On the choosing the installation location the balancing devices in low-voltage distribution electric networks

I V Naumov and S V Podyachikh

1 Irkutsk National Research Technical University, 83, Lermontov Str., Irkutsk, 664074, Russian Federation
2 Irkutsk State Agrarian University Named After A.A. Ezhevsky, 1/1, Molodezhny Str., Irkutsk district, Molodezhny settlement, 664038, Russian Federation

E-mail: professornaumov@list.ru

Abstract. The experimental studies result on the power quality and additional power losses analysis caused by the asymmetric modes occurrence in three-phase four-wire 0.38 kV electrical networks are considered. The operating modes 38 kV networks several types simulation – with power take-off nodes distributed along the power line, and an electric network with a concentrated load is carried out. The programs have been developed that allow to assess the change in indicators characterizing asymmetric modes, as well as programs that allow us to visualize this process change. The most installing special symmetrical devices appropriate places in electric networks with a distributed load (rural electric distribution networks) and concentrated power take-off nodes electric networks (urban electric networks) have been identified to minimize losses and improve the power quality. A numerical studied indicators analysis was performed.

1. Introduction
The operating electric networks modes modeling is the basis for finding the most rational solutions for optimizing these modes in order to obtain the most effective results when using electric energy for the commercial production needs and the population life support. One of the well-known and objective existing low-voltage electrical networks operation modes is the asymmetric (unbalance) mode. Objectively, it is formed due to asymmetric power consumption by the load by to the statistical and probabilistic phase currents unbalance [1 - 6], as well as incomplete-phase and emergency modes [7 - 8]. Numerous publications devoted to the 0.38 kV electric networks operating modes evaluation in unbalancing power consumption conditions [9 - 15] have convincingly proved that reducing the phase currents asymmetric negative effect most effective means is a balancing device (BD) with the minimum possible resistance to zero-sequence currents. The such a device use allows you to improve the power quality and reduce its losses due to the currents unbalance. Repeated models use to evaluate asymmetric operating modes [9 - 12] has convincingly shown that the most appropriate place to BD turn in an electrical network with a distributed asymmetric load in power consumption nodes is the load node closest to the power source busbases. At the same time, it should be noted that the 0.38 kV electric networks configuration, depending on the economic affiliation and these networks purpose, can be very different. Some authors [13 - 14] recommend BD installing on the transformer buses. Therefore, the article purpose is to establish exactly at what distance from the power transformer (TS) busbars, the BD
installation will be most effective in both improving the quality and reducing electrical energy losses terms due to phase current asymmetry. Achieving this purpose is possible when solving the following tasks: 1) simulating the 0.38 kV network work with distributed along a transmission line (TL) three-phase unbalanced load; 2) conducting experiments with the model 0.38 kV network and the BD inclusion in the node with concentrated load at different distances from the transformer busbars; 3) to analyze the calculated indicators, and to develop recommendations for the most effective BD installation at networks.

2. Electrical network modeling and the research tool
The simulation will be carried out according to the following algorithm. At the first stage, will consider the 0.38 kV network model with three-phase asymmetric load concentrated in 4 nodes evenly distributed along an TL with the 1 km length. The configuration and power consumption parameters are detail considered and described in [14 - 15].

For our example, will take next TL cross-section and TS parameters. For the model under study, the most common in rural distribution networks 160 kVA power transformer was adopted [16] with the parameters: 

\[ Z_1 = 0.016 + j0.0417 = 0.045 \times e^{j69.04} \text{ Ohms}; Z_2 = 0.096 + 0.02349 = 0.098 \times e^{j13.76} \text{ Ohms}. \]

As an TL, the 3x25+1x35 cross-section SIP 2A was adopted with the parameters:

\[ Z_1 = 1.2 + j0.0826 \text{ Ohms/km}; Z_2 = 0.986 + j0.0703 \text{ Ohms/km}. \]

The three-phase unbalancing and symmetrical loads in the nodes varies each according to [15]. At the same time, in the fourth node, this unbalance load (pn) corresponds to the values given in the table [15], in the third it is 2 pn, in the second-3 pn, in the first-4 pn. That is, as we approach the power supply buses, the asymmetric load, evenly distributed in equal parts in the nodes, increases. The balancing device parameters are changed corresponds for the changing three-phase symmetric and asymmetric load value (that is, they are calculated for each changing power consumption conditions point, which corresponds to automatic power control BD depending on the changing power consumption unbalancing level). The previously described modes [14 - 15] considered the change in the corresponding indicators for change10 points in the asymmetry level in each node. In order to bring the simulation conditions closer to the power consumption real conditions in the current network, the changes in the three-phase loads power were interpolated, which allows to obtain its intermediate values within a given series. To do this, the made program "Interpolation" in the Matlab environment was used. As a result, the 10 values instead parameters, we get 40. According to these values, the BD parameters and the corresponding current and voltage asymmetry indicators will also change. To calculate the unbalancing modes and BD parameters, the methods described in [15, 17, 18] were used. The first stage experiment is necessary to confirm the thesis that the most rational place to BD install in a network with a distributed load is the load node closest to the TS buses. It should be noted that this electric network model is most rural electric networks typical with power supply consumers in numerous branchers transmission lines.

