Method of manual symmetrization of electric networks

R Yu Zakurdaev¹, I E Chernetskaya¹

¹South-West State University, 50 let Oktyabrya str. 94, Kursk, Russia, 305040

e-mail: romanzakurdaev@yandex.ru

Abstract. The article describes a method of reducing asymmetry in the electrical network supplying the utility load. The essence of the method lies in the uniform distribution of loads by switching branches. The results of experimental studies are presented, confirming that the proposed method actually reduces the asymmetry of the network; and also reduces power loss and voltage loss during the transmission of electricity. It gives a comparison with the existing method of uniform distribution. The high efficiency of the proposed method has been experimentally proved.

1. Introduction

The asymmetry of the currents and voltages of electric networks causes additional losses in the transmission of electricity and this is one of the reasons for the decrease in voltage at consumers with distance from the power source. Without the use of baluns, thereby avoiding significant capital expenditures, it is possible to conduct balancing by the uniform distribution of network loads [1].

2. Formulation of the problem

Existing methods suggest measuring the results of switching from the more loaded phase to the less loaded phase [2], [3].

The asymmetry of the currents (voltages) of the electrical network is a value dependent on the distribution of electrical power across the phases of the network connections (1)

$$k_{sym} = f(S_1, S_2, ..., S_n),$$

where $S_1$ is the power of phase A connection No.1, $S_2$ is the power of phase B connection No.1, $S_{n}$ is the power of phase A connection No.$n$.

Such a distribution of power is probabilistic due to the accidental switching on and off of electrical energy load. It is possible to predict that at certain hours of the daily load schedule or certain periods of the annual schedule there will be a general increase or decrease in electricity consumption. However, it is not possible to predict the level of asymmetry depending on the time of day, season, average daily temperature, length of daylight, and other factors.

For example, there will be a general increase in electricity consumption during the evening maximum. However, this increase will turn out to be even across all phases of the power grid and this will not affect the level of asymmetry. Electricity consumption will remain at the same level, but there will be some redistribution of loads, which will significantly change the asymmetry factor.
Thus, it is required to form possible power distributions over the phases of the network connections and correlate them with the probabilities of the occurrence of such variants to create a mathematical model of the balancing process.

The power model of a three-phase electrical network allows you to mathematically describe any electrical network with \( n \) number of connections. A three-phase electrical network with \( n \) connections has total power \( \sum S \). Total power between \( 3n \) loads can be distributed in an infinite number of options, where \( 3 \) is the number of phases in the power system, \( n - 1 \) is the number of connections. The number of options depends on the total power of the electrical network \( \sum S \) and the step \( b \) and is limited by the computing capabilities of the computer.

The data array is formed in the environment of mathematical programming in the form of a matrix \( S \) of dimension \( 3n \times m \) (2) and contains all possible values of the powers \( 3n \) of the load for a given \( \sum S \) and \( b \). Table 1 shows the power distribution of the connections with \( \sum S = 20 \) and \( b = 1 \). The number of variants \( m \) is 75582 with such values of the total power and step.

\[
S = \begin{pmatrix}
S_{11} & S_{12} & \cdots & S_{1n}
\end{pmatrix}
\]

\[
\text{Table 1. Power distribution of the connections.}
\]

| \( S \)   | 1    | 1    | 1    | 1    | 1 | \ldots | 9 |
|----------|------|------|------|------|---|---------|---|
| \( S_2 \) | 1    | 1    | 1    | 1    | 1 | \ldots | 1 |
| \( S_3 \) | 1    | 1    | 1    | 1    | 1 | \ldots | 1 |
| \( S_4 \) | 1    | 1    | 1    | 1    | 1 | \ldots | 1 |
| \( S_5 \) | 1    | 1    | 1    | 1    | 1 | \ldots | 1 |
| \( S_6 \) | 1    | 1    | 1    | 1    | 1 | \ldots | 1 |
| \( S_7 \) | 1    | 1    | 1    | 1    | 1 | \ldots | 1 |
| \( S_8 \) | 1    | 1    | 1    | 1    | 1 | \ldots | 1 |
| \( S_9 \) | 1    | 1    | 1    | 1    | 1 | \ldots | 1 |
| \( S_{10} \) | 1 | 1 | 1 | 1 | 1 | \ldots | 1 |
| \( S_{11} \) | 1 | 2 | 3 | 4 | \ldots | 1 |
| \( S_{12} \) | 9 | 8 | 7 | 6 | \ldots | 1 |
| \( \sum S \) | 20 | 20 | 20 | 20 | \ldots | 20 |

