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ИССЛЕДОВАНИЕ ПРОБЛЕМ СВЯЗАННЫХ С НЕСИНУСОИДАЛЬНЫМИ ФОРМАМИ НАПРЯЖЕНИЯ
INVESTIGATION OF PROBLEMS RELATED TO NON-SINUSOIDAL VOLTAGE WAVEFORMS

Аннотация: Данная статья рассматривает проблему влияния высших гармоник на качество электрической энергии. Несинусоидальные напряжения и токи с высокими гармониками ухудшают качество электроэнергии, что приводит к дополнительным потерям в двигателях, трансформаторах и других потребителях электроэнергии. Изучены процессы возникновения и снижения высших гармоник в системе электроснабжения металлургического предприятия. В исследовании использовалось программное обеспечение ETAP, на основе которого была создана математическая модель электроснабжения предприятия и проведён анализ процессов формирования гармоник. Улучшение качества электрической энергии достигалось за счет применения трансформаторов с раздельными обмотками, подключения потребителей к отдельным шинам и установки пассивных фильтров. Результаты показывают, что снижение коэффициента несинусоидальности 5-й гармоники существенно улучшает качество напряжения на шинах. Это, в свою очередь, увеличивает срок службы потребителей и снижает количество производственных сбоев. Практическая значимость исследования заключается в использовании его результатов для проектирования систем электроснабжения и снижения влияния высших гармоник.

Abstract: This article examines the issue of the impact of higher harmonics on the quality of electrical energy. Non-sinusoidal voltages and currents with higher harmonics degrade power quality, leading to additional losses in motors, transformers, and other electrical consumers. The study analyzes the processes of generation and mitigation of higher harmonics in the power supply system of a metallurgical enterprise. Using the ETAP software, a mathematical model of the enterprise's power supply was developed, and the formation processes of harmonics were studied. Improvements in power quality were achieved through the application of split-winding transformers, connecting consumers to separate buses, and installing passive filters. The results show that reducing the non-sinusoidal coefficient of the 5th harmonic significantly improves bus voltage quality. This enhancement extends the lifespan of consumers and reduces production disruptions. The practical significance of the study lies in its applicability to the design of power supply systems and the mitigation of higher harmonic effects.

Ключевые слова: Качество электрической энергии, высшие гармоники, несинусоидальное напряжение, Программное обеспечение ETAP, металлургическое предприятие, пассивные фильтры, трансформаторы с раздельными обмотками, потери мощности, система электроснабжения, коэффициент несинусоидальности.

Keywords: Power quality, higher harmonics, non-sinusoidal voltage, ETAP software, metallurgical enterprise, passive filters, split-winding transformers, power losses, power supply system, non-sinusoidal coefficient.

Introduction

The quality of electrical energy is crucial for the efficiency and reliability of power systems, especially in industries like metallurgy. Non-sinusoidal voltage and current waveforms caused by higher harmonics can lead to operational issues such as increased power losses, equipment overheating, and insulation degradation. These harmonics are mainly generated by non-linear loads like frequency converters, welding equipment, and large motors, which distort the normal voltage and current waveforms. This study uses ETAP software to model the internal power supply system of a metallurgical plant, investigate the impact of higher harmonics, and explore solutions like passive filters, split-winding transformers, and load distribution to mitigate their effects and improve system efficiency.

Methods

In this study, the power quality of a metallurgical plant was analyzed using ETAP software to model the plant's electrical network. The focus was on identifying and quantifying higher harmonics in the voltage waveforms [1]. To mitigate the impact of these harmonics, several strategies were applied, including the use of split-winding transformers to isolate non-linear loads, and passive harmonic filters to reduce the levels of specific harmonics, particularly the 5th harmonic. Additionally, harmonic-producing consumers, such as frequency converters and welding equipment, were separated onto dedicated buses to prevent them from affecting other loads. The effectiveness of these strategies was evaluated by comparing the voltage quality before and after their implementation [2-5].

Results

The calculations were carried out using the ETAP software package, a model of the internal power supply of a metallurgical plant was developed, the processes of formation and change of harmonics on the buses of the power supply system of a metallurgical plant were studied, there are in particular the 5th, 7th, 11th, 13th, 17th, 19th, 23rd and 25th harmonics in the voltage waveform. Figure 1 shows scheme of the internal power supply of a metallurgical plant.

When analyzing the voltage waveform on the Bus2 buses, it can be seen that it differs from a sinusoid and contains higher harmonics, in particular, the 5th, 7th, 11th, 13th, 17th, 19th and 23rd orders. The diagram of the higher harmonics and the voltage waveform are shown in Figure 2. The calculation results for levels 1, 2, 3 and 4 of the indicated power supply scheme obtained using the ETAP software are shown in Table 1.

