Researching and modelling of unbalanced regimes in systems of household electric power consumers

O Miroshnyk[1], S Kovalyshyn[2], P Bałdowska-Witos[3] W Kruszelnicka[3] and A Tomporowski[3]

[1]Kharkiv Petro Vasylenko National Technical University of Agriculture, Alchevskyh St, no. 44, 61002 Kharkiv, Ukraine
[2]Lviv National Agrarian University, Volodomyra Velyhoko St, no. 1, 30831 Dublyany, Ukraine
[3]University of Science and Technology in Bydgoszcz, Al. Prof. S. Kaliskiego, no. 7, 85-793 Bydgoszcz, Poland

E-mail: omiroshnyk@ukr.net

Abstract. The modelling of the operation modes of the 0.38/0.22 kV power supply systems by the Monte Carlo method using the Electronics Workbench computer program is considered, and statistical processing of simulation results and testing of the Pearson distribution law hypothesis using the Mathcad program are carried out. An analysis of existing power supply systems has been carried out and an alternative, economically feasible version of the power supply system is proposed, where consumers are powered by low power transformers mounted on supports. The performed studies showed that the variation of the load currents in the segments and the losses of electric energy in an asymmetrically loaded network of 0.38/0.22 kV are subject to the normal distribution law and that the consumers who feed on the traditional power supply system have unsatisfactory quality of electrical energy.

1. Introduction

The improvement of the electric energy quality is an actual problem in rural electrical networks with a voltage of 0.38/0.22 kV and it is inextricably linked with the reduction of additional electric power losses which are caused by an asymmetric phase load [1–5]. Analysis of operating modes of rural networks with a voltage of 0.38/0.22 kV showed that the unbalance of the currents was due to the communal-household load [6–8]. The main part of this load are unevenly distributed over the phases of single-phase electric receivers, which, as a rule, have a random nature of power consumption [9–11]. Knowledge of the values of current asymmetry in the network makes it possible to clarify the level of energy losses and, if possible, apply measures to reduce them [12], [13]. Modern computer software allows modeling unbalanced network mode and calculating additional power losses, which are the result of asymmetric modes [6], [14].

2. Main body

Some change in the load of single-phase household consumers of electric energy is of a random nature and it is very difficult to accurately determine in advance its value at any time. It is possible only with a certain probability to establish those limits for which it does not come out at a given moment in time [15].

Even if single-phase consumers with the same power and equal total daily power consumption are distributed evenly, then due to the probabilistic nature of power consumption for any time in a three-phase supply network, one should always expect asymmetry of the phase currents, and, as a consequence, of the voltages [16].

In the asymmetric mode, the technical and economic performance of the network deteriorates sharply: energy losses increase, voltage deviations from the nominal and the current flowing in the zero conductor causes the appearance of significant potentials on the electrical equipment enclosures connected to the zero wire, which leads to the danger of electric shock. Also, the service life of the asynchronous electric motors connected to the network is dramatically reduced. In addition, a number of negative electromagnetic phenomena are observed both in the network and in the load. Thus, the losses of active energy resulting from the uneven load of phases in 0.38/0.22 kV lines and consumer transformers of 6-10/0.4 kV increase by more than a third comparing with losses that would occur under uniform load [4], [17].
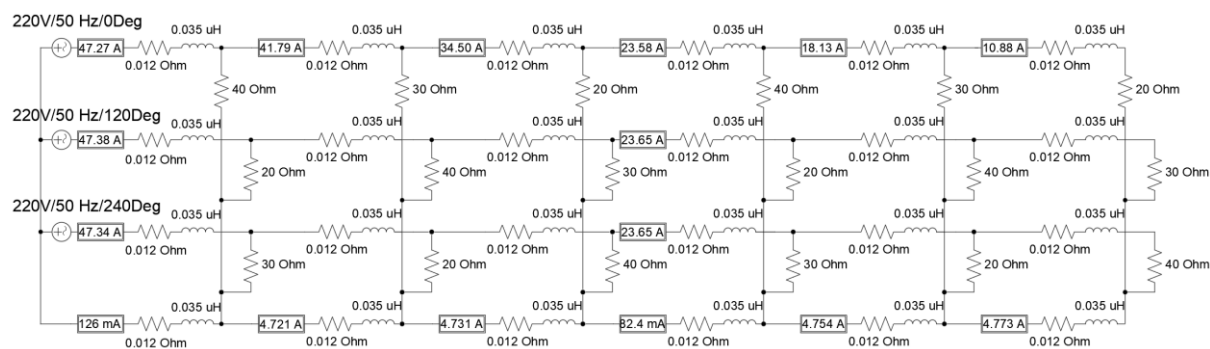

