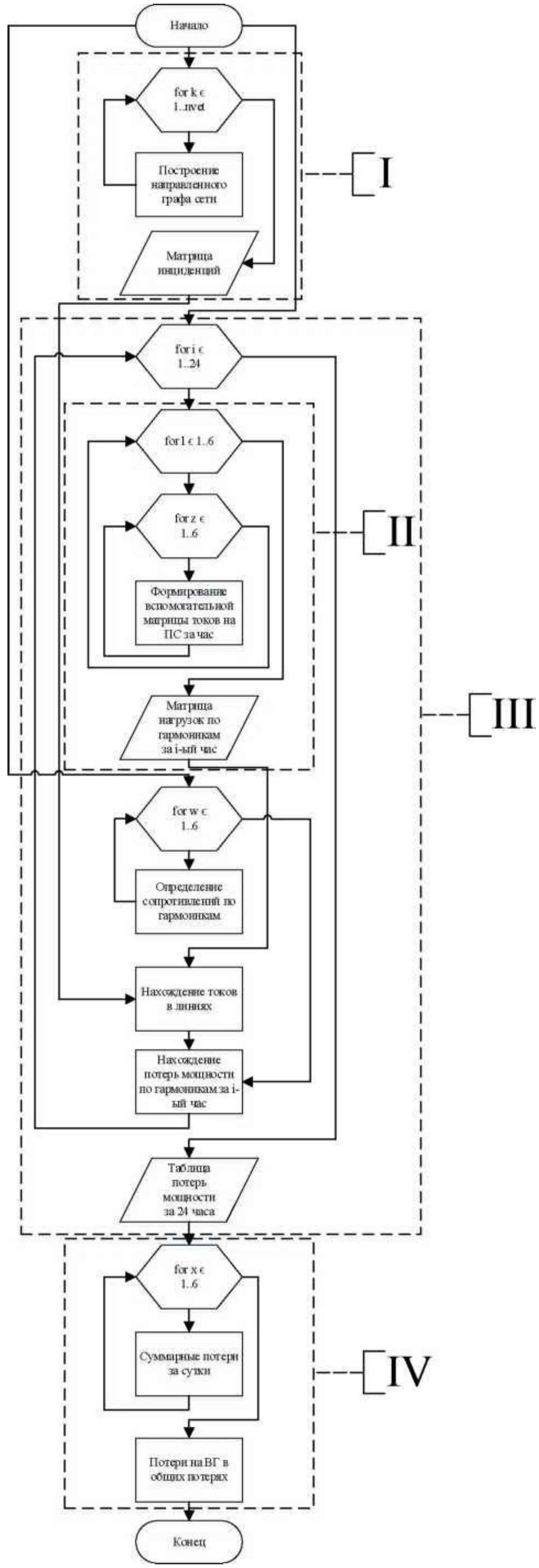

Fig. 6. Block diagram of the algorithm of the program for calculating power losses at non-sinusoidal voltage

(3) listing from the Mathcad program (definition of the first matrix of incidents).

The algorithms presented in Parts II and III in accordance with the block diagram shown in Fig. 7 allow us to determine the power losses in this electrical network presented in (4). Part of the algorithm number II allows us to form a matrix of currents at each substation for the i-th hour over the entire range of harmonics. Part of the algorithm number III generates at its output a matrix (Table 3) of power losses in this electrical network in 24 hours, for all harmonics. The formation of the table and the resulting values are presented below. In the table of the resulting values, the columns correspond to the power losses per harmonic per hour. The lines indicate the number of hours in a day. The received power is represented in watts [14].