It can be seen from this table that the coefficient non-sinusoidal factor of the 5th harmonic on the buses of level 2 (Bus2) is 7.757%, which is 5% higher than the norm adopted in GOST 32144-2013 for the current power quality.

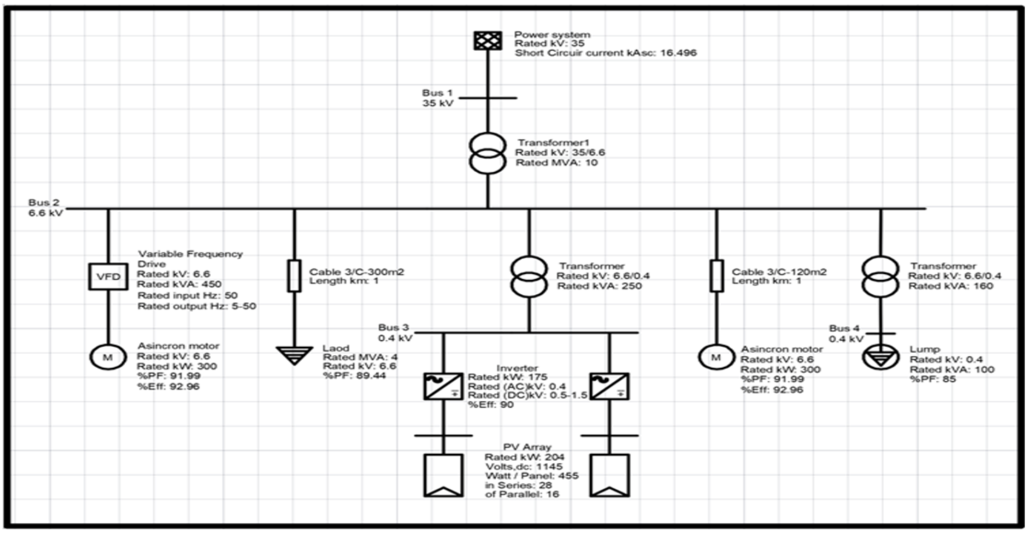

Fig. 1. Scheme of the internal power supply of a metallurgical plant

Table 1

Report									
№	Busbars	Parameters	250Hz (5)	350Hz (7)	550Hz (11)	650Hz (13)	850Hz (17)	950Hz (19)	1150Hz (23)
1	Bus1	Un (V)	290	134	108	50	67	44	48
		Kn (%)	0.828	0.382	0.308	0.142	0.191	0.125	0.137
2	Bus2	Un (V)	512	237	193	90	121	80	88

		Kn (%)	7.757	3.590	2.924	1.363	1.833	1.21	1.33
3	Bus3	Un (V)	29	13	11	5	7	5	5
		Kn (%)	7.25	3.25	2.75	1.25	1.75	1.25	1.25
4	Bus4	Un (V)	29	13	9	4	4	3	2
		Kn (%)	7.25	3.25	2.25	1	1	0.75	0.5

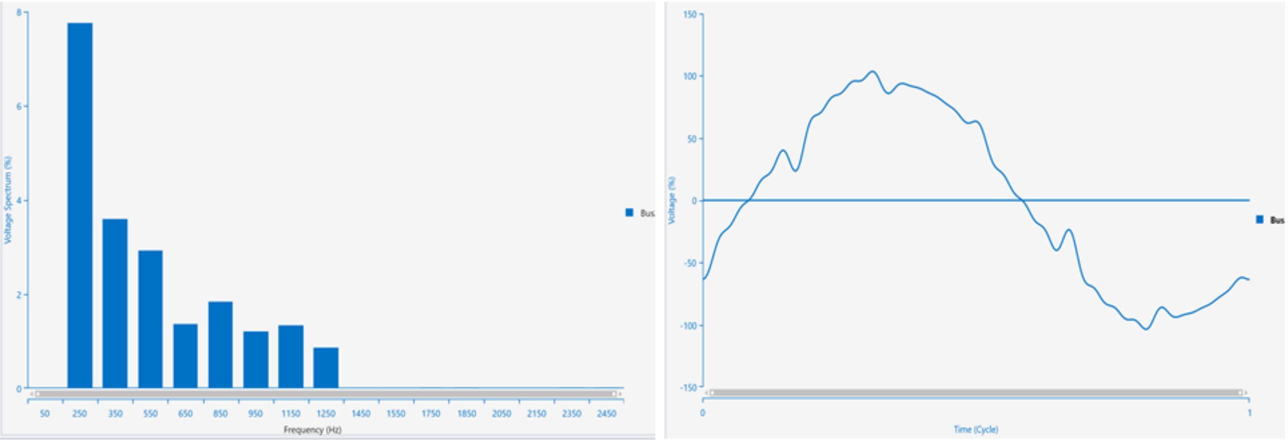
Fig. 2. Harmonic diagram and voltage waveform on bus2

