Analysis of unbalanced load low-voltage electrical networks operating modes

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Abstract. The article discusses distribution electrical networks 0.38 kV operating modes, feeding individual residential buildings. The electrical energy parameters measurement were certified RESURS-UF2M device carried out. The currents and voltages time diagrams based on the measurements made and using Matlab technologies were constructed. It is established that the level of phase currents unbalance is quite high and causes significant three-phase power supply system unbalance voltage accordingly. The power of quality indicators calculations, characterizing voltage unbalance were made, which were based on the measurements and the computer program "Asymmetry" was used. As well as the additional power losses coefficient determining by the phase currents unbalance, were calculations. Time diagrams these indicators are constructed and their analysis were made. As a result, the power of quality is significantly reduced by unbalance power consumption in the studied electrical network were founded. At the same time, the additional power losses are significant increases. Specific recommendations for the normalization electrical network-operating mode are given.

1 Introduction

Recently, quite a lot of the electrical networks analysis operation publications, including low voltage, are based on the operating modes their modeling [1-3]. At the same time, carrying out in operating electrical networks measurements using software products for the mode parameters calculating always remains an urgent task and is the most reliable way to assess the electrical networks operating modes of all voltage levels. The unbalance modes occurrence the low-voltage electrical network operation is due to a number reason, the main of which are the phases, uneven load and the random nature single-phase electric receivers switching in the three-phase electrical network. The most reliable data can be obtained when certified measuring instruments using in accordance with the State Standard established [4]. The unbalance modes evaluation is carried out according to the power quality indicators K2U and K0U established. These indicators values are set in the corresponding measurement time intervals and ranges from 2 to 4% [5]. In addition changes these indicators, there is an active

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power losses increase and electrical energy due to the negative and zero sequences phases currents. As shown in the some works [6, 7], it is the zero-sequence currents increase in four-wire three-phase networks, besides to additional electrical energy consumption and a significant impact on the service life equipment, leads to fire-hazardous situations. The evaluating additional power losses criterion is the coefficient such losses increase, which is the active power losses ratio due to the phase currents unbalance to the corresponding losses due to the direct sequence currents only flow. In accordance with the above, it is obvious that an asymmetric operating modes analysis on modern methods measurement based and calculation in real electrical networks, as well as minimizing these modes recommendations, is an urgent modern electric power industry task.

2 Research methodology

The most reliable calculating method of current and voltage asymmetry parameters is the professor F. D. Kosoukhov modular method [8]. This method essence is as follows.

It is necessary five currents measure to calculations perform: I_A , I_B , I_C , I_{BC} , I_N . Measurements are carried out using ammeters connected via current measuring transformers. The I_{BC} current measured by two ammeters in the B and C phases connected via current transducers. As a transformations result, symmetric currents components expressions are obtains:

$$\left. \begin{aligned} I_1 &= \frac{1}{6 \cdot I_A} \cdot \left\{ \left[3 \cdot I_A^2 - I_A \cdot (d + \sqrt{3} \cdot e) + 2 \cdot \sqrt{3} \cdot g \right] + \right. \\ &\quad \left. j \cdot \left[\sqrt{3} \cdot I_A^2 - I_A \cdot (\sqrt{3} \cdot d - e) - 2\sqrt{3} \cdot h \right] \right\}; \\ I_2 &= \frac{1}{6 \cdot I_A} \cdot \left\{ \left[3 \cdot I_A^2 - I_A \cdot (\sqrt{3} \cdot e - d) - 2 \cdot \sqrt{3} \cdot g \right] - \right. \\ &\quad \left. j \cdot \left[\sqrt{3} \cdot I_A^2 - I_A \cdot (\sqrt{3} \cdot d + e) - 2\sqrt{3} \cdot h \right] \right\}; \\ I_0 &= \frac{1}{3} \cdot (d - j \cdot e), \end{aligned} \right\} \quad (1)$$

$$\begin{aligned} \text{where } g &= b_1 \cdot c_1 + b_2 \cdot c_1, \quad h = b_1 \cdot b_2 - c_1 \cdot c_2, c_1 = \sqrt{I_A^2 - b_1^2}, \\ c_2 &= \sqrt{I_B^2 - b_2^2}, \quad e = \sqrt{I_N^2 - d^2}. \end{aligned}$$

