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Evaluation of additional electricity losses in electric networks using a meter

Allaev Kakhramon Rakhimovich[1], Adeel Saleem[2], Kholiddinov Ilkhombek Khosiljonovich[2], Atif Iqbal[2], Eraliev Khojiakbar Abdinabi Ugli[2]
[1]Department of Network and Systems, Faculty of Power Engineering, Tashkent State Technical University, Tashkent, Uzbekistan
[2]Department of Electrical Engineering, Faculty of Energy, Ferghana Polytechnic Institute, Ferghana, Uzbekistan

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ABSTRACT

In this article, additional electricity losses are calculated using the voltage imbalance factor. There is also a method for predicting extra losses in the case of longitudinal and transverse asymmetry, as well as information on how to measure power quality indicators. It is suggested that home appliances be used to monitor a separate power system's power quality indicators. The findings of investigations on the condition of asymmetry conducted in operational low-voltage electrical networks are presented, along with an illustration of how to calculate additional electricity losses in low-voltage networks. In this article for this purpose, the author developed a Malika device, which is fully capable to measure, store, analyze, and draw conclusions from the results of all electrical quality indicators.

Corresponding Author:

Kholiddinov Ilhombek Khosiljonovich
Department of Electrical Engineering, Faculty of Energy, Ferghana Polytechnic Institute
Fergana, Uzbekistan
Email: i.xoliddinov@ferpi.uz

1. INTRODUCTION

The most significant measure of the effectiveness of electrical networks' functioning is electricity losses, which are also a clear indication of the state of the electricity metering system and the effectiveness of energy supply companies' revenue growth [1]. International analysts claim that, the relative losses of electricity during its transmission and distribution in the electric networks of most countries considered satisfactory if they do not exceed 4-5%. From the perspective of the principles of electricity transmission across networks, losses of power at the level of 10% are considered as the maximum allowed [2]. Now this level has increased by 1.5 and even by 3 times for individual power grid enterprises [3]. It is obvious that against the background of ongoing changes in the economic mechanism in the energy sector, the problem of reducing electricity losses in electrical networks has not only concerning issue. The power systems are feeding by the different modes of generation as solar, wind, hydel and other alternative energies [4]-[7]. However, it has now become one of the concerns for ensuring organizations' financial stability [8]-[11]. In order to improve transmission efficiency and energy distribution, the intelligent network should be capable of self-diagnosis and self-healing and contain cutting-edge sensor, communication, numerical relays and control technology [12]. Since they are among the most significant purposes for the cost-effective and long-term operation of any electronic technology used in various industries, power quality and supply issues have gained particular importance in recent years [13]. A reduction in the quality of electricity results in major changes in the working modes of receivers, which have a negative impact on the quality of products, the performance of work process components, the lifespan of electrical equipment, and the chance of accidents [14]-[16]. The Republic of Uzbekistan's GOST 13109-97

"Electric power" standard specifies the quality requirements for electrical energy in alternating three-phase and single-phase current systems with a frequency of 50 Hz at points to which electrical networks or electrical installations of consumers are connected, electromagnetic and power quality standards in general purpose power supply system's [17].

The current asymmetry is one of the factors that increase losses in networks and power distribution elements. Unbalanced currents and voltages result in decreased service life and energy performance of electrical equipment, an overall decline in electrical network reliability, an increase in active power losses, and overconsumption of active and reactive power [14], [18]-[20]. Asymmetric values of phase voltages lead to additional power losses in electrical networks and the service life of induction motors is significantly reduced due to additional thermal heating of the rotor and stator [18], [21]-[24]. In alternating current (AC) electrical machines, the asymmetry of phase voltages corresponds to the emergence of magnetic fields, the magnetic induction vectors of which rotate with a double synchronous frequency and might interfere with technological operations [14], [18], [25]. Dangerous vibrations may result if the mains voltage used to power synchronous motors is not balanced. The fluctuations can be so severe that there is a danger of destroying the foundation on which the motors are positioned and damaging the welded joints if there is a significant unbalance in the phase voltage. Power transformers' performance is substantially impacted by phase voltage unbalance, which shortens their lifespan. The service life of the transformer insulation is decreased by 16% at rated load and a current imbalance factor of 10%, according to an analysis of the operation of three-phase power transformers.

