Additional Power Losses Under Non-Sinusoidal Conditions in a 22 kV Overhead Power Line

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Abstract — **Non-sinusoidal conditions in the electrical networks cause active power losses at the fundamental frequency, corresponding to the first harmonic, and at harmonic frequencies, which are a multiple of the fundamental frequency. Non-sinusoidal currents flow through network components and create additional active power losses. One of the non-sinusoidal current sources is electronic equipment used in industrial plants to control process equipment. In Vietnam, coal mines use frequency-controlled induction motors when processing coal. The induction motors consume non-sinusoidal current, which creates additional active power losses in the supply network. The harmonic active power does not perform useful work. It causes economic damage to both the supply network and industrial enterprises. The power supply systems in industrial areas of Vietnam, where coal is mined, are characterized by low power quality. Companies engaged in coal mining and processing are forced to pay for additional losses of active power due to the low power quality under non-sinusoidal conditions, which reduces the economic efficiency of the companies' operations.**

The paper presents a review of the literature on the assessment of additional active power losses in overhead power lines at harmonic frequencies. An example of calculating additional losses of harmonic active power is given for a 22 kV overhead power line, through which electrical energy is supplied to the coal grading plant of the Kua Ong-Vinacomin company. Additional losses are calculated using the measurements of harmonic voltage and current at the point of the supply network connection to the 22 kV overhead power line, through which electrical energy is supplied to the coal mine and the coal grading plant. To assess the influence of the electrical equipment of the coal grading plant on the power quality in the supply network, measurements were carried out on 0.4 kV buses of electrical substation of the coal mine.

Index Terms — **power quality, harmonic, non-sinusoidal conditions, measurements, power system, frequency-controlled induction motors.**

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I. Introduction

Non-sinusoidal conditions in electrical networks are one of the acute problems in the field of power quality. Apart from active power losses at the fundamental frequency (corresponding to the first harmonic), the electrical networks under non-sinusoidal conditions experience active power losses at other harmonics, the frequency of which is a multiple of the fundamental frequency. In [1], consideration is given to the economic damage to the supply network and consumers, which is associated with additional active power losses in electrical networks.

Overhead power lines are components of electrical networks. Non-sinusoidal currents flowing in them are not only of the 1st harmonic ($n = 1$), corresponding to the fundamental frequency $f_1 = 50$ Hz, but also of the harmonics that are multiples of the fundamental frequency, i.e., $n \geq 2$, for which $f_n = 50\,n$. Harmonic currents in power lines cause additional active power losses. Determining the magnitude of active power losses in power transmission lines under non-sinusoidal conditions is the focus of many publications as this issue is highly relevant [2–6].

When a load with a nonlinear current-voltage characteristic is powered from a source with a sinusoidal voltage, the flow of active power of the 1st harmonic is directed into it [2]. Most of this power is consumed by the load to perform useful work, which is proposed to be called "working power" in [3]. Part of the active power of the 1st harmonic is converted by the nonlinear load into active power of harmonics with numbers $n \geq 2$ [2]. In [3], such active powers are proposed to be called "detrimental powers."

In [4], metering electrical energy under non-sinusoidal conditions is considered and misunderstandings that arise between energy supply entities and consumers when paying for electrical energy are pointed out. Electric energy meters measure active energy not only of the 1st harmonic but of other harmonics as well. For this reason, energy supply entities and consumers incur additional costs when paying for electrical energy.

Additional losses of harmonic active power in electrical networks can amount to several percent of losses under sinusoidal voltage [5]. Losses in the networks of industrial enterprises and in the networks of electrified railway transport can reach 10–15%. In [6], the values of active power losses at the fundamental frequency and additional losses at harmonic frequencies are given based on the values of harmonic currents measured during the day in a 110 kV power transmission line of Buryatenergo. At some points in time, additional losses amounted to 30% of the losses at the main frequency. The level of additional active power losses per day was 13.1% of power losses at the 1st harmonic. The influence of harmonic currents on the value of active resistance of power transmission line wires is considered in [7–13].

In Vietnam, in coal mining areas, low power quality is observed due to the use of frequency-controlled induction motors in coal mines during coal processing. These motors cause distortion in the shape of voltage and current waveforms, i.e., they are sources of harmonic currents in the supply electrical network. The power quality in the electrical networks of Vietnam must comply with two current regulatory documents [14–15]: "Circular No. 39/2015/ TT-BCT dated 11/18/2015 of the Ministry of Industry and Trade of Vietnam on the distribution of electrical energy" and "Circular of the Ministry of Industry and Trade of Vietnam 25/ 2016/ TT-BCT dated 30/11/2016 on the transmission of electrical energy."