At the second stage, presents a similar model network with a concentrated load, assuming that the distributed load described in the first model is completely located in a limited area, which is 0.38 kV urban electric networks characteristic (for example, electricity supply one or two multi-storey residential buildings). At the same time, will consider several options: the first – BD is turned on directly on the TS tires, the second and third – BD is turned on at the 50- and 100-meter distance from the TS tires. This will correspond to the existing networks real mode, when the TS that feeds the residential complex is installed at this distance from it (which corresponds to the real electricity consumption mode in urban networks). The TS and TL parameters remain the same as at the research first stage. The TL resistances value will vary depending on the distance: on TS tires (the first option) \( Z_1 = Z_2 = Z_0 = 0; \) for 50 m (second option): \( Z_1 = 0.06 + j0.000413 \text{ Ohms/km}; Z_0 = 0.0493 + j0.003515 \text{ Ohms/km}; \) for 100 m (third option): 

\[ Z_1 = 0.12 + j0.00826 \text{ Ohms/km}; Z_0 = 0.0986 + j0.00703 \text{ Ohms/km}. \]

As a calculation tool, the computer program "Unbalance_1” is used, created on the method basis described in [19]. The program is written in the high-level interpreted programming language "Matrix Laboratory" ("Matlab"), which contains a "pre-parsed" programs number that allow, using a graphical editor, to visualize functional changes in the studied indicators in various modeling modes.
3. Research results

The modeling corresponds first stage to the network under study model, shown in figure 1.

![Network model](image)

**Figure 1.** Single-line electric network model replacement scheme with a distributed load and BD.

The studied indicators are: the negative and zero sequence voltage unbalance coefficients $K_{2U}$, $K_{0U}$ – in the asymmetric load nodes; $K_{2UX}$, $K_{0UX}$ – on the TS buses; $K_P$ – coefficient characterizing the power losses excess in the asymmetric mode the corresponding losses conditioned by the positive sequence current [20].

In accordance with the set forth in paragraph 2, will calculate the under-study parameters and analyze them when the BD absence and when it is in the first load node. figures 2 and 3 show $K_{2U}$, $K_{0U}$ и $K_{2UX}$, $K_{0UX}$ changes diagrams respectively. Figure 4 shows the change dependences in the loss coefficient ($K_P$) under the same conditions. These dependencies analysis showed the following.

![Graphs](image)

**Figure 2.** Changes diagrams in the voltages unbalance negative and zero sequences coefficients in the distributed load nodes when the BD is switched in the first node.

In the BD absence in the network, the $K_{2U}$, $K_{0U}$ coefficients have the following average (out of 40) values: on the TS buses – 0.008875 and 0.075616, respectively; in the first node: 0.063589 and 0.13925; in the second – 0.137169 and 0.101452; in the third – 0.10442 and 0.268039 and in the fourth – 0.115061 and 0.209755 (calculation data are given in relative units. The Standard [21] sets values for these indicators, respectively, no more than 2% in 95 percent of the ten-minute measurement interval in one week). At the same time, the average $K_P$ value in the nodes is: in the first – 1.332997, in the second – 1.26557616, in the third – 1.17745 and in the fourth – 1.200541. It should be noted that in the ideal case (symmetric mode), the value the $K_P = 1$, since there are no the negative and zero sequence currents.
Figure 3. Changes in the power quality indicators characterizing the voltage unbalance on the power source busbars.

Figure 4. Change diagrams in the power loss coefficient in the load nodes when BD absence and its inclusion in the first load node.

When BD is enabled in the first load node, the situation with the studied coefficients is as follows. On the transformer buses, the $K_{2U}$ coefficient practically did not change (increased by 1.1 times), the $K_{0U}$ coefficient decreased by 4.2 times (figure 3). In the first node $K_{2U}$ value increased by 17%, and $K_{0U}$ decreases by 4.1 times; in the second node: $K_{2U}$ decreases by 1.8 times, the $K_{0U}$ coefficient increased by 1.33 times; in the third node: $K_{2U}$ decreases by 1.85 times, $K_{0U}$ – by 2.6 times (figure 2). The $K_P$ loss coefficient in the first load node decreased by 1.3 times, in the second – practically unchanged (a slight increase of 1.5%), in the third node the increase was 9.3% and in the fourth its value increased by 11.67% (figure 4). There was no experiment on the inclusion of BD in other load nodes, since this issue was considered in [12, 15, 17] and it was found that the BD inclusion in the first node is the most optimal from the improving quality view point and reducing losses due to phase current unbalance.