2. METHOD

The distribution network used for the study has a relatively simple network topology as shown in Figure 1. It consisting of a low voltage network of 0.4 kV, a step-down transformer substation, and a medium voltage network of 6-10 kV as shown in Figure 1(a). These networks are typically used as overhead wires, which supply single-phase loads to end users. In this study, the MATLAB application was used to generate a virtual model of the power scheme as shown in Figure 1(b). The built-in Simulink building blocks used to calculate the values of the powers, voltages, and currents, as well as their symmetrical components [26], [27].

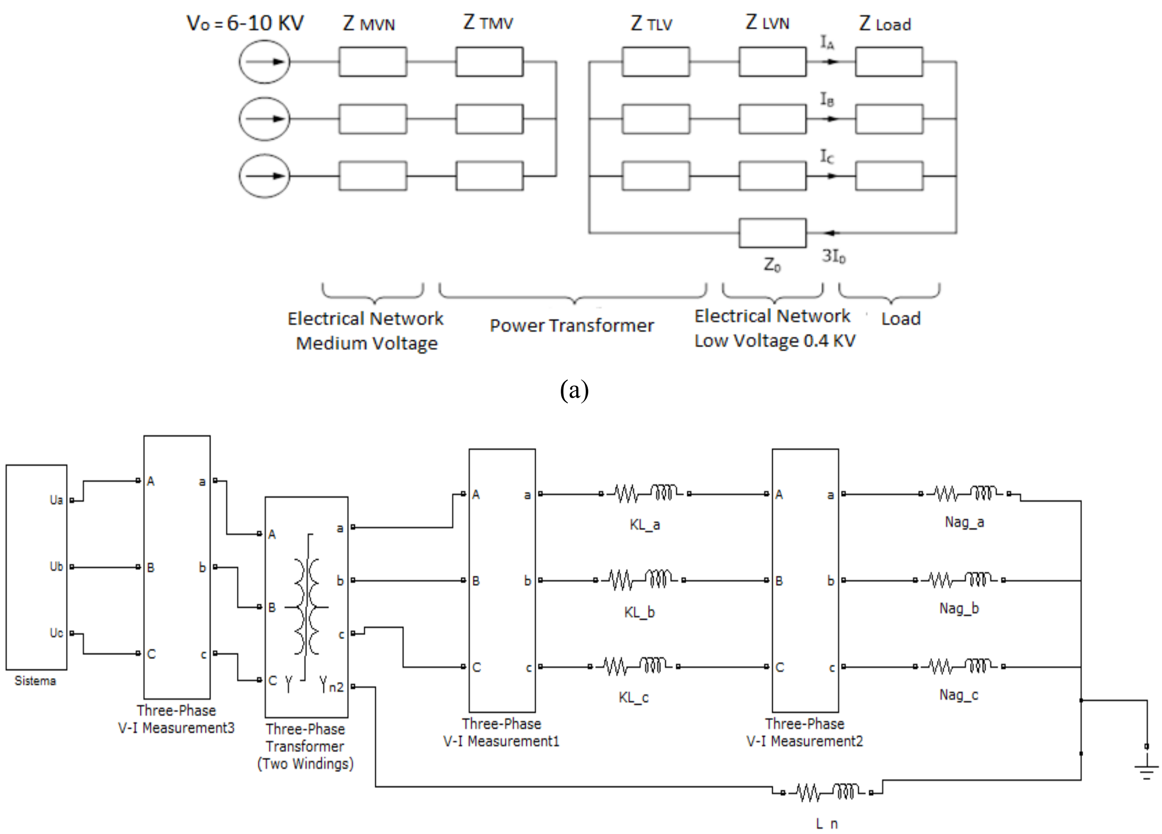


Figure 1. Distribution network (a) network configuration and (b) simulink model

This characteristic results in the fact that it is frequently unable to spread their load uniformly throughout all three phases, which, in turn, results in an increase in network losses. Here U`A – "longitudinal" and U”A – "transverse" asymmetry. A symmetrical vector diagram of the voltages at the terminals of a 0.4 kV transformer Figure 2 gives as an illustration of how voltage unbalance might develop in two situations when the loads are not evenly distributed throughout the phases. Here the load value only modifies the angle of one of the phases (let it be phase A in this case). In the Figure 2(a), such a situation is shown by the vector U’A, the amount of displacemen-by the vector ΔU’ and for