Figure 1. Modeling of network modes 0.38/0.22 kV using the computer program Electronics Workbench

Consider a section of a three-phase four-wire overhead line of 0.38/0.22 kV with a length of 210 m (six supports), one single-phase consumer is connected to each of the three phases at each support. The network is powered by a transformer, the secondary windings of which are connected in the "star with zero" scheme. The circuit of the network is modeled in the Electronics Workbench program [18] (Figure 1), it represents three single-phase voltage sources connected in the "star with zero" scheme, the initial phases of the sinusoid are equal to 0, 120, 240 degrees respectively, the resistance of the aluminum wires of sections of the overhead line between the points of connection of consumers (for air lines it is the distance between supports) are represented by a row of series-connected active resistances (R = 0.012 Ohm, X = 0.011 Ohm for AC-35 wire).
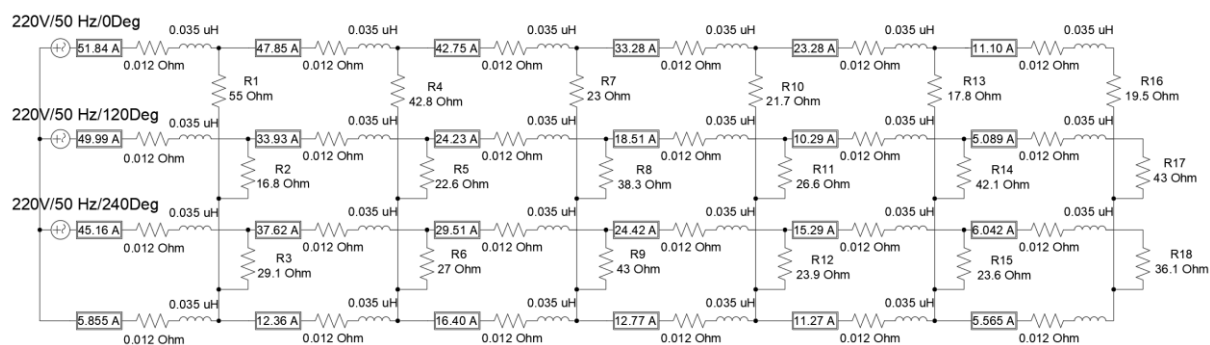

Figure 2. Modeling of network modes 0.38/0.22 kV by the Monte-Carlo method using the computer program Electronics Workbench

The consumers are connected to the phase and zero wires, the load resistance of the consumers have the following values alternating in phases in different sequences on different supports: 20 Ohm, 30 Ohm, 40 Ohm. The consumers are connected to the line in such a way that at buses substation 10/0.4 kV the line 0.38/0.22 kV represents a symmetrical load.

Considering that the change in the load of household consumers is random, subject to the normal distribution law of random variables, we will perform a statistical modeling of the network section scheme using the Monte Carlo method. An example of one test is shown in Figure 2, the current data are given in Table 1.