Based on the expression (1) the negative and zero current sequences coefficients are determined:

$$\underline{K}_{2i} = \frac{I_2}{I_1}; \quad \underline{K}_{0i} = \frac{I_0}{I_1}. \quad (2)$$

Based on the expressions 2, the power loss coefficient is determined:

$$Kp = 1 + K_{2i}^2 + 4K_{0i}^2. \quad (3)$$

Next, the forward, negative and zero voltage sequence symmetric components are determined:

$$\left. \begin{aligned}
 \underline{U}_1 &= \frac{1}{6} \cdot \left\{ 2 \cdot U_A + \sqrt{3} \cdot (s+r) - (p+g) \right\} + j \cdot \left\{ (s-r) + \sqrt{3} \cdot (p-g) \right\}; \\
 \underline{U}_2 &= \frac{1}{6} \cdot \left\{ 2 \cdot U_A - \sqrt{3} \cdot (s+r) - (p+g) \right\} + j \cdot \left\{ (s-r) - \sqrt{3} \cdot (p-g) \right\}; \\
 \underline{U}_0 &= \frac{1}{3} \cdot [U_A + (p+g) - j \cdot (s-r)],
 \end{aligned} \right\} \tag{4}$$

where
 $s = \sqrt{U_B^2 - p^2}$;
 $r = \sqrt{U_C^2 - g^2}$.

Using the (4) expressions, power quality indicators characterize three-phase voltage unbalance system are obtain

$$\underline{K}_{2U} = \frac{\underline{U}_2}{\underline{U}_1}, \quad \underline{K}_{0U} = \frac{\underline{U}_0}{\underline{U}_1}.$$

(5)

The computer program "Asymmetry" algorithm basis is this mathematical apparatus [9]. The program Java language is written, using the Archlinuxx86_64 operating system and Netbeans mathematical coding. Additional J Free Chart libraries are used 1.0.16 – JAVA library; Apache POI the Java API for Microsoft Dokuments 3.8. The calculating the current and voltage unbalance indicators initial data are currents and voltages measured values corresponding to the modular calculation method (Fig. 1).

Fig. 1. Main program window: source data input.

Next, the current and voltage unbalance and power quality indicators and the power loss coefficient calculates corresponding to them (Fig. 2).

Fig. 2. The calculating current and voltage unbalance indicators program window.

The program allows visualize calculation results using time diagrams corresponding indicators changes (Fig. 3):

Fig. 3. Calculations visualization: studied indicators time diagrams.

3 Research results

In the 21(from 13:00) to 28 March (until 13:00) period, 2021, parameters of electric energy measurements were made at the power transmission line departing from the 0.4 kV transformer substation buses. A «Resource UF2M» device certified in the Russian Federation (factory number-No. 2479) carried out the measurements. The connection this device shown in Figure 4. The brand of the power transformer TMG1000-10/0.4. The outgoing power line length, made SIP 4 (4x95) wire, is 800 m. For the analyzed data sample the average daily indicators values for each of the 10-minute measurement intervals are taken. Figure 4 shows the phase currents I_A , I_B , I_C time diagrams, as well as inter-phase current I_{BC} time diagrams and current I_N in the zero wire. The two last currents values were calculation obtained.

Fig. 4. Connecting the "Resurs UF2M" device to the under study electrical network.

Fig. 5. Time diagram of the power line currents changes.

