Estimation of Active Power Loss Due to Supraharmonics in a 22 kV Transmission Line

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***Abstract* — Power systems in Vietnam's coal mining industrial areas supply power of inferior quality. Supraharmonic voltages and currents in power grids serving electric energy to open-cut coal mines were detected by measuring power quality indicators and operating parameters in the power grid serving electric energy to the open-pit coal mine and coal screening plant operated by "Cua Ong-Vinacomin" company. The active powers of harmonics and supraharmonics do not produce any useful work. They induce extra loss of active power. Coal mining and coal processing companies pay for the loss, which results in diminished rate of return for them.**

This paper offers a review of published research on the topic. It presents the results of measuring the operating parameters and power quality indicators for non-sinusoidal conditions at the point connecting a 22 kV power line to the power system that serves electric energy to an open-pit coal mine and coal screening plant. The active power loss caused by supraharmonics is calculated and analyzed.

***Index Terms* — Power quality, supraharmonics, measurements, active power loss.**

I. INTRODUCTION

Electric energy is used in all areas of human life. Maintaining its quality in compliance with the established standards [1] facilitates the efficient use of various material resources, including the reliable operation of energy systems. Energy saving is key in operating the power sector and addressing the issues of its expansion planning. It is directly related to the power quality in power grids, which affects the operation of electrical equipment of power utilities and consumers, and the efficiency of their work [2]. One of the power quality problem is voltage non-sinusoidality [3]. Voltage non-sinusoidality in electrical networks occurs all over the world [4–8]. Non-sinusoidality of voltages and currents gets higher with increased use of electrical equipment having nonlinear current-voltage characteristics, such as generators, motors, transformers, as well as electronic equipment (rectifiers and inverters) and the electrical equipment whose operation is based on electric discharge phenomena (electric welding equipment, arc furnaces) [9–15]. At present, electronic equipment is everywhere, and its use is steadily on the rise. Power electronics is an industry whose products are vital to electrical engineering and electric power industries [16]. At the same time, modern power electronics is a source of high-frequency emissions. They can damage electrical equipment, cause extra power loss, and decrease reliability of serving electric energy to consumers [17].

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Coal mining in Vietnam is an important part of the economy. Underground and open-pit coal mines have become the industrial centers of the country. Power systems of underground and open-pit coal mines have a complex configuration, different voltage levels, loads of various types and powers. Underground mines, open-pit mines, and coal screening plants are actively embracing new process equipment, including electrical equipment with nonlinear current-voltage characteristics that consumes current with non-sinusoidal waveforms. At coal screening plants, the main electrical equipment driving the process equipment is variable-frequency induction motors that cause non-sinusoidal waveforms of voltages and currents. The instrumentation-aided studies of power quality reveal the presence of harmonics, interharmonics, and supraharmonics in non-sinusoidal currents and voltages [18–20]. They create extra loss of active power, cause accelerated aging of electrical equipment insulation, and, as a result, shorten its service life. An increase in the total harmonic distortion of voltage up to 10–15% lowers power factor and torque on the shaft of induction motors [18]. The active energy of harmonics is dissipated in electrical equipment and network components, causes loss of electrical power and, as a consequence, incurs extra costs for electric energy consumed. Consumers also face additional costs in the form of penalties if the load power factor is less than the established standard value [19].

The coal screening plant operated by “Cua Ong-Vinacomin” company in Quang Ninh Province also employs variable-frequency induction motors to drive the plant's process equipment. Harmonics, interharmonics, and supraharmonics in voltage and current in the power grid supplying electric energy to the open-pit coal mine and coal screening plant were detected by measuring power quality indicators and operating parameters.

This paper presents the results of measuring harmonic and supraharmonic voltages and currents at the node connecting a 22 kV overhead power line to the feeding network. The power line supplies electricity to the open-pit coal mine and coal screening plant of the coal mining company. The results of the calculations and the analysis of active power loss resulting from supraharmonics in the power line are also provided.