Table 1. Currents on network sections

Phases	Segments					
	1	2	3	4	5	6
A (A)	51.84	47.85	42.75	33.28	23.28	11.1
B (A)	46.99	33.93	24.23	18.51	10.29	5.09
C (A)	45.16	37.62	29.51	24.42	15.29	6.04
N (A)	5.86	12.36	16.4	12.77	11.27	5.57

Basing on 25 tests, we will perform statistical processing of modeling results and verification of hypothesis of the distribution law according to the Pearson criterion. To do this, we use the Mathcad program (Figure 3).
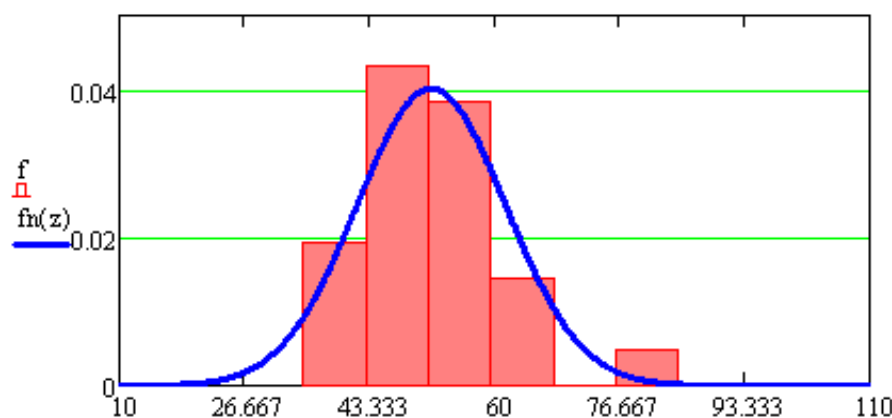

Figure 3. Calculation of the Pearson criterion using the computer program Mathcad

Since the found value of the criterion $\chi_2 = 0.804$ is less than the critical value $\chi_{cr} = 3.8$, the hypothesis H_0 is adopted.

As a result of the statistical processing of the data, we obtain the following values of the mathematical expectation M and the current dispersion s (Table 2) and the electric power losses (Table 3) for the line sections of the 0.38/0.22 kV.

Thus, the performed studies show that the change in the load currents on the network segments and the electric energy losses in an asymmetrically loaded network of 0.38/0.22 kV are subject to the normal distribution law.

Table 2. Mathematical expectation and dispersion of current on network segments A

Phases	Mathematical expectation and dispersion	Segments					
		1 (A)	2 (A)	3 (A)	4 (A)	5 (A)	6 (A)
A	M	51.603	45.163	37.972	26.543	20.389	11.666
	s	9.949	9.021	8.84	6.612	5.706	4.099
B	M	53.184	40.636	34.285	26.216	13.565	7.334
	s	9.894	7.766	7.01	5.638	3.539	2.702
C	M	52.485	44.765	33.887	27.415	18.393	5.558
	s	10.691	9.478	8.911	8.648	6	1.263
N	M	17.323	13.207	12.519	10.546	9.096	6.225
	s	11.934	9.063	9.11	7.389	6.585	3.205

Table 3. Mathematical expectation and dispersion of electric power losses on network segments

Phases	Mathematical expectation and dispersion	Segments					
		1 (W)	2 (W)	3 (W)	4 (W)	5 (W)	6 (W)
A	M	31.954	24.476	17.303	8.454	4.989	1.633
	s	1.1878	0.977	0.94	0.525	0.3907	0.202
B	M	33.943	19.815	14.106	8.247	2.208	0.645
	s	1.175	0.724	0.59	0.382	0.15	0.088
C	M	33.056	24.047	13.78	9.019	4.06	0.371
	s	1.372	1.078	0.953	0.898	0.432	0.019
N	M	3.601	2.093	1.881	1.335	0.993	0.465
	s	1.709	0.986	0.996	0.655	0.52	0.123

With increasing numbers of consumers, the length of the line and the magnitude of the currents flowing along the line increases, which leads to increasing in electric power losses. Therefore, there is a necessary to apply appropriate measures to reduce energy losses. Today, there are many devices for balancing the network, but all of them, because of their high cost and low reliability and inefficiency for long lines feeding the communal-household load, have not been widely used in 0.38/0.22 kV networks. Therefore, with the complete reconstruction of existing transmission lines or during constructing new transmission lines, it is necessary to shift to other power supply systems.

