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

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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].

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).
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](image)

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.
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-

| 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    |

| 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    |
connected active and reactive resistances of segments of an overhead line \((R = 0.012\, \text{Ohms}, \ X = 0.011\, \text{Ohms for wire AC-35})\) 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         | 0.00158         | –               | –               |
| 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%.

| 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](image)

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.

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