II. SUPRAHARMONICS ARE VOLTAGE AND CURRENT COMPONENTS THAT OCCUR UNDER NON-SINUSOIDAL CONDITIONS IN ELECTRICAL NETWORKS

Non-sinusoidal conditions in transmission and distribution networks induce subharmonic, harmonic, interharmonic, and supraharmonic voltage and current in addition to the 1st harmonic of the 50 Hz frequency. Figure 1 shows the frequency ranges that characterize the above periodic components of voltages and currents and non-periodic electromagnetic interference.

Subharmonics are voltage and current components with frequencies below the fundamental frequency of the feeding voltage. Their frequency is an integer number of times less than the fundamental frequency of 50 Hz [21, 22].

As per GOST 32144-2013, harmonics are sinusoidal voltages and currents, the frequency of which is a multiple of the fundamental frequency of the feeding voltage [1].

Interharmonics are voltage and current components whose frequencies are not integer multiples of the fundamental frequency of the voltage. The spectral components of the interharmonics are those located between two consecutive harmonic frequencies. Interharmonic components simultaneously arising at convergent frequencies can form a voltage with a

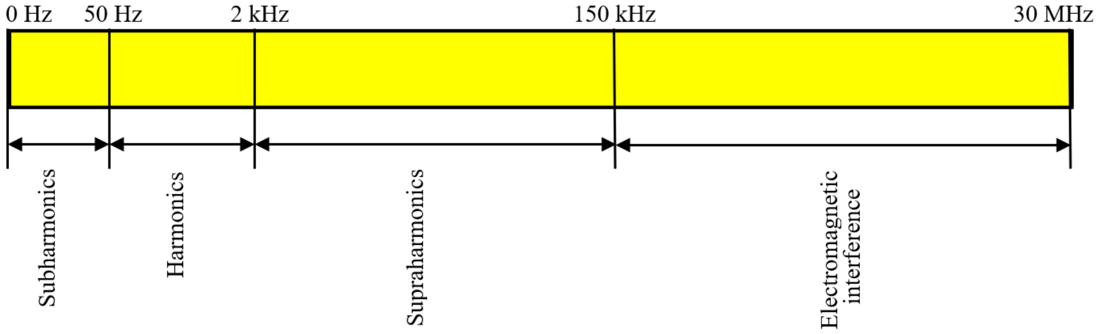

Fig. 1. Distribution of signal components by frequency range.

broadband spectrum [1, 21, 23]. The levels of current interharmonics in arc steelmaking furnaces can reach up to 10–20% of the fundamental frequency current [15].

Numerous publications [24–30] consider the components with frequencies ranging from 2 to 150 kHz as supraharmonics. GOST 30804.4.7.7-2013 defines supraharmonics “as components of signals (currents and voltages) whose frequencies are above the 40th harmonic frequency (approximately 2 kHz) but below the upper limit of the low frequency band (9 kHz)” [23]. Supraharmonics can be caused by the use of control devices in power supply units with pulse-width modulation on the side of connection to the electrical network; the signal transmission in electrical networks; the interference emitted into power supply systems by the technical equipment (voltage converters) connected; and the voltage and current fluctuations induced by narrowband radio emissions. Supraharmonic currents are generated by real distribution systems that are based on smart grids, advanced electronic loads, and distributed generation devices. The IEC standard [23] also notes that the spectral components of supraharmonics have small amplitudes. Supraharmonic numbers are denoted by the frequency value in kHz at 0.2 kHz intervals, i.e., 2.1, 2.3, etc.

This paper considers 35 supraharmonics ranging from 2.1 to 8.9. They are mentioned in [23] and can be measured by purpose-made instruments [8, 31].

Supraharmonics were discussed at the 14th International Conference on Harmonics and Electric Power Quality held in Italy in 2010 [17]. Conference participants raised the issue of supraharmonics measurement technology and the standard [23], which was implemented in 2008 (IEC 61000-4-7:2008) and had to be revised, in particular to introduce changes related to supraharmonics.