Electricity supply schemes and electrical networks configuration were formed in the middle of the last century, taking into account the minimization of capital assets. This has led to their rapid physical and moral deterioration.

Most of the electrical networks today require a complete replacement, since they have lost reliability, are physically obsoleted and do not meet the requirements of energy saving and safety. Therefore, it becomes necessary to use the system of maximum decentralization during reconstructing the existing networks or building new networks, which will significantly reduce losses and investments.

Using the Electronics Workbench software, we will simulate the operation of the existing traditional power supply system (Figure 4). We load network with users, the load resistance of which have the following values: 20 Ohms, 30 Ohms, 40 Ohms, the initial phases of sinusoid voltage are respectively equal to 0, 120, 240 degrees, the resistance of aluminum wires are presented next series-

connected active and reactive resistances of segments of an overhead line (R = 0.012 Ohms, X = 0,011 Ohms for wire AC-35) between the points of consumers' connection (for overhead lines it is the distance between supports), consumers are connected between one of the phase conductors and the neutral conductor (3 consumer at the point of attachment, with different sizes in each of the phases).
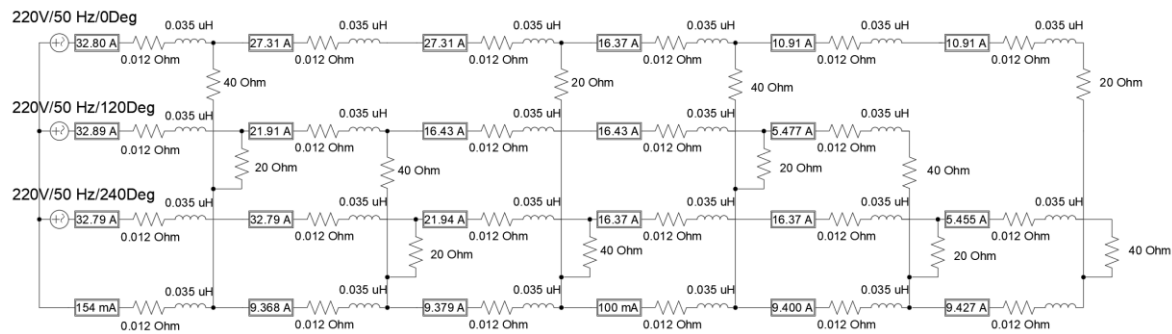

Figure 4. Simulation of network modes

In the above diagram (Figure 4), a full phase segment of a 210 m long line is simulated (six supports, one-phase consumers are connected to each). Table 4 shows the losses in each segment in the phase and zero wires.

Table 4. Distribution of losses in wires in segments

The wire	Segment 0-1 (W)	Segment 1-2 (W)	Segment 2-3 (W)	Segment 3-4 (W)	Segment 4-5 (W)	Segment 5-6 (W)
Phase A	12.91	8.95	8.95	3.22	1.43	1.43
Phase B	12.98	5.76	3.24	3.24	0.36	–
Phase C	12.9	12.9	5.72	3.22	3.22	0.36
Zero wire	–	1.05	1.055	–	1.06	1.066

Total losses in the network will be 105 watts.