simplicity, we call this case "longitudinal" asymmetry. The voltage magnitude is the same in the second case, but the angle of rotation changes, which is shown by the U’A vector and therefore by the voltage change ΔU" and this known as "transverse" asymmetry [26]. Although these two scenarios are combined in real life for all phases at once, it will be helpful to think about them individually and utilize them as limiting scenarios from which the network's actual asymmetry can be built [26]. Everything that was said about voltages also applies to the current load; in this case, the network mode is distinguished by vector diagrams that are exactly the same and we will ignore these for our convenience's. Direct sequence with "longitudinal" asymmetry in accordance with the method of symmetrical components is defined as:

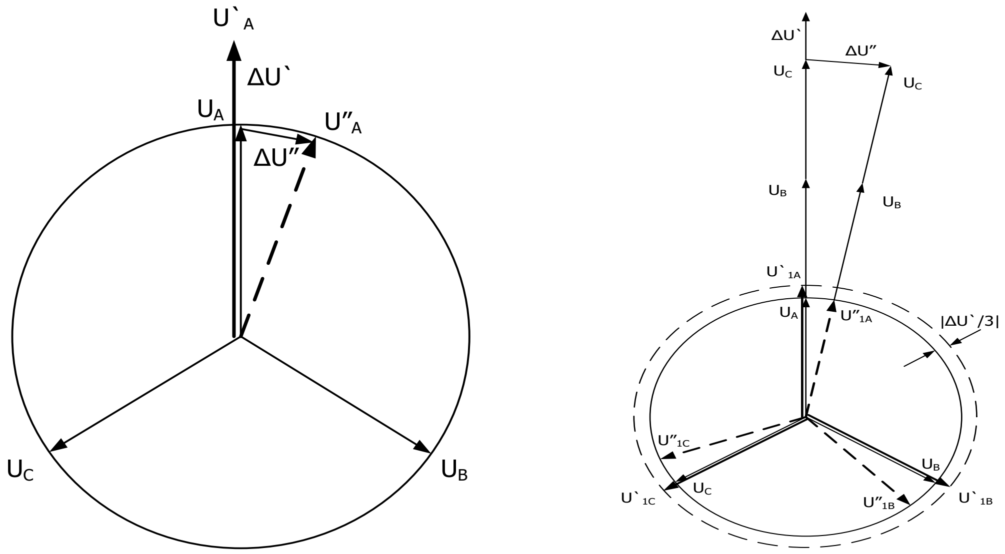
$$U`1 = 1/3 \cdot (U`A + cUB + c2UC) = 1/3 \cdot (\Delta U` + UA + cUB + c2UC) = UA + \Delta U`/3 \ [V] \quad (1)$$

where the variable c denotes the rotation of the vector by +120, and the variable c2 denotes the rotation by +240 as shown in Figure 2(b). In the case of "transverse" asymmetry, similarly to (1), we have voltages as shown in (2). Similarly, for the current we have for the longitudinal and transverse asymmetries as in (3) and (4).

$$U``1 = UA + \Delta U``/3 \ [V] \quad (2)$$

$$I`1 = IA + \Delta I`/3 \ [\mathrm{A}] \quad (3)$$

$$I``1 = IA + \Delta I``/3 \ [\mathrm{A}] \quad (4)$$



(a) (b)