Formation of the data array \( S \) is performed in the environment of mathematical programming «SciLab». The input data is the total power \( S \), step \( b \), and the number of connections \( n \). The sum of the elements in each column is equal to the total power \( \sum S \). The array No. \( 3n \) line is formed by subtracting from the total power \( \sum S \) sums of previous \( (3n-1) \) lines (3).

\[
s_{3n} = \sum S - \sum_{i=1}^{3n-1} S
\]

It needs to enter additional parameters for the formation of the previous \( (3n-1) \) lines:

- Auxiliary parameters \( l_1, l_2, \ldots, l_{3n-1} \). \( l_1 \) takes a value equal to \( \sum S/b - (3n-1) \). \( l_2 \) take a value is \( \sum S/b - (3n-2) - j \), etc. \( l_{3n-1} \) take a value is \( \sum S/b - 1 - \sum_{i=1}^{3n-1} j \). Thus, for each line parameter is calculated variable \( l \).
Auxiliary parameters \( j_1, j_2, \ldots, j_{3n-1} \). \( j_i \) alternately takes values from 1 to \( l_i \). In a nested loop \( j_1 \) alternately take values from 1 to \( l_1 \) etc. In the last nested loop \( j_{3n-1} \) will take values from 1 to \( l_{3n-1} \). Thus, will complete \( \prod_{i=1}^{3n-1} l_i \) iterations.

One line of array \( S \) is filled at each \( \prod_{i=1}^{3n-1} l_i \) iteration. The filling of the data array starts from \((3n-1)\)-th row inside the iteration, the current value \( j_{3n-1} \) is assigned to this element. Then \((3n-2)\)-th line is filled with a value \( j_{3n-2} \) in case the element \((3n-1)\)-th line is 1, etc. The element of the 1st line is filled with value \( j_1 \) in case the element of the 2nd line is 1.

Thus we get the following array fill \( S \) when \( \sum S = 6 \), \( b = 1 \), \( n = 1 \) \( (4) \)

\[
S = \begin{bmatrix}
1 & 0 & 0 & 0 & 2 & 0 & 0 & 3 & 0 & 4 \\
1 & 2 & 3 & 4 & 1 & 2 & 3 & 1 & 2 & 1
\end{bmatrix}
\]

(4)

The zero elements of the matrix are replaced by the elements preceding them. The last line is filled by the expression (3). As a result, we have an array of \( S \) \( (5) \)

\[
S = \begin{bmatrix}
1 & 1 & 1 & 1 & 2 & 2 & 2 & 3 & 3 & 4 \\
1 & 2 & 3 & 4 & 1 & 2 & 3 & 1 & 2 & 1 \\
4 & 3 & 2 & 1 & 3 & 2 & 1 & 2 & 1 & 1
\end{bmatrix}
\]

(5)

The step is taken \( b = 1 \), the number of connections is taken \( n = 4 \) and \( \sum S = 20 \) for further work with the power model of a three-phase electrical network. The number of options is \( m=75582 \) with such input parameters and the formation of the data array takes about 150 seconds with the possibilities of medium-sized computers. The number of options increases sudden when \( (\sum S / b) > 20 \), which causes difficulties in calculations (see Table 2).

A three-phase electrical \( n \) connections network is described by one of the options \( m \), which is one of the columns of the array \( S \) \( (2) \).

**Table 2.** The parameters of the three-phase electric network capacity model when \( n=4, b=1 \), and \( \sum S = 20 \).

| \( b \) | \( \sum S \) | \( i_{\text{max}} = \sum S / a \) | \( m \) | \( t \) computing, sec. | \( t \) computing, min. |
|-------|-------------|----------------|-------|----------------|----------------|
| 12    | 12          | 1              | 1.7   | 0.0           |               |
| 13    | 13          | 12             | 1.7   | 0.0           |               |
| 14    | 14          | 78             | 1.7   | 0.0           |               |
| 15    | 15          | 364            | 1.8   | 0.0           |               |
| 16    | 16          | 1365           | 2.0   | 0.0           |               |
| 17    | 17          | 4368           | 2.5   | 0.0           |               |
| 18    | 18          | 12376          | 5.8   | 0.1           |               |
| 19    | 19          | 31824          | 27.7  | 0.5           |               |
| 20    | 20          | 75582          | 153.5 | 2.6           |               |
| 21    | 21          | 167960         | 740.3 | 12.3          |               |
| 22    | 22          | 352716         | 3246.9| 54.1          |               |

Such an electrical network can be symmetrized by switching the connections with adherence to the phase sequence \( k = 3^{n-1} \) options. For example, the number of options \( k = 3 \) when \( n = 2 \) (see Table 3).
It is required to form an array $A$ of dimension $k \times n$, where the element of the array is one of the sequences of alternating phases (ABC, BCA or CAB) of the electrical network.