Now let us consider a network with the same loads, but with a voltage of 10 kV, in which the 10/0.4 kV transformers are located directly on the supports [19] (Figure 5). There is a scheme in Figure 5 which also shows modeled a full-phase segment of the 210 m length line (six supports, one-phase consumers are connected to each). Table 5 shows the losses in each section of the network.
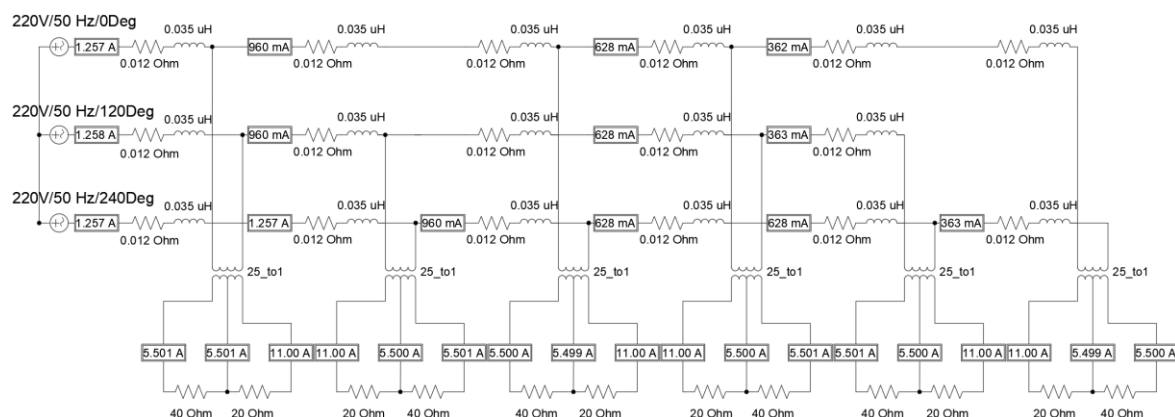

Figure 5. Simulation of network modes

Table 5. Distribution of losses in wires in sections

The wire	Segment 0-1 (W)	Segment 1-2 (W)	Segment 2-3 (W)	Segment 3-4 (W)	Segment 4-5 (W)	Segment 5-6 (W)
Phase A	0.01896	0.01106	0.01106	0.00474	0.00158	0.00158
Phase B	0.01899	0.01106	0.00474	0.00474	0.00158	–
Phase C	0.01896	0.01896	0.01106	0.00474	0.00474	0.00158
Zero wire	–	–	–	–	–	–

Total losses in the network will be 0.15013 watts.

Comparison of losses shows that in the proposed network the losses are 700 times lower (without taking into account losses in the transformers) than in the traditional power supply system. Also in the proposed power supply system, the number of non-ferrous metals decreases by a quarter, since three wires are needed instead of four.

Statistical studies show [20], [21] that it is possible to adopt a network with one 10/0.4 kV transformer and an outgoing cable that has a household loading with length of 700 m as mathematical expectation.

Let's make the comparative analysis of cost of considered networks. The enlarged indicators of the cost of the substations construction and power transmission lines [22] are given in Table. 6. The basic cost of a line constructing consists of the cost of supports, wires, fittings, territory (the land cost allocated for a support or a substation) and work. It is also necessary to take into account the cost of landscaping - 3%, design work - 8%, other work - 3.5%, inflation - 18.09% and hospitality - 5%.

Table 6. Enlarged cost indicators for the construction of substations and transmission lines

Cost of construction of a transformer substation 35/10 kV 2 × 4 MVA, (mln. UAH)	The cost of constructing a 10 / 0.4 kV transformer substation (100 kVA TSZ) 100 kVA, (UAH)	The cost of building a transformer substation 10 / 0.4 kV (16 kVA NEZ) 16 kVA, (UAH)	The cost of construction of 1 km line (AC-70) 10 kV, (UAH)	The cost of construction of 1 km line (SIP 4 2x16) 0.38 kV, (UAH)
3.5	138000	15500	359000	197000

Let us consider the cost of building a power supply system for consumers, which are powered from the 0.38/0.22 kV network (Figure 6).
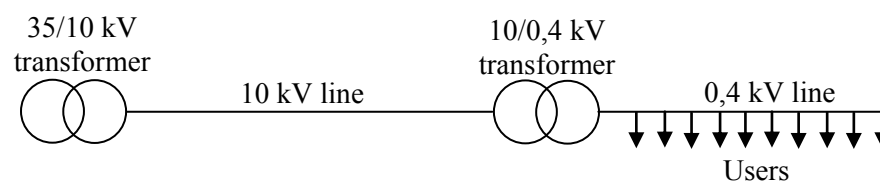
Figure 6. Traditional power supply system

Let us define the cost of building such a power supply system. We take for the calculation the 10 kV line length of which is 10 km and the 0.38 kV line length of which is 700 m (for 40 consumers).