This paper presents the results of measurements of harmonic voltages and currents at the connection point of the supply network and the 22 kV overhead power line, through which electrical energy is supplied to the coal mine and coal grading plant of the Kua Ong-Vinacomin company [16], and on the low-voltage side of the step-down 22/0.4 kV transformer supplying process equipment of the coal grading plant [17]. The article presents the results of calculation and analysis of additional harmonic active power losses in the 22 kV overhead power line feeding the coal mine. To assess the influence of frequency-controlled induction motors on the power quality in the supply network, measurements were carried out on 0.4 kV buses of an electrical substation of the coal mine.

II. Measurement Results for Harmonic Voltage and Current in the Power System of Coal Mine

The power supply diagram for the coal mine is shown in Fig. 1. Measurements were carried out at the beginning of the 22 kV overhead power transmission line at node 6001 and at the low-voltage side of the transformer feeding the coal mine and coal grading plant at node 4143. The PQ-Box150 device [18], manufactured in Germany, was used

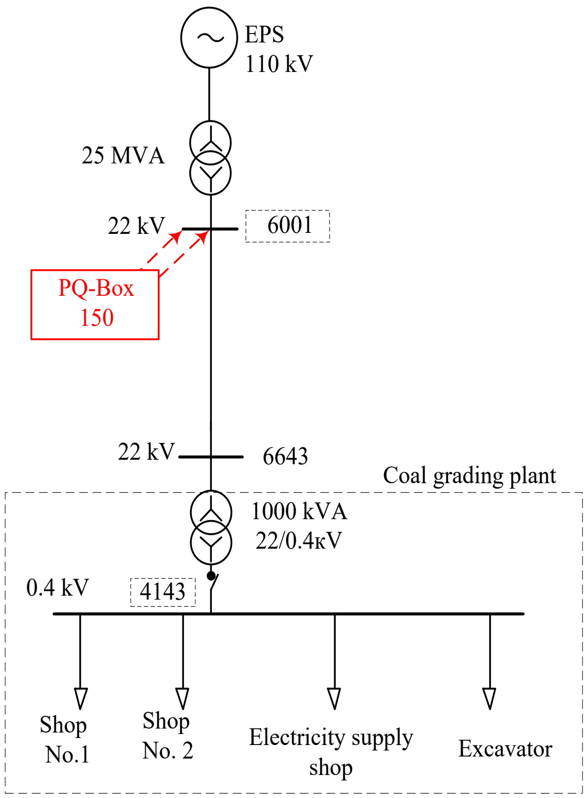

Fig. 1. Power supply system of the coal grading plant.

for the measurements. Measurements of power quality indices and operating parameters were carried out over 24 hours with an interval of 1 second.

A. Measurement results for power quality indices of the coal mine electrical network at node 4143.

There are two operational states at the coal grading plant: operating hours from 7 a.m. to 5 p.m., when all process equipment is in operation; and non-operating hours from 5 p.m. to 7 a.m. of the next day, when the main process equipment is not working.

Figures 2 and 3 show the curves for active and reactive power in three phases consumed by the load of coal mine in 24 hours. The maximum active power consumption during operating hours is 1035 kW, reactive power consumption is 419 kVAr. During the non-operating hours, the maximum active power consumption is 203 kW, reactive power consumption – 94 kVAr.

Figure 4 shows a diagram of the harmonic factors for the n-th harmonic components of voltage for operating hours and non-operating hours, when the load powers are minimum ($K_{U(n)min}$) and maximum ($K_{U(n)max}$).

The values of $K_{U(n)}$ during operating hours for most harmonics exceed the values of the factor during non-operating hours.

Figure 5 shows a graph of changes in the value of the total harmonic distortion of voltage K_U in phase A and its standard value K_{UN}. Most of the measured values of K_U exceed the standard value of 6.5% established in [14]. The highest value of K_U is 16.7%, the lowest – 3.8%.