Figure 2. Original vector diagram (a) direct sequence with "longitudinal" and (b) "transverse" asymmetries

Vector diagram Figure 3 represents the reverse sequence for "longitudinal" asymmetry as in Figure 3(a):

$$U`2 = \Delta U`/3 \ [V] \quad (5)$$

$$I`2 = \Delta I`/3 \ [\mathrm{A}] \quad (6)$$

and for the "transverse" asymmetry as shown in (7) and (8):

$$U``2 = \Delta U``/3 \ [V] \tag{7}$$

$$I``2 = \Delta I``/3 \ [A] \tag{8}$$

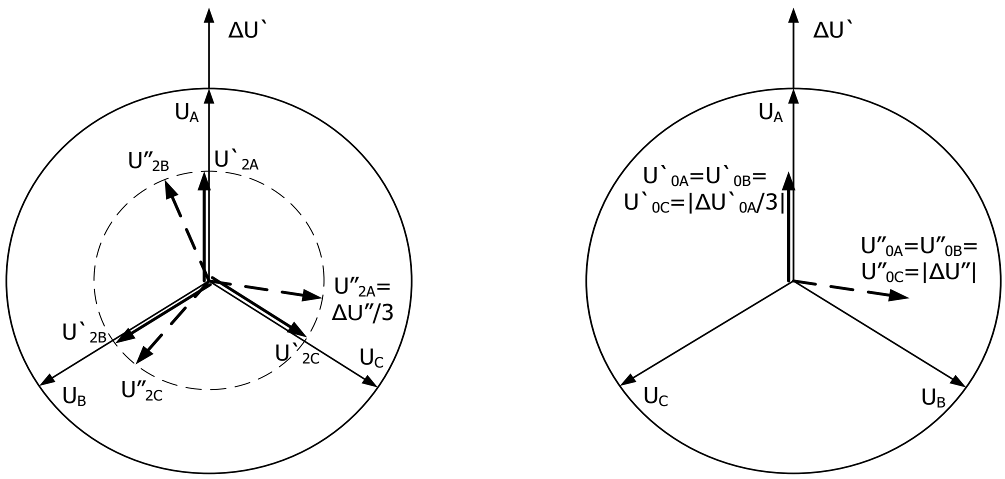
the zero sequence Figure 3(b) in these cases will be defined as [14] (9)-(12).

$$U`0 = \Delta U`/3 \ [V] \tag{9}$$

$$I`0 = \Delta I`/3 \ [A] \tag{10}$$

$$U``0 = \Delta U``/3 \ [V] \tag{11}$$

$$I``0 = \Delta I``/3 \ [A] \tag{12}$$



(a) (b)

Figure 3. Vector diagram (a) reverse sequence and (b) zero sequence

In real practice of supply system network, the asymmetry is measured as the value of the asymmetry coefficient [17] by the inverse as below for reverse and zero sequence. For K2U and K0U their limiting values are normalized by GOST [17], and they are the normally permissible value (in 95% of measurements per week) of 2% and the maximum permissible value (in 100% of measurements per week) of 4% as shown in (13)-(16).

$$K2U = |U2| / U1 \cdot 100 \tag{13}$$

$$K2I = | I2| / I1 \cdot 100 \tag{14}$$

$$K0U = |U0| / U1 \cdot 100 \tag{15}$$

$$K0I = |I0 | / I1 \cdot 100 \tag{16}$$

If measurements are carried out at the terminals of a 0.4 KV transformer substation, we will evaluate what allowable values ΔU` and ΔU`` may exist to ensure these requirements. Let us determine these values for the "longitudinal" asymmetry from the following relation, taking into account (1 and 13) [26].