The total cost of such a power supply system is 7565900 UAH. Now we consider the cost of building a power supply system for consumers that feed on the proposed power supply system (Figure 7).
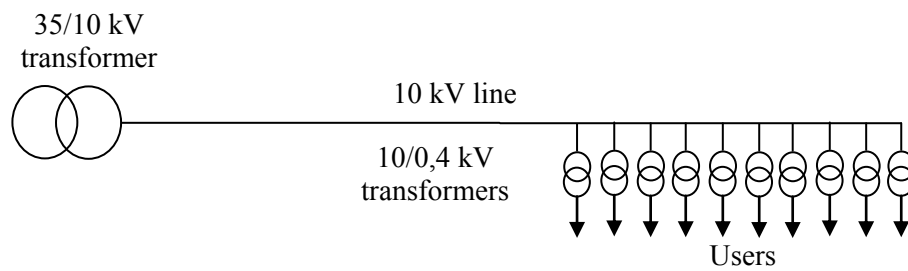
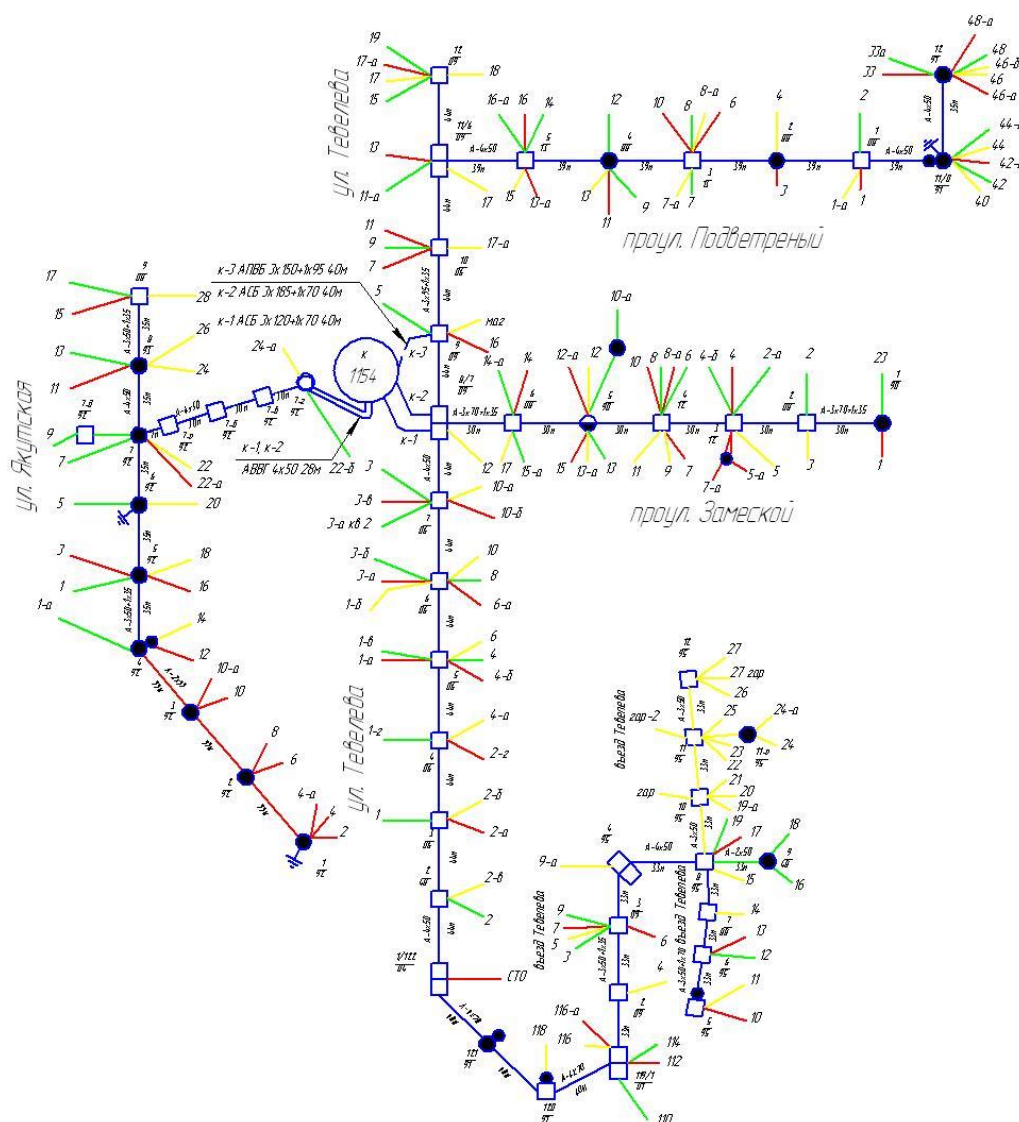**Figure 7.** The proposed electricity supply system

