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In Memoriam Professor Emeritus Mircea-Grigore EREMIA

ENSURING RELIABLE REFRIGERATION THROUGH POWER QUALITY MONITORING. A CASE STUDY

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Keywords: Power quality monitoring; Industrial freezing facility; Power quality indicators; Power flow analysis.

This paper presents a comprehensive assessment of power quality in an industrial refrigeration and freezing facility based on a continuous monitoring campaign, analyzing voltage, current, harmonic distortion, voltage unbalance, flicker severity, power flow characteristics, and load behavior in order to evaluate the influence of electrical supply conditions on the operational reliability, energy performance, and stability of refrigeration equipment under real operating conditions. The results demonstrate that all monitored power quality indicators remained within the limits prescribed by applicable standards, confirming the suitability of continuous power quality monitoring as an effective tool for ensuring reliable and uninterrupted operation of industrial refrigeration systems.

1. INTRODUCTION

Power quality has become increasingly important due to the extensive use of power electronic devices and nonlinear loads, as well as the growing demand for reliable electricity supply. Its evaluation is based on a set of quantitative indices describing voltage and current characteristics, which support regulatory compliance and the assessment of network performance [1]. Power quality disturbances can be divided into quasi-stationary phenomena, such as voltage fluctuations, frequency deviations, and harmonic distortion, and events, including voltage sags, swells, interruptions, and transient overvoltages.

The assessment process relies on the acquisition and analysis of voltage and current waveforms, from which key parameters such as RMS values, frequency, and harmonic content are determined according to standardized procedures [1,2]. Long-term evaluation is typically performed using statistical indicators that characterize the frequency and severity of disturbances. Despite significant advances in monitoring technologies and standards, further research is required to improve the understanding of the spatial and temporal behavior of power quality indices and to enhance the accuracy of assessment methods [1,2].

2. ELEMENTS OF POWER QUALITY MONITORING AND MEASUREMENT

Continuous power quality monitoring provides valuable information not only for assessing voltage and current performance at the customer interface, but also for evaluating the operational behavior of electrical networks. The collected data can be used to analyze voltage disturbances, identify the root causes of system events, characterize the electromagnetic environment experienced by end-user equipment, and support investigations of major network incidents, including large-scale outages.

A comprehensive power quality monitoring framework encompasses the entire process from the acquisition, sampling, and digitization of voltage and current signals to the extraction of electrical parameters, event detection, statistical post-processing, and display of performance indicators, thereby enabling a detailed assessment of power system behavior and reliability (Fig.1). The processing of power quality data differs substantially for continuous variations and discrete events.

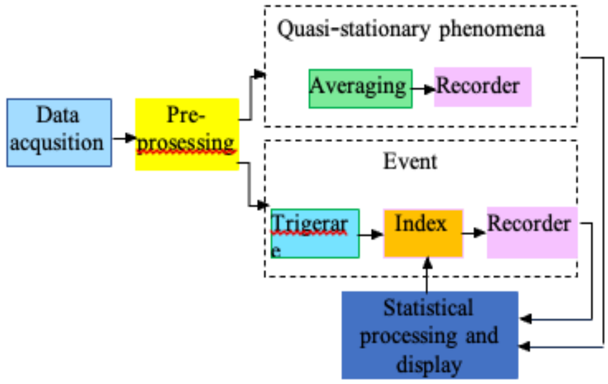

Fig. 1 – General architecture of a power quality monitoring system: calculated electrical parameters and indices extracted from the measured data for subsequent power quality analysis and assessment [1].

For steady-state variations, parameters such as RMS voltage, frequency, and harmonic spectra are calculated over predefined aggregation intervals specified by standards (IEC 61000-4-30) and subsequently subjected to statistical analysis to derive representative local and system-wide performance indices. In contrast, event processing relies on threshold-detection mechanisms to identify abnormal operating conditions, such as voltage sags, swells, and interruptions. Once an event is detected, its key characteristics, including duration and magnitude, are determined and recorded for further evaluation. Long-term assessment relies on statistical indicators describing event occurrence rates and distribution patterns, thereby providing a comprehensive characterization of network performance and supporting reliability and disturbance analyses.