In the power supply system, VFDs and LOAD consumers generate higher harmonic currents, affecting voltage quality. VFDs, used for motor speed regulation, create various harmonic orders, while LOAD consumers, such as low-power converters and arc ovens, impact power quality, causing equipment overheating, reduced lifespan, and increased disruptions. Solar panels connected to Bus3 can also disconnect if voltage quality exceeds norms, disrupting synchronization. To mitigate these effects, devices generating harmonics should be connected to separate buses through split-winding transformers and reactors. Replacing standard transformers with split-winding ones and isolating high harmonic consumers can reduce their negative impact on voltage quality (Figure 3).

The results of the study show that such a separation of consumers leads to an improvement in the quality of the bus voltage. the non-sinusoidal voltage coefficients on both buses are reduced. Forms of voltages and diagrams of higher harmonics are shown in Figure 4. Table 2 shows the results of calculating the parameters for levels 1, 2, 3 and 4 of the power supply circuit.

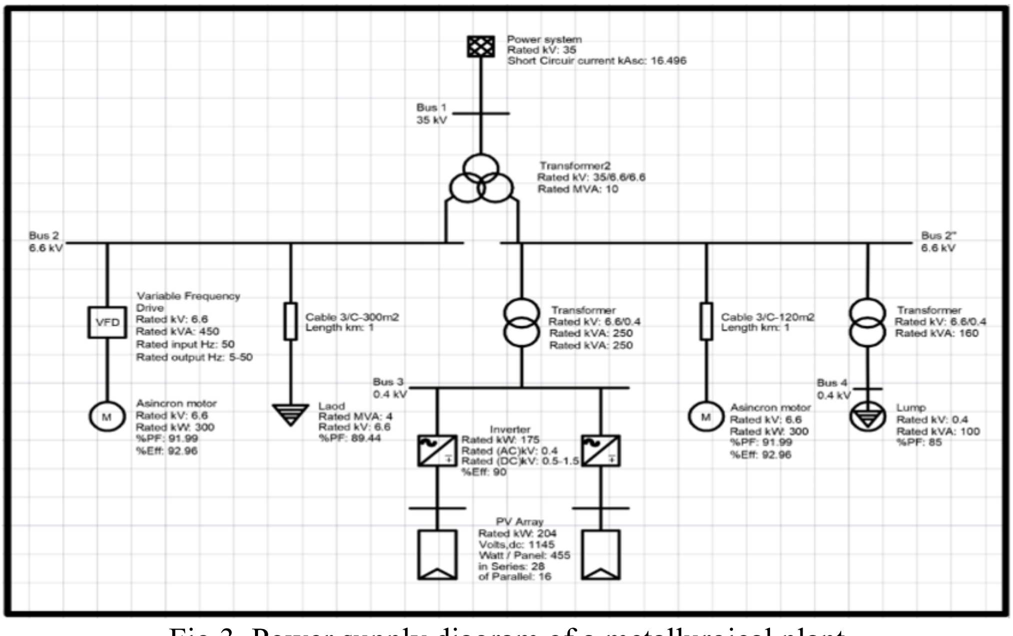

Fig.3. Power supply diagram of a metallurgical plant
after replacing the power transformer