It is convenient to use the ternary number system when forming an array of enumerating variants $A$ since the number of lines $k = 3^{n-1}$ is an indicative number with base 3. Replace the ABC, BCA, and CAB entries with a sequence of ternary numbers $[0,1,2_3]$, $[1,2,0_3]$, and $[2,0,1_3]$. We denote a sequence of numbers by the first number $0$, $1$, or $2$, respectively.

### Table 3. Variants of balancing by switching connections.

| $k$ | Connections No.1 | Connections No.2 |
|-----|------------------|------------------|
|     | phase A | phase B | phase C | phase A | phase B | phase C |
| 1   | A       | B       | C       | A       | B       | C       |
| 2   | A       | B       | C       | B       | A       | C       |
| 3   | A       | B       | C       | C       | A       | B       |

The first column of array $A$ contains values $0$, the remaining elements are the numbers of the ternary notation with the number of the place $(n-1)$. When it translated into the decimal number system, the elements of the matrix $A$ represent a sequence of decimal numbers from 0 to $k$, which ensures the formation of the matrix $A$. For $n=4$, the matrix $A$ is represented as (6)

\[
A = \begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 1 & 1 & 0
\end{bmatrix}
\]

(6)

After the formation of the array $A$, the array $AI$ is formed in which the abbreviated sequence of ternary numbers $0$, $1$, and $2$, converted to sequences $[0,1,2_3]$ and $[2,0,1_3]$. It is required to compare the selected column of the array $S$ with the 1st row of the array $AI$ after the formation of the array $AI$.

\[A1_{1,1} = S_{1,1} \]

(7)

where $k$ is selected matrix column $S$.

The second element of the 1st row of the matrix $AI$ is formed by (8). The further row is formed similarly.

\[A1_{1,2} = S_{1,2} \]

(8)

The element No. $3n$ of the 1st line is formed by (9)

\[A1_{1,3} = S_{1,3} \]

(9)

All elements of the matrix $AI$, equal $A1_{1,1}, A1_{1,2},..., A1_{1,3n}$ are compared with the elements of the matrix $S$ by (7)–(9). Thus, an array $B$ of dimension $(k \times 3n)$ (10) is formed.

\[B = \begin{bmatrix}
B_{11} & B_{12} & \ldots & B_{1,3n} \\
B_{21} & B_{22} & \ldots & B_{2,3n} \\
\vdots & \vdots & \ddots & \vdots \\
B_{k,1} & B_{k,2} & \ldots & B_{k,3n}
\end{bmatrix}
\]

(10)

When $n=2$ and $k=3$ array $B$ looks like (11), containing the powers of the phases of the connections (see Table 3):

\[B_{2,2} = S_{1} \]

(11)

The asymmetry factor $\delta S$ is calculated as the average deviation in power (12) for each variant $k$ after the formation of the $BI$ array.

\[\delta S = \frac{1}{k} \sum_{i=1}^{k} (B_{i} - S_{i})^2 \]

(12)
\[
\delta S = \left| S_A - S_{avg} \right| + \left| S_B - S_{avg} \right| + \left| S_C - S_{avg} \right|
\]

(12)

where \( S_{avg} = (S_A + S_B + S_C)/3 \).