2.1 POWER QUALITY INDEX AND ASSESSMENT METHODOLOGIES

Power quality assessment plays an essential role in the operation of modern electrical networks. The widespread integration of power electronic equipment, renewable energy sources, and nonlinear loads has increased the need for accurate monitoring and evaluation of voltage and current disturbances.

Power quality is described through a set of indices derived from measured electrical data. These indices are based on characteristics such as frequency, voltage magnitude, harmonic distortion, voltage unbalance, and flicker. In many cases, several parameters are combined into a single index, such as Total Harmonic Distortion (THD), to provide a representative evaluation of network performance.

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Since electrical systems are influenced by continuously changing operating conditions, power quality indices exhibit a stochastic nature. For this reason, their assessment relies on statistical methods, including mean values, standard deviations, and percentile-based indicators. International standards commonly use the 95th percentile as a reference criterion for long-term performance evaluation.

The assessment process starts with the acquisition and processing of sampled voltage and current signals. The resulting parameters are aggregated over predefined time intervals and statistically analyzed to obtain local indicators for individual monitoring points.

The most widely used power quality indices include frequency deviation, voltage deviation, harmonic distortion indices, voltage unbalance factors, and flicker severity indices. Together, these metrics provide a comprehensive description of network performance and support the reliable operation, planning, and management of modern power systems.

3. CASE STUDY: POWER QUALITY ASSESSMENT OF AN INDUSTRIAL FREEZING FACILITY

The analyzed facility consists of an industrial refrigeration and freezing system designed to ensure the long-term preservation of food products under strictly controlled temperature conditions. Reliable operation of key components, including refrigeration compressors, ventilation equipment, circulation pumps, and automated control systems, is crucial for maintaining the required thermal environment and safeguarding product quality. Since refrigeration processes are highly dependent on a stable electrical supply, power quality disturbances such as voltage variations, harmonic distortion, or supply interruptions may adversely affect cooling performance and system reliability.

Table 1

Technical data sheet of condensing unit.

Parameter		Unit	Value
Cooling capacity	min. (-35°C vap. temp.)	kW	31.9
	max. (+5°C vap. temp.)		121.9
Power consumption	min. (-35°C vap. temp.)	kW	17.74
	max. (+5°C vap. temp.)		31.30
	Evaporation temperature	°C	-35...+5
Compressor	reciprocating semi-hermetic		6FE-50Y
	cylinders x bore x stroke		6 x 82 x 55
	piston. displacement (50Hz)	m^3/h	151.6
	max. power consumption	kW	51.0
	max. running current	A	96.2
	rotation speed	rad/s (rot/min)	151.8 1450
	Power supply	Ph./Hz/V	3/50/400
	Refrigerant		R404A

These aspects become particularly critical during periods of elevated ambient temperatures, when refrigeration demand increases significantly, and any electrical disturbance may cause temperature deviations in storage chambers, leading to potential product deterioration and economic losses [1,7].

The analysis was performed on an ARKTON AA-BK-R140/6FE-50Y condensing unit, which serves a food refrigeration room, with the technical data sheet presented in Table 1. The design is based on a well-known and proven technology, enabling high efficiency in a compact refrigeration unit. The air-cooled condenser, equipped with variable-speed axial fans, offers very high heat transfer efficiency. The unit is designed for outdoor installation and contains the compressor and condenser. The evaporator together with the expansion valve is mounted inside the refrigeration chamber. The measurements were performed under a load regime close to the nominal one, at a temperature inside the refrigerating room (cold source – *CS*) of -10 °C and an ambient temperature (hot source – *HS*) of +30 °C. The refrigeration circuit is shown in Figure 3, with the values of the main parameters recorded for a regime achieved during testing. The thermodynamic cycle for this regime is shown in Figure 4, and the state parameters at the characteristic points of the cycle are given in Table 2.