The useful work is done at the 1st harmonic [7]. All the above harmonics shown in Fig. 1, except for harmonic 1, are harmful because they do not produce useful work [7, 15]. The sources of harmful harmonics [3, 4, 8, 15, 16, 26, 30, 32–35] are:

- rotating machines such as generators and motors because their rotating field is not perfectly sinusoidal;
- saturated magnetic circuits of transformers;
- power converters of all types;
- equipment that uses electric arc or electric discharge, such as electric arc furnaces and welding machines;
- modern electronic electric devices (variable frequency electric drives, pulsed power supplies, fluorescent and LED lamps, chargers for electric vehicles, etc.);
- medium-voltage wind turbines, medium-voltage solar power plants, low-voltage photovoltaic plants;
- interference fields caused by ultrahigh voltage lines (corona effect);
- narrowband communication over power lines for transmitting meter readings;
- power supply units of computers;
- programmable controllers of control systems for industrial plants and production processes, etc.

All harmonic components degrade power quality; increase power losses; can cause damage, malfunction, or failure of equipment; as well as compromise the reliability of power systems [34].

Study [8] focuses on the calculation of active power loss due to supraharmonics in a 20 kV power cable in an electrical network, which serves electric energy to communities with residential and commercial loads and contains many decentralized energy sources producing renewable energy (wind farm, solar power plants). Low-voltage photovoltaic power plants are connected to low-voltage distribution networks together with other power electronic devices that use high switching frequency power converters such as charging stations, consumer electronics, etc. The authors calculate active power loss based on the measurements of supraharmonic currents in a real medium-voltage cable network and conclude that modern distribution networks have supraharmonic power loss that can amount up to several percent of power loss at the fundamental frequency. Power loss due to supraharmonics can exceed ten percent of the power loss caused by common current harmonics in a medium-voltage cable.

III. ANALYSIS OF VOLTAGE AND CURRENT SUPRAHARMONICS MEASUREMENTS

Measurements were carried out in the distribution network feeding a coal mine power supply circuit via a 22 kV transmission line. Figure 2 shows the diagram of the power supply system of the open-pit coal mine and coal screening plant. The designations used in the Figure are: PS – power system, PTL – power transmission line, W –

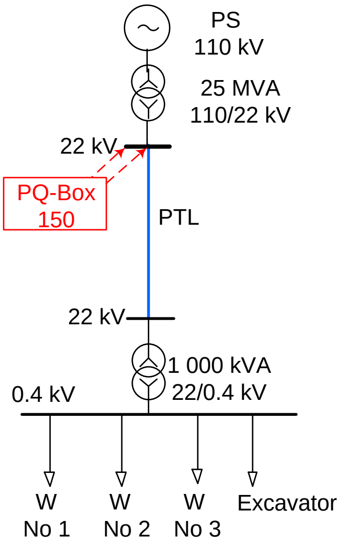

Fig. 2. Fragment of the network feeding the open-pit coal mine and coal screening plant.

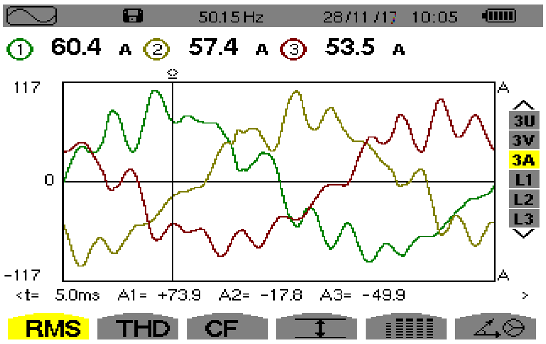

Fig. 3. Oscillograms of phase currents.

works. The three-phase power transmission line, 8 km long, is made with a steel-aluminum wire (AC-185) [36].