The Figure 5 analysis showed the following. The currents average values in A and B phases for the under review period are almost the same (175.3 and 173.1 A, respectively). The difference does not exceed 2%, which can be acceptable considered. However, in C phase the average current value exceeds the other phases currents significantly. It is equal 230 A, almost 33% more than in the two other phases. Based on the currents measurement and the program [9] the KP coefficient was calculated, the time diagram of which in Figure 6 is shown.

As can be seen from Figure 6, the loss coefficient changes from a minimum value of 1.11 (at 11: 30 p.m.) to 1.8 (at 07:10 p.m.). The average daily coefficient value for the measurement period was almost 1.5. Thus, the additional power losses due to the currents unbalance (due to the negative and zero sequence currents) are on average 50% higher than the losses due to the flow the direct sequence currents only (conditionally symmetric mode). Let us consider how the power quality indicators the three-phase voltage system unbalance characterize are change. It is known that an unbalanced current (Figure 2), flowing on the electrical network elements, causes an unbalanced voltage drop on each of these elements. As a result, the entire three-phase voltage system becomes unbalancing (due to the negative

and zero sequence voltages appearance). In this case, the phase-based and interphases voltages values are change (Fig. 7, 8).

Fig. 6. Time diagram of the power loss factor change.

Fig. 7. Time diagram of the phase voltages changes.

As can be seen from the figures presented, the phase-based voltages (U_a , U_b , U_c) vary from the 236 V minimum value to the 241 V maximum value and the inter-phase voltages (U_{ab} , U_{bc} , U_{ca}) vary from 407.5 to 417.5 V. Phase-based and inter-phase voltages values discrepancy corresponds to the stress negative and zero sequences unbalance coefficients change, as shown in Figure 9. These diagrams analysis showed the following. According to [5], the $K2u$ and $K0u$ coefficients values should not go beyond 2% in the 95% measurement range time in one week, and should not go beyond 4% in 5% of this range their value. In fact, these coefficients values goes beyond 2% during the entire measurement interval and beyond 4% for $K2u$ (40.3% of entire measurements interval) and for $K0u$ - 64% entire measurements interval. The maximum coefficients values were 5.55% for $K2u$ (exceeding the limit values by 39%) and 8.45% for $K0u$ (exceeding the limit values by 2.11 time).

Thus, the measurements results and calculations presented convincingly prove that municipal consumers, receiving electric energy through a three-phase four-wire electric network, have a significant phases currents and voltages unbalance level, which worsens the quality and increases additional electric energy losses.

Fig. 8. Time diagram of the phase voltages changes.

Numerous studies showed that the most effective mode balancing means is use the special shunt-balancing devices (SBD) with the lowest possible zero-sequence currents resistance, which has power automatic control due in a zero-sequence current change [10]. Let us consider this device operation.

Fig. 9. Change the negative and zero sequences stress asymmetry coefficients, r. u.

The three-phase networks balancing device with a zero wire is three three-phase electromagnetic devices consists. The device windings are connected according to the oncoming zigzag scheme and have three phase and one neutral terminals. Moreover, each phase pin is to the phase network wires connected designed, and the neutral pin is to the zero wire connected designed. Each three-phase electromagnetic device forms one balancing device power stage. At the first power stage, the first three-phase electromagnetic device is connected.

As the currents and voltages unbalancing increases, the device power is increases. An additional one or two three-phase electromagnetic devices connecting to the electrical network achieve this. When the zero wire current reaches minimum value, the device from the mains is disconnected. At the same time, the values of quality indicators will correspond to the State Standard 32144-2013 [5]. Thus, the device power as a zero wire current function is self-regulated. In this case, the proposed device parameters are adjusted on the 0.38 kV network currents unbalance level, which takes place at a given time. It is proposed to use the following BD automation schemes for automatic control. Fig. 10 a, b shows the BD automatic control scheme which is for the device shown in Fig. 11, a. The circuit includes a current transformer TA, six current relays KA1-KA 6, three time relays KT1-KT3 and three magnetic

starters KM1-KM3. Elements KA1, KA2, KT1 and KM1 are designed to control the first BD power stage; KA3, KA4, KT2 and KM2 – to control the second BD power stage; KA5, KA6, KT3 and KM3 – to control the third BD power stage. But this scheme disadvantage is the relay-contact equipment that it is made. The scheme shown in Fig. 11, c is designed to control the BD in Fig. 10, b. At the first power stage, the first three-phase electromagnetic device is connected. As the currents and voltages unbalance increases, the device power is increases. Additional one or two three-phase electromagnetic devices connecting to the electrical network achieve this.