We obtain a matrix \( C \) of a dimension \((k \times m)\) where the elements are the asymmetry factors \( \delta S \) (13).

\[
C = \begin{bmatrix}
\delta S_{1,1} & \delta S_{1,2} & \cdots & \delta S_{1,m} \\
\delta S_{2,1} & \delta S_{2,2} & \cdots & \delta S_{2,m} \\
\vdots & \vdots & \ddots & \vdots \\
\delta S_{k,1} & \delta S_{k,2} & \cdots & \delta S_{k,m}
\end{bmatrix}
\]

(13)

Choose the smallest asymmetry factor; we obtain the matrix \( C1 \) dimension \( m \) (14).

\[
C1 = \begin{bmatrix}
\delta S_{\text{min} (k)_1} \\
\delta S_{\text{min} (k)_2} \\
\vdots \\
\delta S_{\text{min} (k)_m}
\end{bmatrix}
\]

(14)

The number of the selected option \( k \) is the desired switching option. When combining the matrices \( B1 \) and \( C1 \), we obtain the matrix \( D \) (15) of dimension \((3n \times m)\) containing the powers of the connections for the switching option with the minimum asymmetry for each variant \( m \).

\[
D = \begin{bmatrix}
D_{(3n_1, m_1)} & D_{(3n_1, m_2)} & \cdots & D_{(3n_1, m)} \\
D_{(3n_2, m_1)} & D_{(3n_2, m_2)} & \cdots & D_{(3n_2, m)} \\
\vdots & \vdots & \ddots & \vdots \\
D_{(3n_q, m_1)} & D_{(3n_q, m_2)} & \cdots & D_{(3n_q, m)}
\end{bmatrix}
\]

(15)

Thus, the matrix \( D \) contains the distribution of capacities among load with minimal network asymmetry.

The power values \( S_1, S_2, \ldots, S_{3n} \) are probabilistic in nature due to accidental switching on and off of electrical appliances in the utility network.

Suppose that the law of probability distribution has the form of a normal (gauss) distribution where the thickest value corresponds to the average power \( S_{avg} = \Sigma S / 3n \), and the abscissa and ordinate axes contain relative values of power \( S \) \( n \) the interval \([0, \Sigma S] \), and relative probabilities of finding the power at a given step \( b \ S(b_i) \) respectively. We assume that the power that is within the step \( b_i \) take the maximum value in it. Suppose also that the power of any phase of any connection has an equal probability of being both within \([0, S_{avg}]\) and within \([S_{avg}, 2 S_{avg}]\) (16).

\[
\sum_{i=b}^{S_{avg}} S(b_i) = \sum_{i=S_{avg}}^{2S_{avg}} S(b_i)
\]

(16)

where \( i \) is step sequence number.

We will assume in the general case the probability of finding the power within \([0, \Sigma S]\) the limits is defined as the product of the previous probabilities with a multiple power step \( S_{avg} \) :

\[
\sum_{i=(j-1)S_{avg}}^{jS_{avg}} S(b_j) = \prod_{i=1}^{j} \left( \sum_{i=(j-1)S_{avg}}^{jS_{avg}} S(b_i) \right)
\]

(17)

where \( j \) is natural number.

The probability \( b_i \) is numerically equal to the area of the normal distribution function in the area \([b - (i - 1), b - i]\) and is calculated using the integral normal distribution function:
\[ F(x; \mu, \sigma) = \int_{-\infty}^{+\infty} \frac{1}{\sigma \sqrt{2\pi}} \exp \left[ -\frac{(z - \mu)^2}{2\sigma^2} \right] dz \]  

(18)

The parameters of the normal (gauss) distribution function are the parameters \( \mu = 0.2 \) and \( \sigma = 0.2 \) when \( s_{\text{avg}} = 1/12 \) relative units with the specified conditions with sufficient accuracy.

The dependence of the probability of reducing asymmetry on the magnitude of such a reduction is presented in Table 4 and in Figure 1.

The graph shows 21 segments, since the number of non-recurring variants of asymmetry decreases when \( s_{\text{avg}} = 1/12 \) relative units with the specified conditions with sufficient accuracy.

Thus, each probability of occurrence of one of the options is associated with an achievable decrease in asymmetry. The dependence obtained shows what the probability is in an arbitrary electrical network with a known number of connections, the total capacity, it will be possible to reduce the asymmetry by a certain amount.

Mathematically determining the probability of reducing asymmetry in a network with arbitrary parameters, the following conclusion was made. The probability that the reduction of asymmetry will be provided in the interval \([0\%, 50\%]\) will be 67.28\%, and in the interval \([50\%, 87.5\%]\) – 25.86\%. Besides, there is a probability equal to 6.87\%, that as a result of balancing, asymmetry, on the contrary, will increase by an amount from 14.29\% to 300\% [4].