The PQ-Box 150 instrument was used for measuring the operating parameters and power quality indicators [31]. Measurements were conducted continuously for 24 hours, with data collected at 1-second intervals. 86 754 values were obtained for each of the measured parameters. The operation of the coal screening plant involves the process of coal grading followed by service break. Figure 3 presents the oscillograms of phase currents captured at a specific moment during the measurements.

The oscillograms reveal that the current curves are non-sinusoidal and exhibit substantial distortion. The effective values of currents in phases, given all of the above components, are 60.4 A, 57.4 A, and 53.5 A.

Figure 4 plots changes in active power supplied to the open-pit coal mine and coal screening plant over 24 hours. The maximum active power consumption during operational hours reaches 1 035 kW, with 203 kW consumed during the break in operation.

Figure 5 shows the measured values of the indicator - the total harmonic distortion of the voltage in three phases. The standard value of 6.5% is set for the indicators in [19]. The graph shows that throughout the majority of the measurement period, the indicators exceed the standard value, reaching their peaks during the break in operation. They surpass the standard value by more than 2.5 times.

Figure 6 demonstrates supraharmonic voltage changes in phase B. The voltage of supraharmonic 2.1 has the highest value during operational hours. It is equal to 1.6 V.

IV. Estimation of Additional Active Power Losses Due to Supraharmonics in a 22 kV Overhead Power Transmission Line

The additional active power losses due to supraharmonics is calculated in accordance with the technique presented in [37]. The calculation procedure is as follows:

1. Calculating extra loss of active power in one phase of the line for one of the supraharmonics, using the expression

$$\Delta P_{isn} = I_{isn}^2 R_{isn}\,, \tag{1}$$

where isn is the number of supraharmonics, I_{isn} is the measured effective value of current flowing through the wire of a single phase; R_{isn} is the ohmic resistance of the wire, which, given the skin effect [4, 5, 8, 11] and ambient temperature [24], is defined as

$$R_{isn} = R_{20} + \alpha_T (t - 20)\,, \tag{2}$$

where R_{20} is wire resistance at 20°C; R_{isn} is wire resistance at ambient temperature; α_T is temperature coefficient of wire resistance; t is ambient temperature;

2. Calculating total active power loss due to supraharmonics ranging from 2.1 to 8.9, i.e. for 35 supraharmonics, using the expression

$$\Delta P_{isn\Sigma} = \sum_{isn=1}^{35} I_{isn}^2 R_{isn}\ ; \tag{3}$$

3. Calculating additional loss of active power due to the 1st harmonic, for the ambient temperature

$$\Delta P_{1\Sigma} = I_1^2 R_1\,, \tag{4}$$

where I_1 is the measured RMS value of positive-sequence current of the fundamental frequency, R_1 as calculated by (2);

4. Calculating total additional active power loss due to supraharmonics relative to active power loss of the 1st harmonic, according to the expression

$$\Delta P_{isn\%} = \Delta P_{isn\Sigma} / \Delta P_{1\Sigma} \cdot 100\% . \qquad (5)$$

The additional loss of active power due to supraharmonics is calculated based on the measurements performed for 24 hours.

Winter temperatures are around +10°C and summer temperatures can reach +40°C in the area of Vietnam where the measurements were made. Additional loss of active power in the transmission line was determined for these temperatures. Figure 7 shows the changes in the resistance of the wire of one phase of the line as a function of temperature and skin effect coefficient. When the

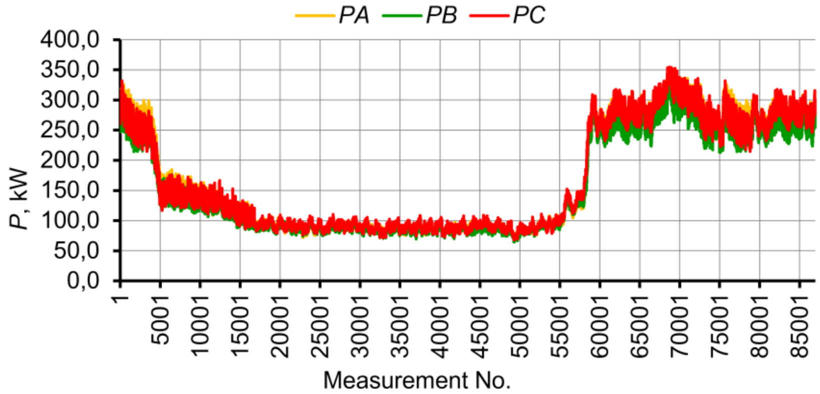

Fig. 4. Changes in phase active powers.