At the second modeling stage, the electric network replacement scheme looks like this (figure 5).

Will perform an experiment under the same designated conditions for three variants, namely: in the BD absence in the network under consideration, when it is turned on the power transformer tires, in a load node located at a distance of 50 m from the TS tires and it is turned on in a node at a distance of
100 m. The experiment hypothesis is that since the BD resistance has a minimum value to zero-sequence currents, when it is turned on the TS buses, an artificial decrease in the resistance to these currents will occur on the transformer buses as well. Consequently, this should lead to an increase in zero-sequence currents and, accordingly, an increase the additional power loss. At the same time, the indicators characterizing the power quality may improve.

Figure 5. 0.38 kV electric network model with a concentrated load.

The figures 6 - 8 analysis showed the following. In the BD absence in the studied electrical network, the loss coefficient ($K_P$) value is: on TS tires – 1.497572 (option 1), in the load node at the 50 m distance (option 2) – 1.453252, if the load node is located at the 100 m distance (option 3) – 1.416104; the $K_{2U}$ coefficient changes as follows: in option 1 – 0.018363, in the second – 0.029711, in the third – 0.040397; for the $K_{0U}$ coefficient, the changes are as follows: in option 1 – 0.119259, in the second – 0.1211954, in the third – 0.124567. When BD is turned on TS tires, $K_P$ is reduced by 34.7 %, and the $K_{2U}$ coefficient increases by 6.9 %. Such an increase in the negative sequence voltage asymmetry coefficient (as well as in the simulation at the first stage) is due to the three-phase symmetrical load action (usually a three-phase asynchronous motor having a negative sequence resistance 5-6 times less than the positive sequence resistance). Accordingly, the BD will always have the opposite effect on the network negative sequence voltage, slightly increasing the $K_{2U}$ index, since the symmetrical action of BD is based on its minimum resistance to zero-sequence currents. The $K_{0U}$ coefficient in this experiment decreases by 4.89 times. If BD is turned on at a node located at a 50 m distance from the TS tires (2 experience), the $K_P$ coefficient decreases by 36.4 %, the $K_{2U}$ coefficient increases by 9.4 %, and the $K_{0U}$ coefficient decreases by 4.7 times. And finally, in the third experiment (at a distance of 100 m), when BD is turned on at this node, the $K_P$ coefficient decreases by 37.7 %, for $K_{2U}$ the increase is 11.7 %, and the $K_{0U}$ coefficient decreases by 4.52 times.

Figures 6, 7 and 8 show changes diagrams in the studied indicators depending on the three-phase asymmetric load power.

Figure 6. The power loss coefficient change load diagrams with BD connection various combinations.
Figure 7. The change diagrams of the negative (a) and zero (b) sequences voltages coefficient with BD connection various combinations.

Figure 8. The change diagrams of the negative (a) and zero (b) sequences voltages coefficient on the TS-busbars with BD connection various combinations.

Thus, it is established that the BD inclusion on the power supply buses can serve as a basis for improving the power quality from the zero-sequence voltage asymmetry coefficient viewpoint reducing, but at the same time additional power losses increase due to an artificial decrease in the zero-sequence resistance at the BD connection point. If the BD is connected in a load node located at a certain distance from the power supply buses, in this case there is both an improvement in the power quality and a significant additional losses minimization.

Based on the above, can draw the following conclusions.

4. Conclusions

The electric low-voltage networks operation asymmetric mode is an objective factor, due to the asymmetric power consumption.

The most characteristic evaluating criteria the 0.38 kV networks operation are the zero sequence voltage unbalance coefficient, as well as the power loss coefficient due to the asymmetric currents flow. The negative sequence voltage asymmetry coefficient can be an essential evaluating asymmetric modes criterion in cases where a significant proportion three-phase symmetrical load (three-phase electric motors) is involved in power consumption.

The most installing balancing devices rational place in electrical networks with a distributed load is the load node closest to the power supply buses.

In electric networks with a concentrated load (mainly urban electric networks), the power supply buses can be considered as the connection BD point, but only if the distance from the TS buses to the power consumption node is minimal. Otherwise, the installation of BD is more appropriate on the tires of the input and residential complex distribution devices.