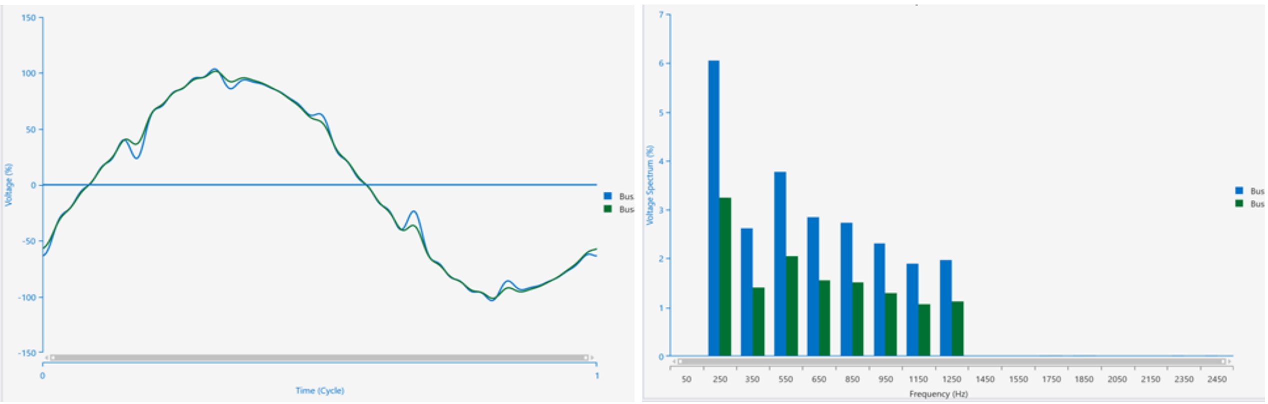

Fig. 4. Voltage waveform and harmonic diagram for bus2 and Bus2',
(the blue lines in the figures belong to Bus2 buses, and the green ones to Bus2')

Table 2

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№	Busbars	Parameters	250Hz (5)	350Hz (7)	550Hz (11)	650Hz (13)	850Hz (17)	950Hz (19)	1150Hz (23)
1	Bus1	Un (V)	191	82	117	88	83	69	55
		Kn (%)	2.893	1.242	1.772	1.333	1.257	1.045	0.833
2	Bus2	Un (V)	399	173	249	188	180	152	125
		Kn (%)	6.04	2.621	3.772	2.848	2.727	2.303	1.893
3	Bus2"	Un (V)	214	93	135	102	100	85	71
		Kn (%)	3.242	1.409	2.045	1.545	1.515	1.287	1.075
4	Bus3	Un (V)	12	5	8	6	6	5	4
		Kn (%)	3	1.25	2	1.5	1.5	1.25	1
5	Bus4	Un (V)	12	5	6	4	4	3	2
		Kn (%)	3	1.25	1.5	1	1	0.75	0.5

The voltage waveform differs from a sinusoid, with blue indicating the voltage of buses connected to consumers generating higher harmonics and green representing the voltage of consumers with minimal impact on electricity quality. The waveforms are similar in shape, but the higher harmonic coefficients in the green waveform are smaller, making it closer to a sinusoid. Results show a decrease in the 5th harmonic voltage ratio on Bus2 from 7.76% to 3.242%, and on Bus3 and Bus4 from 7.25% to 3%. This improves power supply quality and increases the service life of non-harmonic generating consumers. Power quality was assessed using ETAP software, with Figure 5 showing the plant model and higher harmonic currents.

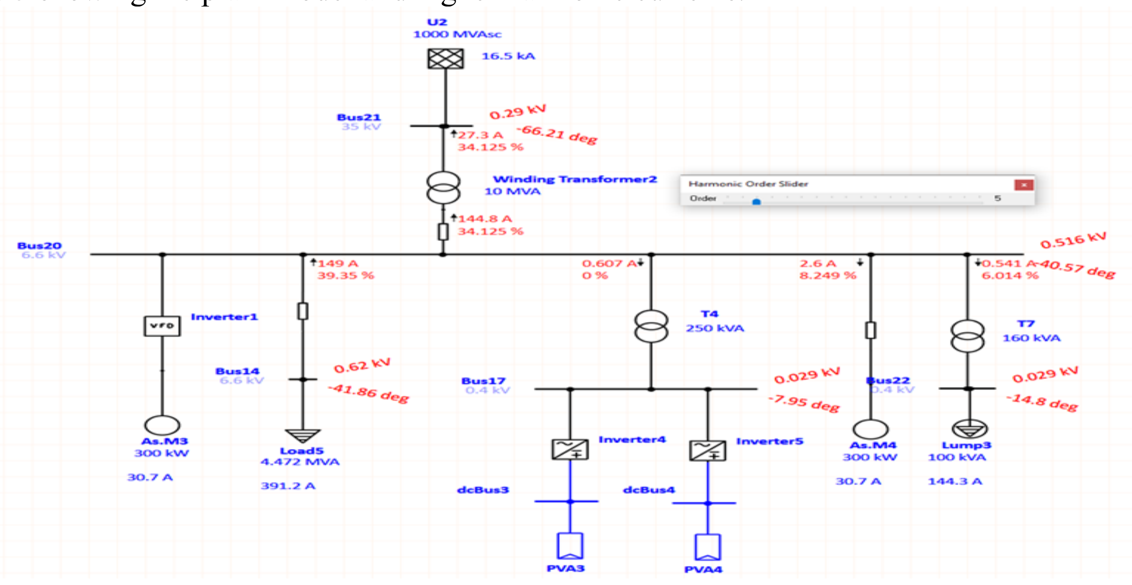

Fig. 5. Power supply diagram of a metallurgical plant showing
5th harmonic currents prior to filter installation

It can be seen from the figure that due to the fact that in the system among the consumers of the plant there are loads that create currents of higher harmonics (VFD and Load 5) and currents of the 5th harmonic flow through other consumers.