The measurements of power quality indices on the 0.4 kV buses of electrical substation show that the values of the indices during operating hours and non-operating hours are different. This indicates the influence of the electrical equipment of the coal mine and coal grading plant on the operating parameters of the electrical network. The change in the values of power quality indices, which characterize the distortion of voltage and current

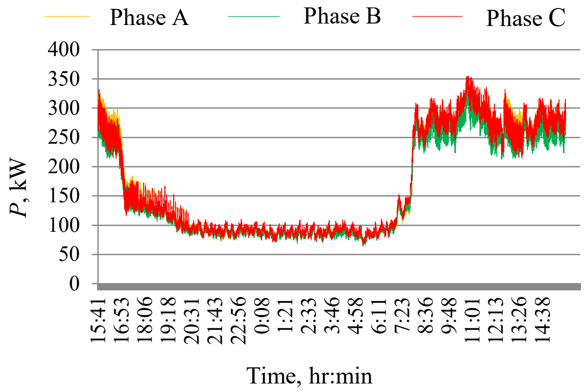

Fig. 2. Change in active power.

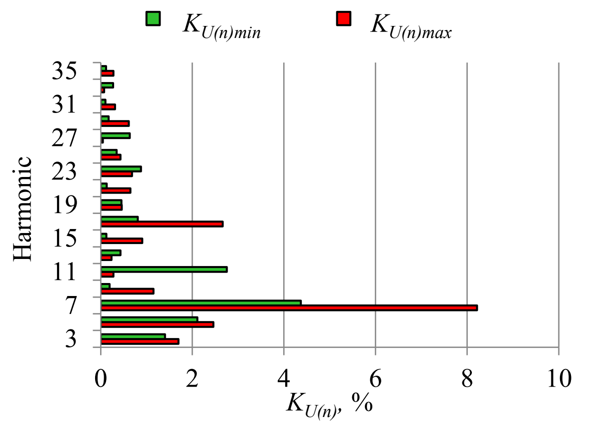

Fig. 4. Diagram of $K_{U(n)max}$ and $K_{U(n)min}$ in phase A.

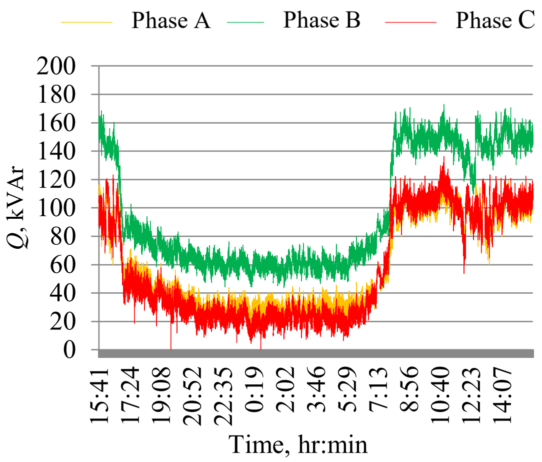

Fig. 3. Change in reactive power.

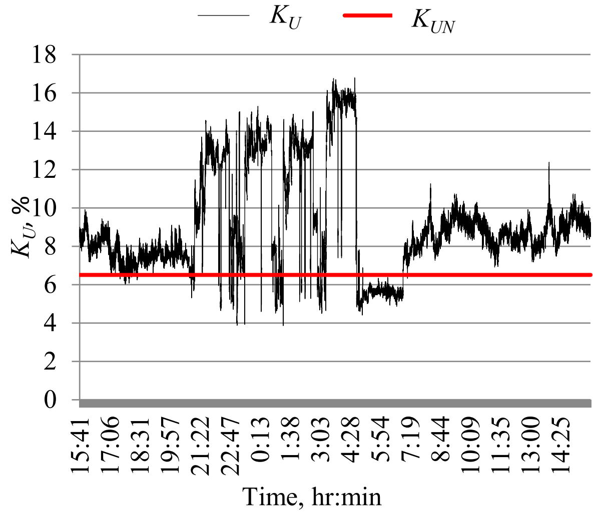

Fig. 5. Changes in K_U in phase A.

waveforms at node 4143, demonstrates the influence of the electrical equipment of the grading plant on the voltage and current of the 22 kV overhead power line supplying electrical energy to the coal mine and the coal grading plant.

When non-sinusoidal current flows through the power line, additional active power losses occur.

B. Power quality measurement results for node 6001 of the electrical network of the 110 kV power system.

The 22 kV overhead power line is connected to the 110 kV power system through a 25 MVA two-winding transformer at node 6001. Node 6001 is the beginning of the overhead power line that supplies electrical energy to the coal mine and coal grading plant. This three-phase power line is made with AS-185 wires [19] and has a length of 8 km. Measurements of operating parameters and power quality indices were carried out with PQ-Box 150 device for 24 hours with a measurement interval of 1 second. The results of calculations and analysis are presented for two operating conditions of the coal grading plant.