| \( i_{\text{max}} \) | \( m_1 \) | \( m_2 \) | \( f = P(\Delta \delta P) \) |
|---|---|---|---|
| \( \Delta \delta \), \% | 0 | 12.50 | 18.75 | 20 | 23.08 | 28.57 | 30 |
| \( r_{\text{c1}} \), \% | 24.18 | 0.16 | 0.00 | 1.60 | 0.08 | 0.20 | 0.71 |
| \( \Delta \delta \), \% | 37.5 | 42.86 | 46.15 | 50 | 56.25 | 60 | 61.54 |
| \( r_{\text{c1}} \), \% | 0.51 | 3.20 | 0.26 | 15.83 | 0.03 | 23.76 | 0.28 |
| \( \Delta \delta \), \% | 68.75 | 69.23 | 71.43 | 75 | 80 | 84.62 | 87.5 |
| \( r_{\text{c1}} \), \% | 0.03 | 0.39 | 13.12 | 9.32 | 7.5 | 5.35 | 0.90 | 0.07 |

Figure 1. The dependence of the probability of reducing asymmetry on the magnitude of the reduction in the proposed method.
Therefore, there is a need to create a method in which the final value of asymmetry will be predictable; and the amount of reduction of asymmetry, and the effect of balancing will be significant consequently. Also, when creating a method, it should be taken into account that manual balancing performed by the operatively-mobile team cannot be carried out more often than 1-2 times a year.

3. Description of the method and mathematical model

Baseline data for the calculations are formed using current and voltage sensors installed in the head section of the electric network to be symmetric [1]. The data are collected for a long period, and taking into account the collected data, the optimal variant of switching the branches is calculated. To perform the calculation, it is necessary to create a mathematical model of the electrical network, including network parameters and describing the balancing process. Directly switching branches, that is, reattachment the branch from phase A, for example, to phase B, is performed by an on-site field crew of electricians.

It is required to measure the currents of outgoing connections, enter data into the automated system using terminals and obtain the proposed switching solution.

The data of the measurements taken will correspond to the data obtained using an automated data collection system. The sum of the current values of all measured connections is equal to the current flowing in the head section of the network as in equation (19).

\[
I = I_{\text{sym}1,\text{ph}A} + I_{\text{sym}1,\text{ph}B} + \ldots + I_{\text{sym}1,\text{ph}C},
\]

where \( n \) is the number of level connections.

Assuming that the equality of equations (20) during the entire observation period is preserved, the results of the measurement can be used to calculate the current of all phases of all connections at any time.

\[
\begin{align*}
\frac{I_{\text{sym}1,\text{ph}A}}{I} & = \text{const}, \\
\frac{I_{\text{sym}1,\text{ph}B}}{I} & = \text{const}, \\
\frac{I_{\text{sym}1,\text{ph}C}}{I} & = \text{const}, \\
& \vdots
\end{align*}
\]

According to the known values of current and voltage for each phase of connection at each time point, network parameters are calculated. For the entire observation period, the total phase resistance for each possible switch is theoretically calculated. From the proposed options, the option with the smallest asymmetry factor value is selected, which is the total power deviation (21).

\[
k_{\text{asym}} = |P_A - P_{\text{avg}}| + |P_B - P_{\text{avg}}| + |P_C - P_{\text{avg}}|
\]

Over the entire observation period for each switching option, we obtain the total deviation in power over the entire observation period for which is minimal. Following the theoretically determined switching option, the operatively-mobile team performs re-interconnections of wires of outgoing connections. After the balancing is completed, the data will continue to flow, and based on the new data obtained, it will be possible to evaluate the beneficial effect of balancing.

4. The work of the method on the example and comparison with the existing option

Suppose we have a network with 4 connections, shown in figure 2. At the initial moment, the network has certain resistance values representing the resistance of the wires of the phases and the neutral wire and the resistance of loads of each phase (see table 5). At the moment \( t=15 \) min. there is a change in the resistance of loads multiply existing - resistance increases by \( 300 \pm 10\% \) (see table 5).
Currents \( I_A = 301 \text{ mA} \), \( I_B = 255 \text{ mA} \), \( I_C = 721 \text{ mA} \), \( I_N = 402 \text{ mA} \) flow in the head section of the network at the moment \( t=0 \). The absolute value of the asymmetry factor in the form of the average deviation in power is \( \sum k = 135.2 \) (see table 6). At the moment \( t=15 \text{ min} \), the load resistances have changed and currents \( I_A = 74 \text{ mA} \), \( I_B = 64 \text{ mA} \), \( I_C = 207 \text{ mA} \), \( I_N = 133 \text{ mA} \) flow before balancing asymmetry factor is \( \sum k = 38.8 \) (see table 6).