Fig. 10. The balancing devices schemes with adjustable parameters: a) BD for mixed load electric networks , b) BD for municipal load electric networks feeding.

Fig. 11. BD automatic control schemes: a, b – relay-contact elements schematic diagram and control scheme based on; c-control scheme using contactless elements.

As mentioned above, when the zero wire current reaches the minimum value corresponding to the voltage unbalance indicators value permissible, the proposed device is disconnected from the network completely.

The such device parameters can be determined using the method, described in [11]. To calculate the BD parameters depending on the current and voltage unbalance level changing, the following expressions proposed to use:

$$\begin{cases} Y_{cy1} = Y_{s1} - Y_1 - Y_{s1} \\ Y_{cy2} = Y_{s2} - Y_2 - Y_{s2} \\ Y_{cy0} = Y_{s1} - Y_0 \end{cases}, \quad (6)$$

where

$$\begin{aligned} Y_{s1} &= \frac{U_A \cdot Y_A + \underline{a} \cdot U_B \cdot Y_B + \underline{a}^2 \cdot U_C \cdot Y_C}{3 \cdot (U_{s1} - U_{H1})}; \\ Y_{s2} &= \frac{(-U_A \cdot Y_A - \underline{a}^2 \cdot U_B \cdot Y_B - \underline{a} \cdot U_C \cdot Y_C)}{3 \cdot U_{H2}}; \\ Y_{s0} &= \frac{(-U_A \cdot Y_A - U_B \cdot Y_B - U_C \cdot Y_C)}{3 \cdot U_{H0}}. \end{aligned} \quad (7)$$

In expressions (7):

- Direct sequence voltage:

$$U_{H1} = \frac{U_a}{1 + K_{2uH} + K_{0uH}}. \quad (8)$$

- Negative sequence voltage:

$$U_{H2} = U_{H1} \cdot K_{2uH}. \quad (9)$$

- Zero sequence voltage:

$$U_{H0} = U_{H1} \cdot K_{0uH}. \quad (10)$$

- Direct sequence current:

$$I_{H1} = \frac{I_a}{1 + K_{2iH} + K_{0iH}}. \quad (11)$$

- Negative sequence current:

$$I_{H2} = I_{H1} \cdot K_{2iH}. \quad (12)$$

- Zero sequence current:

$$I_{H0} = I_{H1} \cdot K_{0iH}. \quad (13)$$

In formulas (8) – (13) $K_{2uH}, K_{0uH}, K_{2iH}, K_{0iH}$ – the voltages and currents unbalance coefficients, by the negative and zero sequences, which are calculated to the program "Asymmetry".

4 Discussion of the results

The performed studies reliability is confirmed by the methods correctness used the currents and voltages symmetric components calculating. The researches results extended Power Supply Department and Electrical Engineering meeting of the Irkutsk State Agrarian University after A. A. Yezhevsky named were reported and discussed (Protocol No. 10 of 04.06.2021).

5 Conclusion

Based on the above, can be drawn the following conclusions:

- In three-phase four-wire distribution electrical networks, supplying only utility loads, there are a high three-phase voltage system unbalance. It leads to a 50% and more electrical energy losses increase and a significant decrease the power quality level of (for the considered example, K_{2u} increases more than 4 times).
- The most effective means of normalizing power quality for supply utility-butte load electrical networks an electromagnetic shunt-balancing device with a minimum resistance to zero-sequence currents and automatically controlled power can be used.

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