$$K2U = (\Delta U`/3) \ / (UA + \Delta U`/3) \cdot 100 = 2\% \tag{17}$$

$$\Delta U` = 0.061 \cdot UA \ [V] \tag{18}$$

Similarly, we calculate the same value for the maximum allowable value of asymmetry in the reverse order, also in the case of "longitudinal" asymmetry [26]. Thus, we can say with certainty in advance that if the "longitudinal" unbalance at the low voltage terminals of the transformer on any phase exceeds at least 6.1% of the normal voltage (in the case of a voltage of 220 V this value is 13.5 V), the power quality may not meet regulatory requirementsas in (19).

$$\Delta U` = 0.125 \cdot UA. \ [V] \quad (19)$$

With a voltage unbalance on one of the phases of 27.5 V, the quality of electricity is absolutely exactly in the entire 0.4 kV network beyond the permissible limits [26]. Let us consider a similar question for the case of "transverse" asymmetry. we can write the following expression as in (20). To change the value of the angle Δφ from 0 to 20 degrees, the error of such an approximation lies within 1%. Then, taking into account (13, 15), we can write expression as in (21).

$$\Delta U`` = U1 \cdot sin\, \Delta\varphi = 0.0175 \cdot U1 \cdot \Delta\varphi \ [V] \quad (20)$$

$$K2 = K0 = (\Delta U``/3) \,/\, U1 \quad (21)$$

Further equating this expression, respectively (2) and (4), we obtain that when one of the voltage vectors is rotated by 3.44 degrees, we obtain a normally permissible asymmetry value for the entire network of 0.4 kV, and when this vector is rotated by 6.88 degrees, we get the maximum allowable value of this parameter. Thus, we have demonstrated that the emergence of an asymmetric mode in the network is caused by a change in one of the voltage vectors, both in absolute magnitude and in angle. In order to determine the point at which the quality of electricity throughout the entire 0.4 kV network no longer meets the necessary standards, the limit values of these permissible changes on the low side of the transformer are determined. All conclusions drawn for voltages can be applied to currents in the 0.4 kV network. At the same time, it is no longer so important what kind of asymmetry takes place, “longitudinal” or “transverse”. Although it is really difficult to expect a large amount of "transverse" current asymmetry, since the composition of various loads is usually quite homogeneous (all electrical devices are similar - i.e. the same type). A relatively significant "longitudinal" asymmetry caused on by an imbalance in the loads of the different phases is much more realistic. In this case, the main role is played by the magnitude of the current unbalance in phases - ΔI , which determines the magnitude of the current unbalance coefficient in the reverse (6) and zero (8) sequences. In this case, the value of power losses in the network of 0.4 kV can be determined in the (22).

$$\Delta P = 3 \cdot I12 \cdot R1 + 3 \cdot I22 \cdot R2 \cdot 3 \cdot I02 \cdot R1 + (3I0)2 \cdot R0 \ [W] \quad (22)$$

Where R1 and R2 are the active resistances of the positive and negative sequence of the 0.4 kV network, in this case they are equal to each other; R0 active resistance of the neutral wire for currents of the zero sequence (phase-zero loop) [26]. Here it should be borne in mind that, until recently, the neutral wire of cable and overhead lines was made with a smaller diameter (by two sections) compared to the phase. Now, due to a sharp increase in the magnitude of distortion in electrical networks, due to the appearance of a large number of non-sinusoidal loads, the cross section of the neutral wire is usually the same as for phase wires. Therefore, at present, we can consider the relation R0=R1 [26]. Then, taking into account (14) and (16), expression (22) can be rewritten in the (23):

$$\Delta P = 3 \cdot I12 \cdot R1 \cdot [1 + K22 + K02 \cdot (1 + 3R0/R1)] \ [W] \quad (23)$$

taking into account expressions (3) to (14), we obtain as in (24).