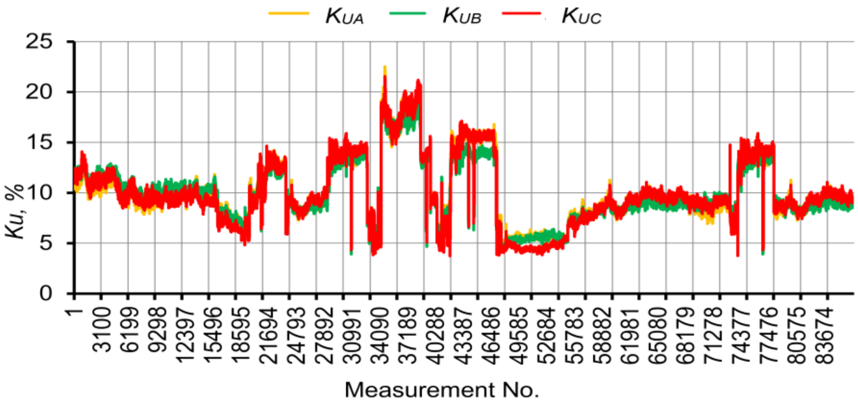

Fig. 5. Graphs of changes in the K_U indicator in three phases.

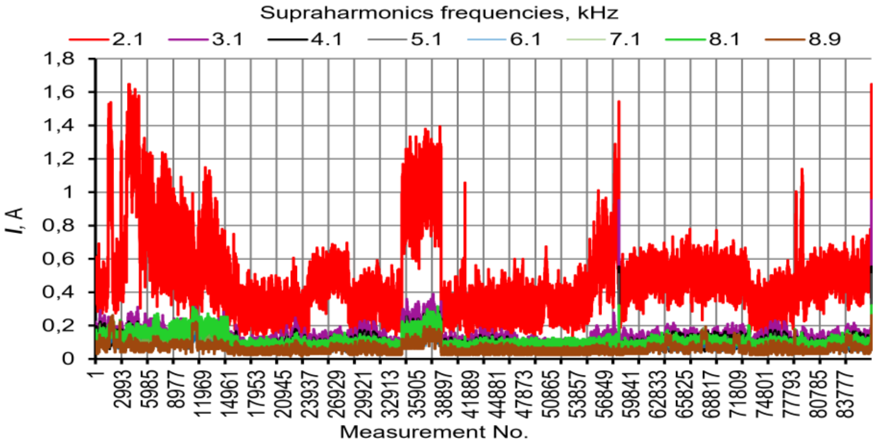

Fig. 6. Changes in voltage at supraharmonic frequencies in phase B.

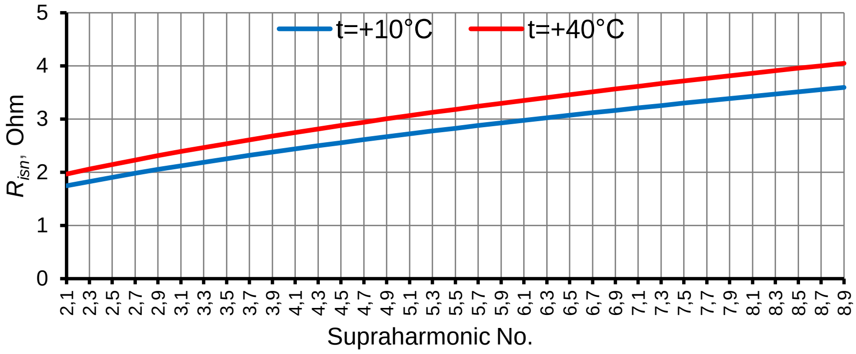

Fig. 7. Changes in the resistance of a single-phase wire.

ambient temperature changed from +10°C to +40°C, the resistance of the wire increased two-fold.