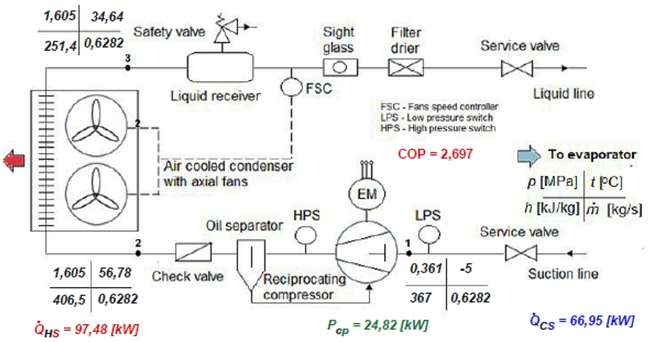

Fig. 3 – Refrigerating circuit.

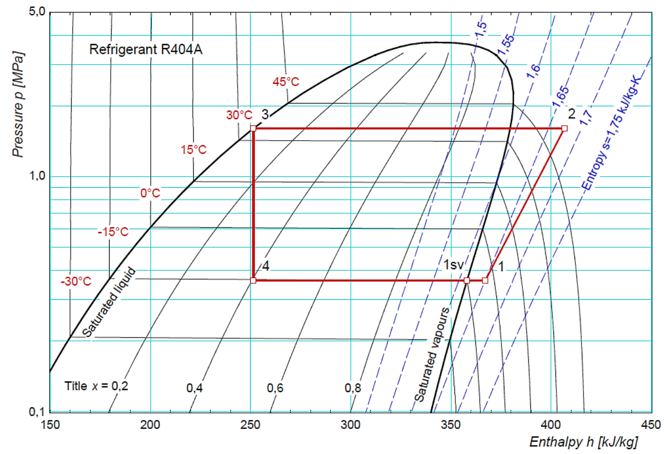

Fig. 4 – Thermodynamic cycle.

Table 2

The state parameters at the points of the cycle.

Point	Pressure *p* [MPa]	Temperature T [°C]	Enthalpy *h* [kJ/kg]	Entropy *s* [kJ/kgK]	Title *x*
1	0.361	-5	367.0	1.650	-
2	1.605	56.8	406.5	1.674	-
3	1.605	34.6	251.4	1.174	0
4	0.361	-15	251.4	1.202	0.405
1sv	0.361	-15	357.9	1.616	1

The electrical power consumed by the compressor is a function of the agent flow rate and the compression ratio corresponding to the evaporation and condensation temperatures. The Bitzer reciprocating compressor 6FE-50Y has a fixed rotation speed and a piston displacement independent of evaporating temperature. Figure 5 shows the dependence of power consumption and cycle efficiency on temperature inside the refrigerating room. To evaluate the electrical operating conditions of the installation, a power quality monitoring campaign was conducted at the main low-voltage distribution board that supplies the refrigeration equipment. Measurements were performed with electrical parameters recorded every 10 minutes [1, 2].

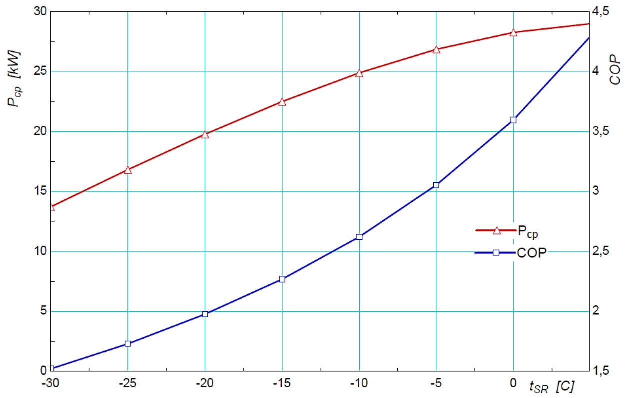

Fig. 5 – The dependence of power consumption and cycle efficiency on temperature inside the refrigerating room.

Power quality indices exhibit significant stochastic variability due to the continuous fluctuations of load demand, distributed generation, and network operating conditions; therefore, their assessment commonly relies on probabilistic approaches and statistical models based on probability density functions, cumulative distributions, confidence intervals, and percentile-based indicators. Advanced mathematical techniques, including time-series analysis, stochastic processes, regression methods, and machine learning algorithms, are increasingly employed to characterize the temporal behavior of power quality disturbances, predict future trends, and improve the accuracy of network performance evaluation [1,2].