$$K2 = K0 = (\Delta I/3)/(I1 + \Delta I/3) \quad (24)$$

Substituting this expression into (25), and proceeding to the calculation of the relative value of power losses in the network (relative to power losses only for losses from direct sequence ΔP’= ΔP/ 3·I12·R1, after transformations, we get (25)/:

$$\Delta P' = 1 + 5 \cdot K\text{н}2 \,/(3 + K\text{н})2 \quad (25)$$

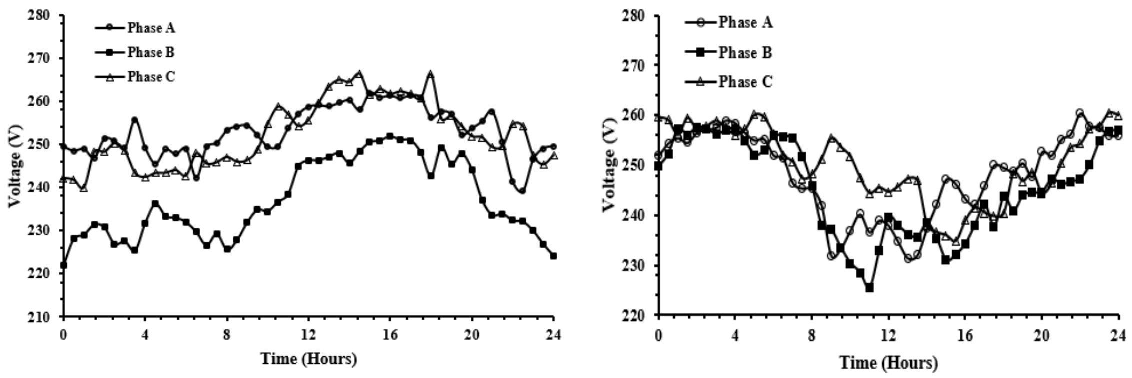
where Kн = ΔI / I1 is the coefficient of uneven current load by phase. The number of losses in the network increases by more than 30% when the current imbalance in one of the phases is 100% (Kn = 1.0). With an imbalance of 200%, it almost doubles. Of course, strictly speaking, such a comparison has a slight methodological flaw because, with such imbalances, the direct harmonic's magnitude also fluctuates considerably, but the qualitative reliance is still shown as intended. The author has created an innovative device based on a modern microprocessor base. This measuring device has high metrological characteristics and meets the requirements of GOST 13109-97.

3. RESULTS AND DISCUSSION

For the analysis, the meter is made in the form of a single device assembled in a plastic case, which provides mechanical and electrical protection for both the meter itself and the personnel working with it. By this device, we obtain information about the deviations of one of the main indicators of power quality-voltage and current unbalance in the network. A preliminary analysis of the economic sustainability of taking certain methods to reduce the amount of current and voltage unbalance is the primary objective of the accurate definition of economic damage. To study the quality of electricity, consumer transformer No. 763 was selected and recorded by the device the voltage changes are higher than the maximum allowable values for one month. Table 1 shows the average values of currents on all phases of line 1 during May 04-05, 2022. To equalize the currents by phases in this line, the load is change from phase B to phase C. In this case, Table 1 shows the change of current values for all phases of line 1 during May 17-19, 2022. The waveforms of the phase voltages and currents before equalizing the loads of line 1 is shown in Figure 4 for the consumer transformer No 763. From Figure 4(a), it can be seen that the voltage value of phase B before load equalization is lower than the requirements, after load equalization Figure 4(b), the stress values approached.