These currents lead to the appearance of the 5th harmonic voltage on the main bus. The results show that the 5th harmonic ratio of the main bus voltage is 7.75%.

In the ‘Harmonic Filter Editor’ interface, by navigating to the ‘Size Filter’ section, you can select the ‘Harmonic Filter Sizing’ option. In the Harmonic Order section, the value -5 is entered, and in the Harmonic Current section, the current is set to 144.8 A. In the Power Factor Correction section, the existing power factor of 89% is entered before the filter installation, with the desired power factor set to 95%, which should be achieved after the filter is installed. After inputting these parameters, clicking the "Size Filter" and "Replace" buttons allows the system to automatically calculate the required filter parameters according to the scheme.

After installing the filter, you can conduct a harmonic study in the program.

Table 3

Report									
№	Busbars	Parameters	250Hz (5)	350Hz (7)	550Hz (11)	650Hz (13)	850Hz (17)	950Hz (19)	1150Hz (23)
1	Bus1	Un (V)	138	106	94	45	61	40	44
		Kn (%)	0.394	0.302	0.268	0.128	0.174	0.11	0.125
2	Bus2	Un (V)	245	189	169	81	111	74	83
		Kn (%)	3.71	2.86	2.56	1.227	1.681	1.121	1.257
3	Bus3	Un (V)	14	11	10	5	6	4	5
		Kn (%)	3.5	2.75	2.5	1.25	1.5	1	1.25
4	Bus4	Un (V)	14	10	8	3	4	2	2
		Kn (%)	3.5	2.5	2	0.75	1	0.5	0.5

As you can see from the figure above, after installing the filter, the value of the non-sinusoidal factor of the 5th harmonic of the voltage on the main bus decreased from 7.75% to 3.71%, and the 5th harmonic current flowing from the bus to the system decreased from 144.8A to 71.9A.

It should be noted that it is interesting to study the dynamics of changes in higher harmonics when switching consumers and when transferring power, which can be carried out using conventional and contactless switching devices [6-10].

Discussion

The results of this study highlight the significant impact that higher harmonics can have on power quality in industrial systems, particularly in metallurgical plants. Harmonics, especially the 5th and 7th orders, were found to distort the voltage waveforms, leading to additional losses in electrical components such as transformers, motors, and cables. These distortions not only cause operational inefficiencies but also shorten the lifespan of equipment and increase maintenance costs.

By modeling the power supply system using ETAP software, it was possible to identify the specific points where harmonic distortions were most pronounced. The use of split-winding transformers and passive harmonic filters proved effective in reducing the magnitude of these higher harmonics. Isolating non-linear loads, such as frequency converters and welding equipment, onto dedicated buses minimized their impact on other consumers, thus improving overall voltage quality.

The implementation of a split-winding transformer resulted in a significant reduction in the 5th harmonic, with a decrease in the non-sinusoidal factor from 7.75% to 3.71%. This improvement indicates that carefully designing the electrical system and employing appropriate mitigation techniques can significantly enhance power quality, making it more reliable and efficient for industrial consumers.

Overall, the findings suggest that by addressing the issue of harmonic distortion through system design adjustments and the use of filters and transformers, metallurgical plants can reduce energy losses, improve equipment lifespan, and enhance operational efficiency. Further research could explore the long-term effects of these mitigation measures and their scalability to other industrial sectors.

Conclusion

This study demonstrates the significant impact of higher harmonics on the power quality in metallurgical plants, where non-sinusoidal voltage waveforms can lead to increased losses, equipment damage, and reduced operational efficiency. The analysis showed that higher harmonics, particularly the 5th and 7th orders, distort the voltage and cause additional strain on electrical components.

The implementation of mitigation techniques such as split-winding transformers and passive harmonic filters effectively reduced harmonic distortion, particularly the 5th harmonic, thereby improving the quality of the electrical supply. Separating non-linear consumers, such as frequency converters and welding equipment, onto dedicated buses further minimized their impact on the overall power system.

The results highlight the importance of considering harmonic mitigation strategies when designing industrial power supply systems. Proper system design, coupled with appropriate filtering and load separation, can significantly improve power quality, reduce energy losses, and extend the lifespan of electrical equipment. This approach can be applied not only to metallurgical plants but also to other industries where harmonic distortion is a concern.

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