Since the disturbances that can affect the quasi-steady state of the power supply are the frequency deviations Δf, voltage deviations ΔU, level of asymmetry $K_{n,}$ voltage harmonic distortion level *THDU,* and level of voltage fluctuations K_{st} for the initial assessment of the overall quality level k_{cal} the equation is proposed

$$k_{cal} = k_f \cdot \Delta f + k_u \cdot \Delta U + k_n \cdot K_n + k_a \cdot THDU + \\ + k_{st} \cdot K_{st}, \qquad (1)$$

in which the factors affecting the quality index were evaluated for the analyzed user, based on the damages that could arise from deviations from the standardized quality index.

$k_f = 0.01$ (the probability of the frequency falling outside the specified limits is very low);

$k_u = 0.5$ for $U > U_r$+10% (power surges can lead to equipment damage);

$k_u = 0.6$ for $U < U_r$–10% (voltage drops can lead to reduced performance or even the disconnection of equipment)

$k_n = 0.3$ for $K_n > 2\%$ şi $U > U_r$+10% (asymmetry can lead to the mechanical overloading of asynchronous electric motors)

$k_n = 0.2$ for the asymmetry/skewness indicator $K_n > 2\%$ and $U < U_r$–10% (low voltage and asymmetry can affect the performance of asynchronous machines)

$k_a = 0.1$ for $THDU > 8\%$ (distorted operating conditions can lead to transformer overheating and a reduction in service life)

$k_{st} = 0.09$ for the short-term flicker indicator $K_{st} > 0.8$.

Of course, the sum of the factors affecting the quality indicators is equal to one

$$k_f + k_U + k_n + k_a + k_{fl} = 1. \qquad (2)$$

The values of the factors affecting quality indicators are specific to each user and must be estimated by the auditor specialists.

3.1 VOLTAGE QUALITY ASSESSMENT

The voltage quality assessment revealed that both phase-to-neutral and line-to-line voltages remained stable throughout the monitoring period, with recorded values consistently meeting the requirements specified in EN 50160 for low-voltage distribution networks [3].

The recorded data showed that during the measurements, the supply voltage frequency remained practically constant at 50 Hz. In relation (1) for evaluating electric power quality, it can be assumed that $k_f = 0$.

Figure 6 shows the voltage variation in the user's low-voltage network. The recorded data demonstrate that the voltage remained within the prescribed limits throughout the measurement period U_r±10% (207-253 V) where U_r =230 V is the standardized voltage in the low-voltage network, with an average value U_{med}= 232 V (Fig. 6). In relation (1) for evaluating electric power quality, it can be assumed that $k_u = 0$.

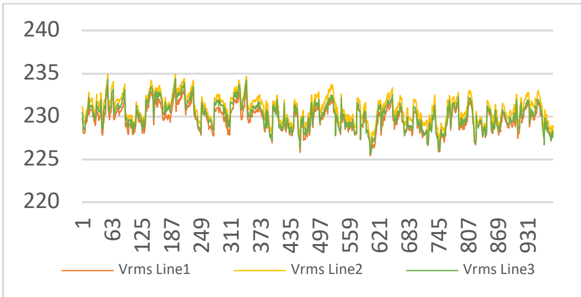

Fig. 6 – Voltage profiles at the TGD supply busbars phase-to-neutral voltage [V].

Furthermore, the total harmonic distortion of voltage (THDU) remained relatively low, varying between 1.8% and 7.5%, well below the recommended threshold of 8%.

Since the THDU distortion level remains within the limits imposed by current standards for distribution systems, with an average value of 4% (Fig. 7) [3], in eq. (1) it can be assumed that $k_a = 0$.

The voltage unbalance factor also remained significantly lower than the admissible limit of 2%, indicating a balanced three-phase supply system. In addition, the measured flicker indices were maintained within acceptable ranges, demonstrating that voltage fluctuations did not adversely affect the operation and reliability of the refrigeration process [1,3].