Table 1 shows the calculated additional power loss in three phases of the transmission line along with the maximum and average values of active power loss due to supraharmonics for one day. The additional loss of active power due to supraharmonics in phases A and C reach 0.0004% of the active power loss due to the 1st harmonic and 0.0079% in phase B. The loss is very little but the line is only 8 kilometers long. The 22 kV transmission lines in Quang Ninh Province, where the open-pit coal mine and coal screening plant are located, are 1 700 kilometers long. Their total additional loss due to supraharmonics for one day can amount to about 1 133 MW.

The results of calculations and analysis of harmonic active powers for the same 22 kV overhead transmission line feeding an open-pit coal mine and coal screening plant are presented in [37]. The value of harmonic active power for the operation time relative to the value of the first harmonic active power was 6.5%, for the period of routine break – 1.5%. The loss caused by supraharmonics relative to the loss due to harmonics was calculated to be about 0.001%. In [8], the authors believe that the correct estimation of the total active power loss in modern distribution networks that have electronic equipment requires considering the loss caused by supraharmonics.

Study [27] indicates that there is a continuous shift of the electrical equipment emissions from the common harmonic range below 2 kHz to the supraharmonic range above 2 kHz (up to 150 kHz). The shift is accompanied by interference (reversible faults) and hidden effects that come in the form of elevated voltages applied to shunt capacitors, which can be observed even at relatively low levels. The authors emphasize the necessity for a comprehensive system of standardization (the establishment of compatibility levels, emission limits, and interference immunity) – an area that requires further investigation.

V. CONCLUSION

Power quality problems call for a system of power quality management, including standards and technical

TABLE 1. Additional Loss of Active Power Due to Supraharmonics

t, °C	Parameter	Phase		
		A	B	C
+10	$P_{isn\,max}$, W	162.977	47.217	49.307
	$P_{isn\,avg}$, W	0.574	10.460	0.567
	$P_{isn\,\Sigma}$, W	49 803.020	907 442.978	49 176.590
	$P_{1\,max}$, W	276 275.875	270 414.518	275 944.305
	$P_{1\,avg}$, kW	1 366.286	132.476	135.279
	$P_{1\Sigma}$, MW	11 823.069	1 149.255	11 735.752
	$P_{isn\,\Sigma}/P_{1\Sigma}$, %	**0.0004**	**0.0079**	**0.0004**
+40	$P_{isn\,max}$, W	182.382	53.166	55.518
	$P_{isn\,avg}$, W	0.646	11.778	0.638
	$P_{isn\,\Sigma}$, kW	56.077	1 021.760	55.372
	$P_{1\,max}$, kW	311.080	304.481	310.707
	$P_{1\,avg}$, kW	153.455	149.165	152.321
	$P_{1\Sigma}$, MW	133 125.000	12 940.348	13 214.187
	$P_{isn\,\Sigma}/P_{1\Sigma}$, %	**0.0004**	**0.0079**	**0.0004**

documents concerning voltages and currents at interharmonics and supraharmonics.

In order to study the operating parameters in electrical networks at interharmonic and supraharmonic frequencies, it is necessary to develop special devices. Such devices are already used in various countries.

To estimate additional loss at harmonic, interharmonic, and supraharmonic frequencies, it is essential to develop specialized techniques. Electricity meters should be designed and installed at the consumer's end, including households, to measure the power flow direction at harmonic, interharmonic, and supraharmonic frequencies. This capability is essential to calculate the cost of electricity provided to the consumer.

Resolving the issue of non-sinusoidal conditions in power grids necessitates installing special devices in existing power systems at the request of non-distorting consumers. Their incorporation into power systems must be anticipated during the design phase.

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