$$
power := \left| \begin{array}{l}
for\ \ i \in 1 \ldots 24 \\
\quad \left| \begin{array}{l}
for\ 1 \in 1 \ldots \text{пр}s \\
\quad for\ z \in 1 \ldots cols\,(n) \\
\qquad \left| \begin{array}{l} d \leftarrow i + (1-1) \cdot 24 \\ P_{1,z} \leftarrow I\_n_{d,z} \end{array} \right. \\
for\ w \in 1 \ldots cols\,(n) \\
\quad \left| \begin{array}{l}
pov^{\langle w \rangle} \leftarrow n^{\langle w \rangle} \\
RI^{\langle w \rangle} \leftarrow `Re(Z) \cdot \sqrt{pov^{\langle w \rangle}} \\
I_{lin}^{\langle w \rangle} \leftarrow M^{-1} \cdot p^{\langle w \rangle} \\
AS \leftarrow 3 \cdot \overrightarrow{\left[I_{lin}^{\langle w \rangle} \cdot I_{lin}^{\langle w \rangle} \cdot (RI^{\langle w \rangle}) \right]} \\
AS\Sigma \leftarrow \sum AS \\
O_{i,w} \leftarrow AS\Sigma
\end{array} \right.
\end{array} \right. \\
O
\end{array} \right. \qquad (4)
$$

(4) listing from the Mathcad program (Algorithm for calculating power losses taking into account higher harmonics).

Discussion. To find the specific weight of the power losses attributable to the higher harmonics in the total losses, in accordance with part IV of the algorithm, the following result was obtained.

$$
\mathbf{poteri} := \begin{array}{l}
\mathbf{for\ x \in 1 \,..\, cjls(power)} \\
\left| \begin{array}{l}
\mathbf{p}^{\langle x \rangle} \leftarrow \sum \mathbf{power}^{\langle x \rangle} \\
\mathbf{p}
\end{array} \right.
\end{array}
$$

$$
\mathbf{poteri} = (346562.985;\ \ 1715.880;\ \ 1635.453;\ \ 224.098;\ \ 79.440;\ \ 84.759 \qquad (5)
$$

$$\mathbf{Poteri}\sum = \frac{\sum \mathbf{poteri} - \mathbf{poteri}_{1,1}}{\sum \mathbf{poteri}}$$

Table 3. Power losses in the electrical network in 24 hours, for all harmonics

Harmonic Hour	**1**	3	5	7	**11**	13
	ΔP, W					
1	11010.754	83.097	77.914	12.574	5.242	4.185
2	7786.433	58.737	59.949	8.654	4.585	3.389
3	6254.566	37.269	45.826	6.414	3.319	2.464
4	5808.782	27.602	42.806	5.908	2.519	1.855
5	5005.961	24.302	38.707	6.507	2.276	1.503
6	5226.745	20.477	34.043	5.287	1.933	1.336
7	6141.078	24.833	33.887	5.515	2.103	1.563
8	9670.277	30.863	35.572	4.569	1.713	1.839
9	11377.034	43.353	36.486	4.889	1.666	2.872
10	10951.621	46.188	45.813	4.501	1.693	2.677
11	10489.677	56.843	62.110	7.543	2.762	2.994
12	11907.181	67.776	69.888	8.033	3.038	3.551
13	12638.175	74.256	79.678	10.081	3.575	3.938
14	13592.510	85.581	88.220	10.950	3.728	4.135
15	15655.950	84.163	100.897	10.840	3.996	4.869
16	13725.182	88.164	91.659	9.734	4.290	5.360
17	17018.386	96.534	93.913	10.658	3.658	4.765
18	20933.234	91.222	67.713	10.056	3.195	4.596
19	23836.045	89.909	66.447	8.211	3.306	3.847
20	29994.343	99.203	81.743	11.797	3.755	4.470
21	28130.182	103.674	80.184	14.544	3.787	4.531
22	27883.533	111.704	96.191	15.437	4.321	4.258
23	24004.112	146.641	107.233	15.497	4.665	4.776
24	17521.221	123.490	98.574	15.899	4.314	4.987

As can be seen from expression (5), the total power loss in this electrical network is 350,302 kW. Among them, losses from higher harmonics amount to 3739 kW. Consequently, high harmonic losses account for 1.068% of the total power loss.

Conclusion. From this it can be concluded that the losses arising from the flow of higher harmonics of the current in this electrical network do not make a big contribution. However, with an increase in power consumption, it is possible to increase this indicator in a big way. With the growth of nonlinear loads, losses to higher harmonics can be significant, which can lead to consequences caused by poor-quality electricity.

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