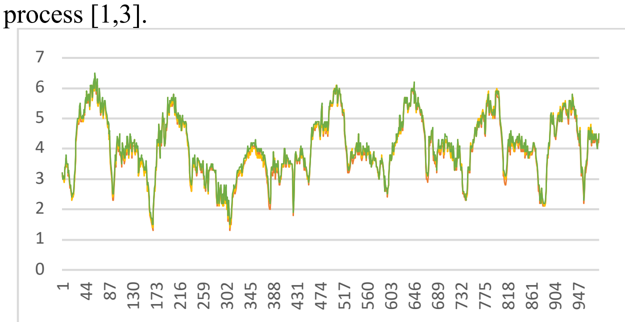

Fig. 7 – Monitored voltage total harmonic distortion (THD-U) for phases A, B, and C [%].

The distortion of the voltage waveforms is primarily due to the 5th and 7th harmonics (indicated in Figure 8 in yellow and blue, respectively), which commonly appear in low-voltage networks with AC-DC converters.

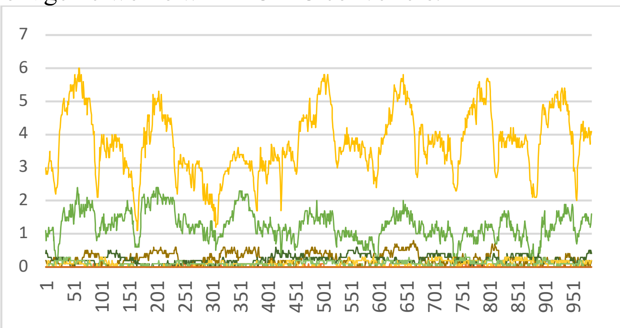

Fig. 8 – Voltage harmonic spectrum measured at the TGD supply busbars; the harmonic characteristics observed on phases 1, 2, and 3 exhibit similar behaviors

The level of supply voltage unbalance remains below the 2% limit accepted by current standards throughout the recording period (Fig. 9) [3], which leads to the value $k_n = 0$.

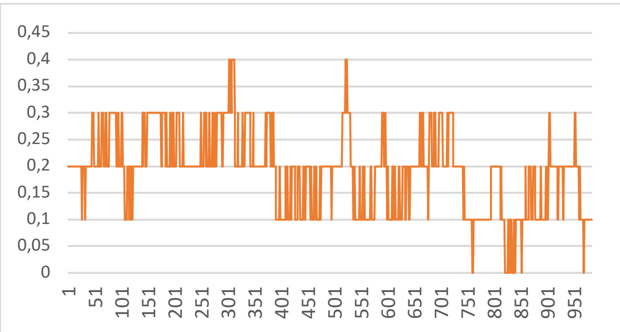

Fig. 9 – Negative-sequence voltage unbalance factor (k_s) measured at the TGD supply busbars [%].

The measurements performed to analyze voltage fluctuations (Fig. 10) revealed that the short–term flicker indicator K_{st} remains below the 0.8 threshold accepted by current standards [3] throughout the monitoring period; the factor can be considered $K_{st} = 0$.

The determined values of the factors defining the quality level of the electricity supplied to the user allow for the assessment of the factor $k_{cal} = 0$ and the assessment of the fact that the electricity supplied during the user monitoring period is of a quality within the limits accepted by the regulations in force [4]

As shown in Figs. 6–10, the monitored voltage parameters indicate stable operating conditions at the TGD supply busbars. The recorded voltages remained within acceptable limits, while voltage harmonic distortion, unbalance, and fluctuation levels were low, confirming satisfactory power quality and balanced network operation throughout the monitoring period [1,3].

The analysis of the power quality supplied to the user was conducted based on the indicator values accepted by the distribution system operator. In some cases, the user may specify different values in their own electrical installations that correspond to the operating conditions required for their equipment.

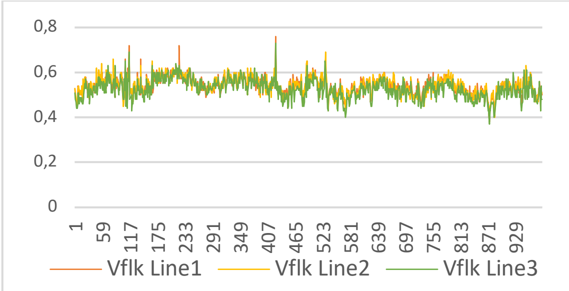

Fig. 10 – Variation of voltage fluctuation levels recorded at the TGD supply busbars [%].