Table 5. Values of resistance of phase conductors, neutral wires, and load connections.

| t, min. | No. connections | \( R_{\text{phase wire}} \), Ohm | \( R_{\text{phase wire}} \), Ohm | \( R_{\text{phase wire}} \), Ohm | \( R_{\text{phase wire}} \), Ohm | \( R_{\text{phase wire}} \), Ohm | \( R_{\text{phase wire}} \), Ohm | \( R_{\text{phase wire}} \), Ohm | \( R_{\text{phase wire}} \), Ohm |
|--------|-----------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
|        |                 | \( A \),Ohm                  | \( B \),Ohm                  | \( C \),Ohm                  | \( A, No. n \),Ohm | \( B, No. n \),Ohm | \( C, No. n \),Ohm | \( R_{\text{load}} \),Ohm | \( R_{\text{load}} \),Ohm |
| 1      | 203             | 201                          | 202                          | 30.0                         | 49.5                        | 43.8                        | 46.7                        | 65.6                        | \( \infty \)                  | 1920                         | 2390                         |
| 0      | 203             | 201                          | 202                          | 30.0                         | 49.5                        | 43.8                        | 46.7                        | 65.6                        | \( \infty \)                  | 7640                         | 9500                         |
| 15     | 203             | 201                          | 202                          | 30.0                         | 55.5                        | 42.9                        | 48.5                        | 65.5                        | 6010                         | \( \infty \)                  | 3900                         |
| 4      | 203             | 201                          | 202                          | 30.0                         | 48.1                        | 47.8                        | 48.5                        | 69.4                        | 9840                         | 1588                         | 3470                         |

Table 6. Phase currents, phase voltages, and asymmetry factor before and after symmetrization.

| Symmetrization | The moment of time t, min | \( I_A \),mA | \( I_B \),mA | \( I_C \),mA | \( I_N \),mA | \( U_A \),V | \( U_B \),V | \( U_C \),V | \( k \) |
|----------------|---------------------------|-------------|-------------|-------------|-------------|-----------|-----------|-----------|-----|
| Before symmetrization | 0                         | 301         | 255         | 721         | 402         | 230       | 235       | 202       | 135.2 |
| After symmetrization | 15                        | 74          | 64          | 207         | 133         | 227       | 224       | 221       | 38.8  |
| Before symmetrization | 0                         | 451         | 410         | 455         | 26          | 220       | 224       | 221       | 11.2  |
| After symmetrization | 15                        | 122         | 107         | 117         | 12          | 225       | 227       | 225       | 4.5   |

Suppose that at the moment \( t=0 \) measurements of outgoing connections were taken. For the available version, before the network is balancing, the total asymmetry factor is \( \sum k = 174.0 \). Assuming that relation (21) is also preserved for all other moments of time, we calculate the total asymmetry factor for all variants. The minimum total asymmetry factor is \( \sum k = 43.3 \) for option number 8. We perform balancing, switching branches in accordance with option number 8. As a result of switching, currents \( I_A = 451 \text{ mA} \), \( I_B = 410 \text{ mA} \), \( I_C = 455 \text{ mA} \), \( I_N = 26 \text{ mA} \) began to flow in the head section of the network for \( t=0 \) asymmetry factor is \( \sum k = 11.2 \). For the moment of time \( t=15 \text{ min} \), we have the currents \( I_A = 122 \text{ mA} \), \( I_B = 107 \text{ mA} \), \( I_C = 117 \text{ mA} \), \( I_N = 12 \text{ mA} \), asymmetry factor is \( \sum k = 4.5 \) (see table 6).

Thus, the voltage loss decreased from 21.3% and 5.0% for option No. 1 to 14.8% and 2.7% for option No. 8. The total power loss decreased from 33.8W and 3.0W for option No. 1 to 29.7W and 2.3W for option No. 8. The additional losses of the symmetrized area decreased from 7.7W and 1.0W for option No. 1 and from 0.83W to 0.05W for option No. 8.
Taking into account that the experimental model of the power line is built on a 1:100 scale of power, the total electric power losses for two periods from \( t=0 \) to \( t=15 \text{min.} \) and from \( t=15 \text{min.} \) to \( t=30 \text{min.} \) for option No. 1, it will be 0.92kWh, for option No. 8, it will be 0.80kWh.