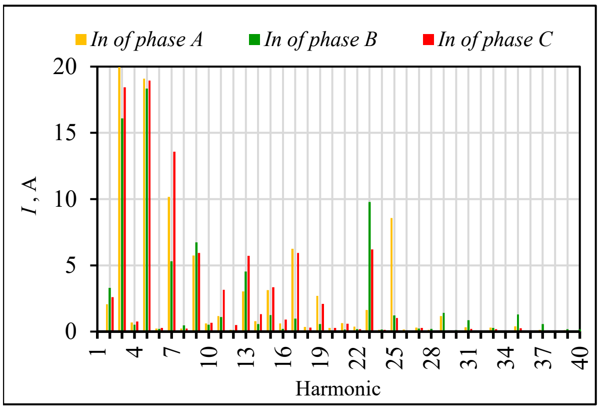

Fig. 6. Diagram of harmonic currents for operating hours.

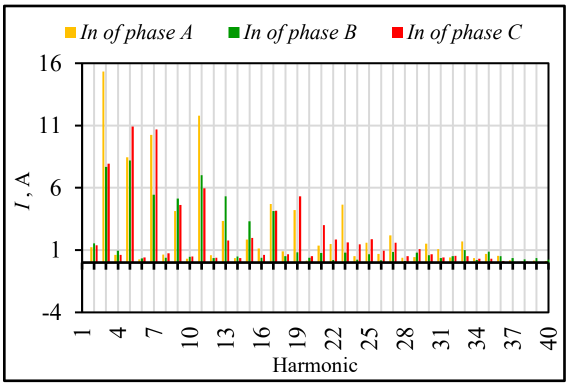

Fig. 7. Diagrams of harmonic currents for non-operating hours.

Figure 6 shows a diagram of the effective values of harmonic currents (I_n) based on one of the measurements performed during operating hours. The diagram illustrates that when all the process equipment is in operation, the currents of the 3rd, 5th, 7th, 23rd, and 25th harmonics have the highest values. The values of even harmonic currents are insignificant.

The parameters of harmonic conditions are probabilistic in nature [20]. Table 1 shows the maximum and minimum values of the measured harmonic currents in the phases, corresponding to the maximum (max) and minimum (min) values. The arrays of measured harmonic currents contain outlying observations [21], which significantly exceed the others in magnitude. Table 1 presents the values of the 23rd harmonic current in phases B and C and the value of the 25th harmonic current in phase A. They are highlighted in bold.

Figure 7 shows a diagram of the effective values of the harmonic currents of one of the measurements for the non-operating hours of the plant. As seen in the Figure, their magnitude is smaller than that of the harmonic currents during operating hours. The currents of the 3rd, 5th, 7th, and 11th harmonics have the highest values. The even harmonic currents are significantly less than the odd harmonic currents.

Table 2 presents the maximum and minimum values of odd harmonic currents for the non-operating hours. The Table contains outliers that have larger values. As in the operating hours, during the non-operating hours, these are the values of currents of the 23rd harmonic in phases B and C and the 25th harmonic in phase A. The harmonics of currents during the non-operating hours are smaller in magnitude than the those during the operating hours. The currents of the 3rd, 5th, 7th, and 11th harmonics have the

TABLE 1. Maximum and Minimum Values of Harmonic Currents for Operating Hours, A

Harmonic	I_n *of* phase A		I_n of phase B		I_n of phase C	
	max	min	max	min	max	min
1	478.75	5.99	473.64	2.80	478.46	3.08
3	53.92	0.36	46.11	0.28	40.43	0.26
5	59.3	0.30	52.40	0.12	54.68	0.32
7	24.78	0.11	15.63	0.04	32.31	0.14
9	15.88	0.09	18.78	0.10	19.11	0.13
11	8.24	0.00	7.60	0.00	13.37	0.01
13	12.44	0.02	12.13	0.04	16.95	0.04
17	16.60	0.03	4.77	0.01	17.35	0.01
19	8.70	0.01	3.91	0.00	9.27	0.01
21	7.57	0.00	1.70	0.00	4.51	0.00
23	9.52	0.01	**1 611.23**	0.50	**2 068.39**	0.81
25	**2 426.76**	0.34	4.32	0.01	8.21	0.01

highest values.