3.2 CURRENT QUALITY ANALYSIS

To identify the causes affecting the quality of the electric power at the user's supply busbars, the characteristics of the electric current were also monitored.

The current measurements revealed a relatively uniform distribution of electrical loading across the three phases, indicating satisfactory operating conditions of the monitored installation (Fig.11).

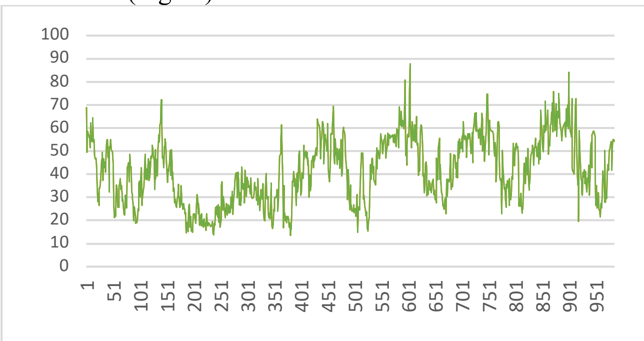

Fig. 11 – Load current profiles measured at the TGD supply busbars [A].

Although the harmonic content of the electric currents across the three phases is not regulated by standards, it significantly affects voltage distortion at the supply busbar and the enterprise's energy efficiency, due to increased power losses in lines and equipment.

Although the current harmonic distortion was higher than the corresponding voltage distortion, this behavior is commonly encountered in industrial facilities equipped with motor drives, compressors, and electronic control devices [1,3]. Despite the presence of harmonic components, the current waveforms remained sufficiently close to sinusoidal conditions, confirming the proper operation of the electrical system (Fig.12).

Furthermore, the current unbalance factor remained within acceptable limits throughout the monitoring period, with the observed asymmetry primarily attributable to minor voltage unbalances recorded at the supply point [1,4].

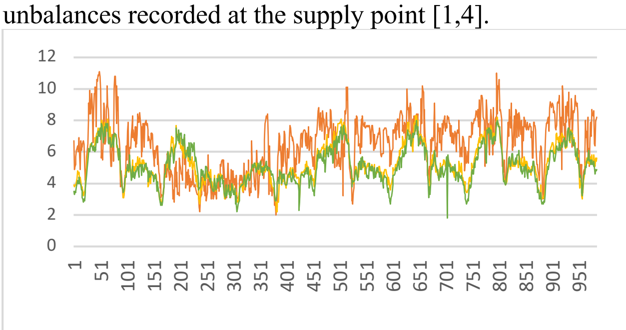

Fig. 12 – Monitored current total harmonic distortion (THD-I) for supply phases A, B, and C [%].

Figure 13 presents the evolution of the negative sequence current unbalance factor measured at the TGD supply busbars. The results indicate a balanced distribution of electrical loading among the three phases, moderate harmonic distortion associated with the operation of non-linear refrigeration equipment, and low current unbalance levels, confirming stable operating conditions and satisfactory power quality performance of the monitored installation.

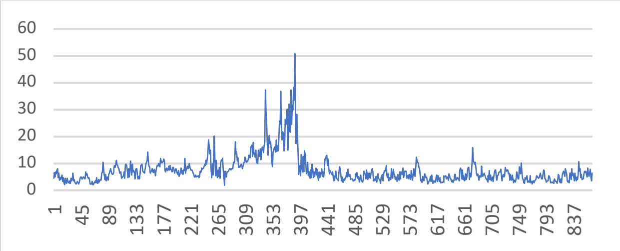

Fig. 13 – Variation of the negative-sequence current unbalance factor (k_s) at the TGD supply busbars [%].

3.3 LOAD AND POWER FLOW ANALYSIS

The observed active, reactive, and apparent power fluctuations are directly related to compressor loading cycles and refrigeration demand. The recorded values indicate stable operating conditions without abnormal loading events.

The transformer operated significantly below its rated capacity during the monitoring period, ensuring sufficient reserve capacity for peak cooling demands during warm weather conditions. The recorded power factor values indicate the presence of reactive power circulation associated with the inductive nature of compressor motors and refrigeration equipment [2].