Table 1. Average values of current recorded by device

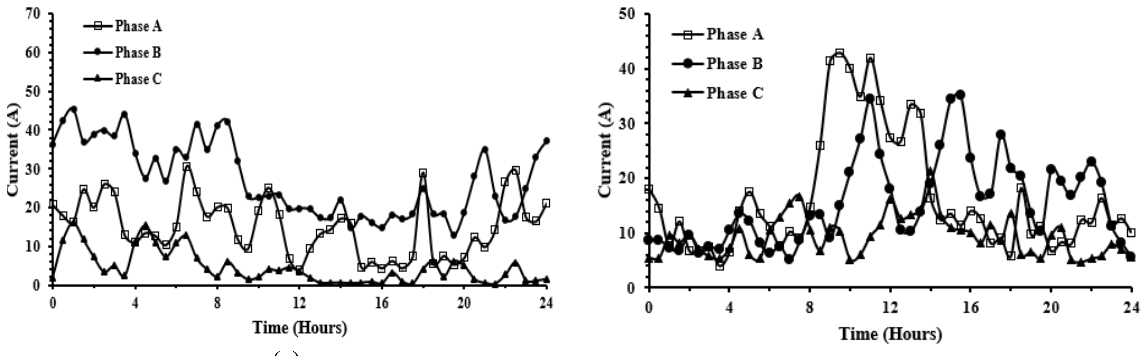
04-05 May 2022				17-19 May 2022			
Ia(A)	Ib(A)	Ic(A)	Kn	Ia(A)	Ib(A)	Ic(A)	Kn
15.07	27.42	4.32	1.36	17.89	15.07	7.87	1.09



(a) (b)

Figure 4. Phase voltage (a) before load balancing and (b) after load balancing

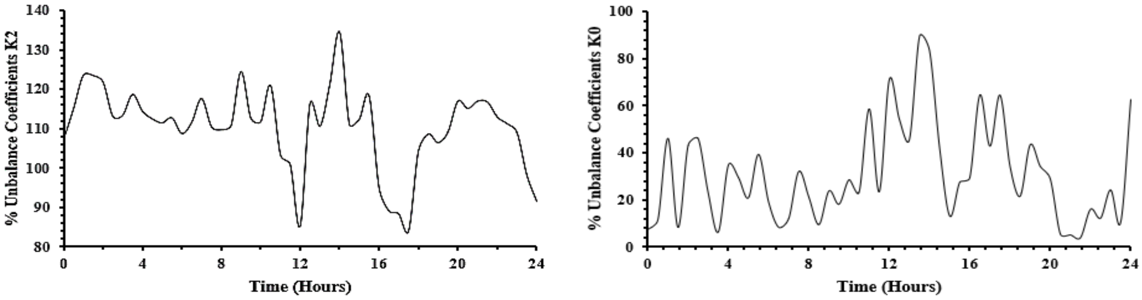
The waveforms of the phase voltages and currents after equalizing the loads of line 1 is shown in Figure 5 for the consumer transformer No 763. From Figure 5(a) it can be seen that before the load leveling, the values of phase B currents are higher than the requirements. After the load leveling Figure 5(b), the values of the currents approached.



(a) (b)

Figure 5. Phase currents (a) before load balancing and (b) after load balancing

From the results of measurements of power quality indicators at the Consumer Transformer of the Ukchi feeder and comparison with the requirements of the GOST listed in their clauses 2,3 and 4, it concludes the quality of electrical energy as follows: i) It was found that the voltage variations is occur within 240-265 V and does not meet the requirements. The transformers are inadequately loaded, and after the winter season, the voltage regulation device without excitation step has not been modified. Voltage variation is not in compliance with the criteria, ii) frequency deviation meets the requirements of GOST in all technical specifications, iii) consumer transformer substations do not meet the requirements in terms of the distortion factor of the sinusoidal voltage, iv) consumer transformer substations in terms of the coefficient of the n-th harmonic component of the voltage do not meet the requirements, v) the voltage imbalance factor in reverse order requirements are not met by all transformers in the substations, and vi) the voltage asymmetry coefficient in zero sequence requirements are not met by all transformers in the substations. After organizational steps were taken to reduce the amount of asymmetry Figure 6 shows timing diagram, the coefficients of the present asymmetry changed as shown in Figure 6(a) and Figure 6(b). To normalize these values when performing technical measures, it is advisable to use a balancing device.