Figure 8. Supported diagram of the 0.38 / 0.22 kV power supply system

Define the cost of building such a power supply system. Take for calculation the 10 kV line length of which is 10.7 km (for 40 consumers). As a result, we get the cost of such a power supply system 7496300 UAH.

As a concrete example, we consider a real power supply system of 0.38/0.22 kV (Figure 8). To determine the level of current asymmetry, we simulate the operation of this power supply system in Multisim.

As a result of simulation, we have got such phase currents in the head of the line $I_A = 83,3$ A, $I_B = 59,5$ A, $I_C = 80,4$, and the current in the zero wire is $I_N = 22,1$ A. The total losses in the network are 783.93 Wh • h.

Now we simulate the operation of an energy-saving power supply system with the same loads. As a result of simulation, we have got such phase currents in the head of the line $I_A = 3,31$ A, $I_B = 3,67$ A, $I_C = 3,23$ A. The total losses in the wires of the power supply system are 2.03 W · h.

A comparative analysis of power supply system's shows that consumers who feed on the proposed power supply system (from small power transformers installed on supports) have power quality parameters that fully satisfy GOST 13109-97.

3. Conclusions

The performed studies showed that the variation of the load currents in the segments and the losses of electric energy in an asymmetrically loaded network of 0.38/0.22 kV are subject to the normal distribution law. With increasing the number of consumers, the length of the line and the magnitude of the currents, flowing along the line, increase which lead to increasing in power losses. Therefore, there is a need to apply appropriate measures to reduce energy losses.

The studies have shown that the consumers who feed on the traditional power supply system have unsatisfactory quality of electrical energy (exceeding the coefficients of non-sinusoidal, zero and reverse sequences several times), high level of voltage losses (unacceptable voltage deviations in remote consumers), which is inadmissible by GOST 13109 -97.

In addition, in the proposed power supply system, the energy losses in the wires are much lower than in the traditional power supply system. Investment in both projects is equally economical. Therefore, with the complete reconstruction of existing or the constructing new transmission lines, it is necessary to shift to the proposed power supply system, which allows to significantly reduce the losses of electricity in the network, while ensuring, at the same time, higher energy quality indicators.