The analysis of power flow parameters provides valuable information regarding the electrical loading conditions of the refrigeration facility and the operating behaviors of the supplied equipment. As shown in Fig. 14 – 16, the variations of active and reactive power reflect the cyclic operation of refrigeration compressors and auxiliary systems, with the recorded fluctuations corresponding to changes in cooling demand during the monitoring period [4, 7]. The absence of abrupt power variations or abnormal peaks indicates stable operating conditions and a properly dimensioned electrical infrastructure [1,5].

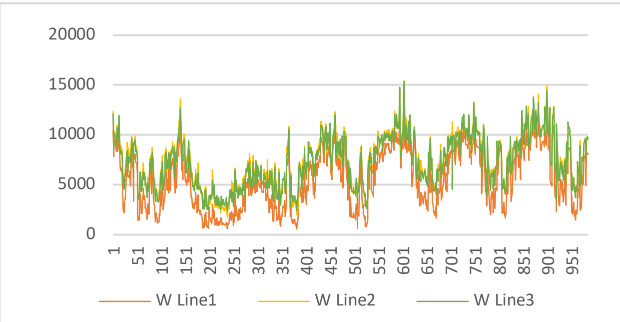

Fig. 14. Active power (P) variation at the medium-voltage busbars supplying the TGD [W].

Further insight into the loading characteristics is provided by the apparent power profiles shown in Fig. 17. The results demonstrate a balanced distribution of apparent power among the phases and confirm that the overall loading level remained well within the supply system's available capacity. The observed behaviors highlight the electrical installation's ability to accommodate variations in refrigeration demand without approaching critical loading conditions [1,5].

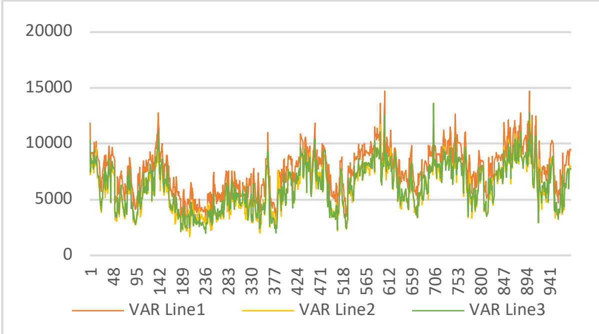

Fig. 15 – Reactive power (Q) variation at the medium-voltage busbars supplying the TGD [VAr].

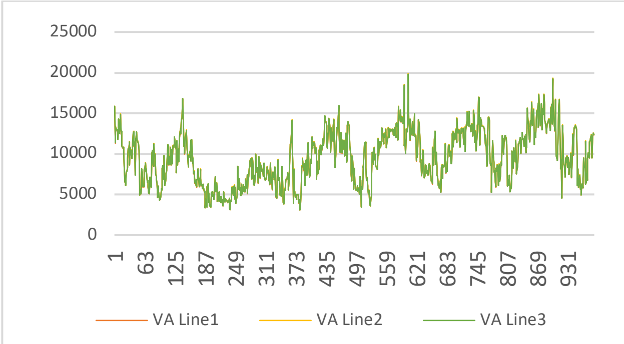

Fig. 16 – Single-phase apparent power flows through the TGD installation (S) [VA].

Monitoring the power factor in the circuit supplied by the transformer substation (Fig. 18) allows for an initial assessment of the efficiency of purchased energy usage.

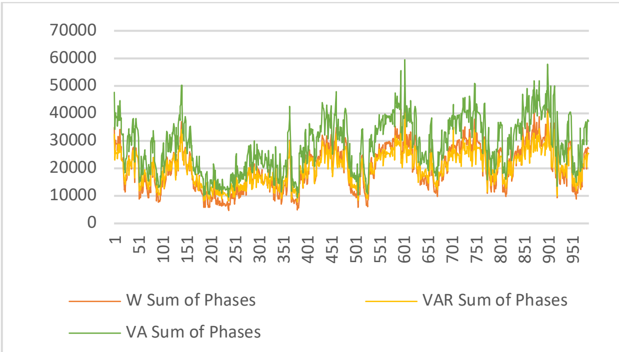

Fig. 17 – Three-phase apparent power transferred through the TGD installation.