(a) (b)

Figure 6. Timing diagram of changes in current unbalance coefficients (a) on the reverse and (b) null sequence

4. CONCLUSION

Low-voltage power networks are considered responsible for the reduction in the quality indicators of electricity. Therefore, in this article the authors developed a movable and stationary Malika device that measures the quality of electricity in networks with a voltage of 0.4 kV. According to GOST specifications, the developed Malika device, like other modern analyzers, has the capacity to measure, store, analyze, and draw conclusions from the results of all electrical quality indicators. The benefit of using the device is that it can shut down and restart on its own in the case of a power outage and does not need a network connection for this to happen. In order to increase the accuracy of the calculation of the asymmetry indicator, the method of calculating the degree of asymmetry developed by the author is included in the device, in which the values of vector and angle values are taken into account when calculating the asymmetry indicators. The device is intended for low-voltage electrical networks makes its internal circuits simple, its size is reduced, it does not require extra space for use, and its weight is reduced.

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BIOGRAPHIES OF AUTHORS

Allaev Kakhramon Rakhimovich is a scientist who has made a worthy contribution to the energy of the Republic of Uzbekistan. He did his BS.c in the hydroenergetics and electromechanics in 1963 from Moscow Energy Institute. In 1979 he defended his doctoral dissertation on the topic "analysis of transition procedures of electronic systems with an asynchronous turbogenerator". He started his educational career as Assistant in 1969 and then promoted to several positions such as Senior Lecturer, Associate Professor at the Tashkent Polytechnic Institute. In 1979 deputy dean of the energy faculty and then in 1986 dean of the same faculty. From 1992, he worked as a vice-rector, 1st Vice-Rector for scientific work of Tashkent State Technical University. From 1994, he has been deputy minister of higher and secondary special education of the Republic of Uzbekistan He is also the editor-in-chief of the journal problems of energy and resource saving. He can be contacted at email: allaev099@gmail.com.

Dr Adeel Saleem is working as Associate Professor in the department of electrical engineering, faculty of energy, Ferghana Polytecnic Institute, Ferghana, Uzbekistan. He received his B.Sc. degree in electrical engineering from The University of Lahore, Lahore, Pakistan, in 2011. In his bachelor's program, he received the Gold Medal. In 2015, he completed his M.Sc. in electrical engineering at The University of Lahore in Lahore, Pakistan, yet again received the Gold Medal. He received his Ph.D. degree in electrical engineering from the North China Electric Power University, Beijing, China in 2021. His research work is on electrical vehicles, power system and distribution, control systems, and electrical losses in distribution systems. He can be contacted at email: metadeelsaleem@gmail.com.

Kholiddinov Ilkhombek Khosiljonovich is working as Associate Professor and head of department of electrical engineering, faculty of energy, Ferghana Polytecnic Institute, Ferghana, Uzbekistan. He is also the head of department in the univ. He received his B.Sc. degree in electrical engineering from Ferghana politechnic institute, Ferghana, Uzbekistan in 2008. He completed his M.Sc. and Ph.D. in electrical engineering at Tashkent State Technical University, Tashkent, Uzbekistan, in 2010 and 2017 respectively. He can be contacted at email: i.xoliddinov@ferpi.uz.

Dr. Atif Iqbal is working as Associate Professor in the department of electrical engineering, faculty of energy, Ferghana Polytecnic Institute, Ferghana, Uzbekistan. He received his B.E degree in electrical engineering from NED UET, Karachi, Pakistan, in 2013. In 2017, he completed his M.Sc. in electrical engineering at The Superior University Lahore, Pakistan. He received his Ph.D. degree in renewable energy from the North China Electric Power University, Beijing, China in 2021. His research work is on renewable energy, power system and distribution, control systems, wind turbines, and grid integration. He can be contacted at email: Iqbal.atif@ferpi.uz.

Eraliev Khojiakbar Abdinabi Ugli received his B.Sc. and M.Sc. degree in electrical engineering from Ferghana Polytechnic Institute, Ferghana, Uzbekistan, in 2012 and 2014 respectively. He also did his research in North China Electric Power University, Beijing, China for one year 2018-2019. Now he is a doctoral student at the Ferghana Polytechnic Institute, Ferghana, Uzbekistan. His research work is on electrical losses in the low-level distribution systems. He can be contacted at email: eraliyevhojiakbar@gmail.com.