References

[1]   Kumar C and Mishra M K 2013 *Energy conservation and power quality improvement with voltage controlled DSTATCOM*, Annual IEEE India Conference (INDICON), Mumbai, India, December 13-15, pp 1-6

[2]   Mazumder S, Ghosh A, Zare F and Ledwich G 2013 Improving Power Quality in Low Voltage Networks Containing Distributed Energy Resources, *International Journal of Emerging Electric Power Systems* **14**(1) 67-78

[3]   Tran T S, Nguyen D T and Fujita G 2019 The Analysis of Technical Trend in Islanding Operation, Harmonic Distortion, Stabilizing Frequency, and Voltage of Islanded Entities, *Resources* **8**(1) 14

[4]   Miroshnuk O and Tymchuk S 2013 Uniform distribution of loads in the electric system 0.38/0.22 KV using genetic algorithms, *Technical Electrodynamics* **4** 67-73

[5]   Tymchuk S and Miroshnyk O 2015 Calculation of energy losses in relation to its quality in fuzzy form in rural distribution networks, *Eastern-European Journal of Enterprise Technologies* **1**(8) 4-10

[6]   Buła D and Lewandowski M 2018 Steady state simulation of a distributed power supplying system using a simple hybrid time-frequency model, *Applied Mathematics and Computation* **319** 195-202

[7]   Bazmi A A and Zahedi G 2011 Sustainable energy systems: Role of optimization modeling

techniques in power generation and supply—A review, *Renewable and Sustainable Energy Reviews* **15**(8) 3480-500

[8] Habijan D, Čavlović M and Jakšić D 2013 *The issue of asymmetry in low voltage network with distributed generation*, 22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013), Stockholm, Sweden, June 10-13, pp 1-4

[9] Georgiou P N 2016 A bottom-up optimization model for the long-term energy planning of the Greek power supply sector integrating mainland and insular electric systems, *Computers & Operations Research* **66** 292-312

[10] Kong X, Yong C, Wang C, Li P, Yu L and Chen Y 2020 Multi-objective power supply capacity evaluation method for active distribution network in power market environment, *International Journal of Electrical Power & Energy Systems* **115** 105-112

[11] Tellez A A, Galarza D F C and Matos L O 2015 Analysis of power losses in the asymmetric construction of electric distribution systems, *IEEE Latin America Transactions* **13**(7) 2190-2194

[12] Tomporowski A, Flizikowski J, Kasner R and Kruszelnicka W 2017 Environmental Control of Wind Power Technology, *Rocznik Ochrona Środowiska* **19** 694-714

[13] Tarasov E V, Bulyga L L, Ushakov V Ya and Kharlov N N 2015 Additional Energy Losses from Asymmetric and Non-Sinusoidal Current in an Electrical Facility and Methods of their Reduction, *MATEC Web of Conferences* **37** 10-17

[14] Worku G B and Kebede A B 2018 Autotransformer fed traction power supply system: analysis, modeling and simulation, *Global Energy Interconnection* **1**(2) 187-196

[15] Maksimov S, Trofimova S and Maksimova A 2016 *The means of losses reduction and electric lines operation reliability increase*, 2016 2nd International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM), Chelyabinsk, Russia, May 19-20, pp 1-4

[16] Zhukov O 2019 A scheme of three electrical quantities method, *International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies* **10**(9) 1-14

[17] Chembe D K 2009 *Reduction of Power Losses Using Phase Load Balancing Method in Power Networks*, World Congress on Engineering and Computer Science 2009 vol 1, San Francisco, USA, October 20-22, pp 1-6

[18] ***National Instruments 2005 Electronics WorkbenchTM MultisimTM 8 Simulation and Capture User Guide, National Instruments Corporation, Austin, Texas, USA

[19] Zotov A 2007 A mixed three-phase and single-phase electricity distribution system, *Energetik* **5** 18-22

[20] Bakshaeva N S, Suvorova I A and Cherepanov V V 2017 V*oltage quality improving in power distribution networks with abruptly variable load by application of reactive power series compensation devices*, 2017 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM), St. Petersburg, Russia, May 16-19, pp 1-5

[21] Sychenko V G, Bosiy D O and Kosarev E M 2015 Improving the quality of voltage in the system of traction power supply of direct current, *The Archives of Transport* **35**(3) 63-70

[22] ***JSC, Institute "Energosetproekt" 2007 The integrated cost indicators of electric networks (SO 00.03.03-07), JSC, Institute "Energosetproekt", Moscow, Russia