Additional losses of electricity from the area to be symmetric will be 0.22kWh for option No. 1 and 0.02kWh for option No. 8 (see table 7).

**Table 7.** The maximum voltage losses on the load, the total losses, including losses in the wires of the symmetrized section, the asymmetry factors of currents, and voltages for the reverse, and zero sequences.

| Symmetrization | The moment of time t, min | k | \( \Delta U_{\text{max}} \), % | Sum \( \Delta P \) | k\(_{12}\), % | k\(_{10}\), % | k\(_{21}\), % | k\(_{01}\), % | Option number |
|---------------|--------------------------|---|------------------|-----------------|-----|-----|-----|-----|--------------|
| Before | 0 | 135.2 | 21.3 | | | 33.8 | 7.7 | | 1.35 | 6.20 | 38.0 | 31.8 | 3 | 1 | |
| symmetry | 15 | 38.8 | 5.0 | 3.0 | 0.83 | | 1.51 | 2.44 | | 40.9 | 7 | 39.2 | 2 | 1 | |
| After | 0 | 11.2 | 14.8 | 29.7 | 1.0 | | 0.13 | 1.99 | | 4.27 | 3.18 | | | 8 | |
| symmetry | 15 | 4.5 | 2.7 | 2.3 | 0.05 | | 0.30 | 0.30 | | 6.18 | 8.84 | | | 8 | |

**Figure 2.** Electric network.
When trying to balance the network in an existing way, i.e. switching phases from more loaded to less loaded will be obtained the following option. Following with [3], the phases with the highest current value are connected to the phase with the lowest effective value of the phase voltage and vice versa. Switching is not performed with the phases occupying an intermediate position.

Let switching in this way will affect half of the connections. Otherwise, if all connections are involved, the least loaded phases will become the most loaded and vice versa, which will not affect or worsen the situation. For example, performing switchings for all connections as a result of calculations using a mathematical model, we obtain an increase in the total power loss from 33.8W to 38.1W, i.e. by 12.7%.

Performing switching with half of the connections, we obtain for the time point t=0 a decrease in total losses from 33.8W to 32.1W, which is 5.0%. The proposed method is 12.1%. The largest voltage deviation is 15.0%, in the proposed method it is 14.8%. For the moment t=15min. we have a decrease in total losses from 3.0W to 2.5W, which is 16.6%. The decrease in the proposed method is 23.3%. The largest voltage deviation is 3.8%, in the proposed method it is 2.7%.

5. Conclusion

The proposed method provides a more efficient balancing, in which power loss and voltage loss is less. The efficiency of balancing the proposed method experimentally confirmed.

The possibility of calculating network parameters and create a mathematical model for determining the option with the least asymmetry confirmed.

6. References

[1] GOST 32144-2013. Electrical energy. Electromagnetic compatibility of technical equipment Standards of quality of electrical energy in general-purpose power supply systems URL: http://docs.cntd.ru/document/1200104301 (18.11.2018)
[2] Zakurdaev R Yu and Chernetskaya I E 2017 Review of existing tools for reducing asymmetry and analysis of its compliance with the current and future level of informatization of utility electrical networks Proceed. of the Southwest St. Univ. 74 16
[3] Orlov A I and Saveliev A A 2018 Load balancing device: RF patent №RU162639U1 URL: https://patents.google.com/patent/EN162639U1/
[4] Digital substation Power engineers from Mari El developed a balancing device that reduces network losses URL: http://digitalsubstation.com/blog/2017/07/17/zapatentovano-innovatsionnoe-ustroystvo-snimayushchee-poteri-v-setyah (18.11.2018)
[5] Piyakov A V, Rodin D V, Rodina M A, Telegin A M and Kondratev S N 2018 Simulation of the control system of the electrodynamic accelerator of dust particles IV Intern. Conf. Information Technology and Nanotechnology 158-164
[6] Pyatkov P Ya 2009 Loss of power and electricity in electrical networks: a series of lectures for students Ekat: UrGUPS 36
[7] Kostinsky S S 2013 Reduction of electric power losses in transformers of distribution networks by internal balancing of their loads (Novocherkassk)
[8] Dulepov D E, Tyundina I E 2015 Calculation of the asymmetry of the SES voltages Bull. NGIEI 47 35-42
[9] Mishanov R O, Tyulevin S V, Piganov M N and Erantseva E S 2017 Forecasting models generation of the electronic means quality 3rd Intern. conf. Information Technology and Nanotechnology 124-129