C. Additional active power losses

Alternating electric current is distributed unevenly across the cross-section of the wires [22]. The current density is greatest on the surface of the wire and decreases with distance from the surface into the depth of the wire. The phenomenon of surface effect occurs in the wire, which is characterized by an increase in the active resistance of the wire. Since the power transmission line supplying electrical energy to the coal grading plant is of insignificant length, the value of the active resistance of the line can be determined using expression (1) proposed in [12, 13]

$$R_n = R_1\sqrt{n}\ , \qquad (1)$$

TABLE 2. Maximum and Minimum Values of Harmonic Currents for Non-Operating Hours, A

Harmonic	I_n of phase A		I_n of phase B		I_n of phase C	
	max	min	max	min	max	min
1	441.91	5.63	437.8	2.64	442.04	2.89
3	38.37	0.21	29.99	0.12	26.11	0.05
5	42.21	0.01	35.78	0.01	38.57	0.07
7	35.96	0.08	16.90	0.03	31.70	0.08
9	15.00	0.07	13.45	0.06	15.08	0.03
11	20.59	0.03	16.02	0.03	19.60	0.02
13	9.76	0.02	11.14	0.04	14.05	0.01
17	11.86	0.04	6.10	0.01	12.33	0.02
19	9.77	0.01	5.72	0.00	12.12	0.01
21	10.51	0.00	3.20	0.00	9.74	0.00
23	11.79	0.01	**182.66**	0.09	**585.33**	0.31
25	**506.45**	0.18	2.53	0.00	6.77	0.00

TABLE 3. Total harmonic active power, W

Harmonic	Operating hours			Non-operating hours		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
2	3.7	27.0	23.8	1.3	1.4	1.1
3	1 246.9	1 149.9	816.3	463.9	324.9	138.0
4	2.8	1.5	3.5	0.6	1.2	0.6
5	2 255.6	1 803.3	1 809.4	193.9	138.5	275.7
7	368.4	109.7	757.8	329.2	107.0	354.7
9	175.4	299.6	304.8	122.4	140.8	106.7
11	16.9	10.6	49.1	79.3	44.9	84.7
13	88.0	119.0	165.2	33.7	65.0	34.3
22	1.0	0.1	0.7	5.1	0.3	3.4
23	46.8	3 667.2	7 824.3	73.5	125.6	705.3
24	0.7	0.2	0.7	3.6	0.2	4.1
25	11 136.2	18.7	20.5	325.2	1.2	18.9

TABLE 4. Total Harmonic Active Power

Active power	Operating hours	Non-operating hours
P_1, W	542 006.1	314 370.1
$(P_2 - P_{40})$, W	108.3	55.5
$(P_3 - P_{39})$, W	34 919.3	4 640.7
$P_{n\Sigma}$, W	35 027.6	4 696.2
$P_{n\Sigma} / P_1 \cdot 100$, %	6.5	1.5

where R_1 and R_n are the values of the active resistance of the wire at the fundamental frequency and at the harmonic frequency, n is the harmonic number. Additional active power losses at the n-th harmonic frequency are determined by the expression

$$P_n = I_n^2 R_1 \sqrt{n}\ . \qquad (2)$$

Table 3 shows the values of the calculated phase active powers for some even and odd harmonics. As seen in the Table, the operating conditions at each of the harmonics are unbalanced.

The results of calculations and analysis of the total active harmonic powers for three phases are given in Table 4. In the Table, P_1 is active power of the first harmonic, performing useful work; $(P_2 - P_{40})$ is total active power of even harmonics from 2 to 40, which do not perform useful work [3]; $(P_3 - P_{39})$ is total active power of odd harmonics from 3 to 39, which do not perform useful work [3]; $P_{n\Sigma}$ is total active power of even and odd harmonics. The value of harmonic active power for operating hours relative to the value of active power of the first harmonic is 6.5%, and for non-operating hours – 1.5%.

III. CONCLUSION

The results of calculation and analysis of additional active power losses in an overhead power line caused by harmonic currents that occur under non-sinusoidal conditions demonstrate that active power losses at harmonic frequencies can exceed 6% of active power losses at the fundamental frequency.

Loss of harmonic active power can be used as a metric to assess the efficiency of the use of electrical energy and its transmission through electrical networks. It is an assessment of the work performed by the network and supply companies, consumers, and government authorities to maintain power quality in accordance with the regulatory requirements.

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