Reference

[1] Kozlovskaya V B and Kalechys V N 2019 Asymmetrical modes of outdoor lighting lines. Energetika Proc. of CIS Higher Education Institutions and Power Engineering Associations 62(3) 232-46
[2] Du F, Cheng X, Zhou Q and Xu F 2020 Influence of three-phase imbalance and harmonic on line loss of three-phase four-wire low-voltage distribution network Dianli Xitong Baohu yu Kongzhi/Power System Protection and Control 48(21) 22-30

[3] Bao G and Ke S 2019 Load transfer device for solving a three-phase unbalance problem under a low-voltage distribution network Energies Multidisciplinary Digital Publishing Institute (MDPI) 12 2842

[4] Girshin A, Goryunov V, Kuznetsov E and Safonov D 2016 Analysis of Asymmetrical Modes in Medium Voltage Electrical Grids with Compensated Neutral MATEC Web of Conf. 70 10008 1-5

[5] Kulagin S A 1980 Resistance of the reverse sequence of the agricultural load node Sb. nauch. trudov LSHI 18-24

[6] Dulepov D E and Kondranenkov T E 2017 Reduction of losses and improvement of the quality of electric energy under asymmetric modes in rural distribution electric networks Materials of the VIII Int. Scientific and Technical Conf. "Electric power engineering through the eyes of youth" (Samara: Samara State Technical University) 328-31

[7] Sbitnev E A and Zhuzhgin V S 2020 Accident rate analysis of rural electric networks 0.38 kV of Nizhny Novgorod power system Bulletin NGIEI 11(114) 36-47

[8] Sidorov S V, Sukhachev I S, Sushkov V V and Antropova V R 2020 Operation Efficiency Evaluation of the Electrotechnical Complex of Branch Power Lines 14th Int. IEEE Scientific and Technical Conf. Dynamics of Systems Mechanisms and Machines Dynamics 9306118

[9] Naumov I V, Savina N V and Shevchenko M V 2018 Modeling of three-phase electric motor operation by the MATLAB system with deteriorated power quality in the 0.38 kV distribution networks E3S Web of Conf. 58 03016 Rudenko Int. Conf.: “Methodological problems in reliability study of large energy systems” Section: «Energy Security, Reliability and Quality of Energy Consumption, Modeling and Information Technology» 1-4

[10] Naumov I V and Podyachikh S V 2021 Green technologies in rural electric powerindustry IOP Conf. Ser.: Earth Environ. Sci. 808 012006

[11] Polkovkaya M and Yakupova M 2020 Mathematical Modeling of the Causes of Failure of Elements of the Urban Electrical Network (10 kV) Int. Multi-Conf. on Industrial Engineering and Modern Technologies, FarEastCon 9271114

[12] Naumov I V, Podyachikh S V and Ivanov D A 2021 Efficiency of the balancing devices to power quality improve SAHD 2021 SHS Web of Conf. 101 02012

[13] Lukovenko A S, Kukartsev V V, Tynchenko V S, Mikhailev A S, Kukartsev V A and Bashmur K A 2019 Calculation of balancing and filter compensating devices of the power supply system Journal of Physics: Conf. Series. Int. Scientific Conf. "Conf. on Applied Physics, Information Technologies and Engineering - APITECH-2019" (Krasnoyarsk Science and Technology City Hall of the Russian Union of Scientific and Engineering Associations; Polytechnical Institute of Siberian Federal University) 55086

[14] Oskin S V, Makarenko A S and Miroshnikov A V 2020 Increased Probability of Proper Operation of Filter Protection Devices against Phase Failure at Voltage Asymmetry in Rural Electrical Networks Proc. - 2020 Int. Ural Conf. on Electrical Power Engineering 9216236

[15] Naumov I V 1989 Methods and technical means of reducing the asymmetry of currents and losses of electric energy in rural distribution networks of 0.38 kV Dissertation for the degree of Candidate of Technical Sciences (Leningrad)

[16] Naumov I V, Karamov D N, Tretyakov A N, Yakupova M A and Fedorinova E S 2020 Investigation of the loading of power transformers in rural power supply systems Reliability and safety of energy 2020 13(4) 282-9

[17] Naumov I V 2002 Reducing losses and improving the quality of electric energy in rural distribution networks of 0.38 kV with the help of symmetric devices Dissertation for the degree of Doctor of Technical Sciences (St. Petersburg-Pushkin)

[18] Naumov I V and Belousova E A 2017 Choice of the device parameters of balancing in distribution
networks 0.38 kV *Vestnik Krasgau* 1 99-107

[19] Naumov I V 1989 Method and program for calculating power losses and current and voltage asymmetry indicators in a 0.38 kV distribution network with a balancing device *Mechanization and socialist agriculture electrification* 3

[20] Kosoukhov F D 1984 *Calculation and analysis current and voltage asymmetry indicators methods in rural distribution networks* (Leningrad: LSKhI)

[21] GOST 32144-2013 Electrical energy Compatibility of technical means is electromagnetic Standards for the quality of electrical energy in general-purpose power supply systems