The evolution of the power factor, illustrated in Fig. 18, reveals the influence of the predominantly inductive nature of refrigeration compressors, motors, and auxiliary equipment [1,4]. The data shown in Figure 18 indicate that, on the first phase, the power factor undergoes cyclic variations within a range that can cause significant losses in the power supply system. It is therefore necessary to connect an active power filter to this phase to ensure real-time power factor correction to a value of 0.9.

On phases 2 and 3, the power factor remains practically constant but at an average value of approximately 0.8, suggesting the need to improve it by installing capacitors on these two phases [1,6].

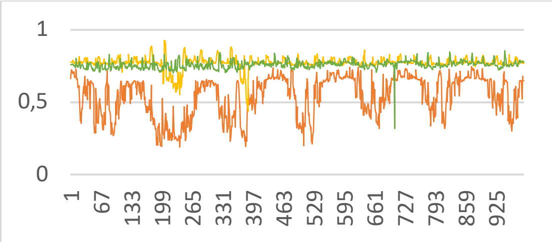

Fig. 18 – Power factor variation at the TGD supply busbars for phases A, B, and C.

3.4 HARMONIC ANALYSIS OF THE ELECTRIC CURRENT CURVES

The harmonic spectra of current were characterized by the predominance of the fifth harmonic component, whereas the higher-order harmonics exhibited comparatively low amplitudes. The observed distortion levels were primarily generated by refrigeration compressors and associated non-linear electrical equipment, yet remained within acceptable operational limits, indicating that no dedicated harmonic filtering solutions are currently required.

Figure 19 presents the current harmonic spectra measured at the TGD supply busbars [1,2]. The results indicate a similar harmonic distribution on all three phases, with low-order harmonics being predominant and higher-order components exhibiting considerably lower amplitudes [1,7]. The observed harmonic behavior reflects the balanced operation of the installation and confirms that harmonic distortion levels remain within acceptable limits for satisfactory power quality [1,6].

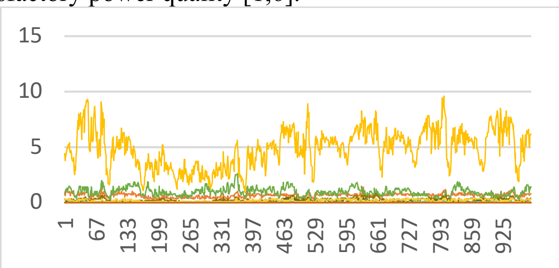

Fig. 19 – Current harmonic spectrum measured at the TGD supply busbars; comparable harmonic characteristics were recorded on phases 1, 2, and 3.

The results from the monitoring campaign indicate that the electrical supply system of the industrial freezing facility maintains adequate power quality, with voltage levels, harmonic distortion, flicker indices, and voltage unbalance consistently within the recommended operational limits [1,3]. These favorable electrical conditions contribute to the reliable performance of refrigeration compressors and control equipment, minimizing the likelihood of operational disturbances, cooling capacity degradation, or unintended shutdowns. As a result, the refrigeration process can be maintained under stable conditions, reducing the risk of temperature deviations and preserving the quality of stored food products, particularly during periods of elevated cooling demand. Therefore, continuous power quality assessment represents an effective strategy for enhancing the operational reliability, energy performance, and long-term security of industrial refrigeration systems [1,8].

4. CONCLUSIONS

The results of the power quality monitoring campaign confirmed that the electrical supply system of the investigated industrial freezing facility operated in compliance with the applicable standards, with voltage magnitude, harmonic distortion, flicker severity, and voltage unbalance remaining within acceptable limits. Furthermore, the analysis of current, power flow, and harmonic characteristics demonstrated the stable operation of refrigeration compressors and auxiliary equipment, indicating that the existing electrical infrastructure provides adequate conditions for the reliable, efficient, and uninterrupted operation of the refrigeration process.

The total quality factor proposed in this paper can serve as an initial tool for assessing quality; however, the constituent parameters in relationship (1) must be determined for each user based on the specifics of the production process and the process equipment.

The obtained results highlight the importance of continuous power quality assessment as a preventive tool for industrial refrigeration applications, contributing to improved operational reliability, reduced risk of temperature deviations, and enhanced protection of stored food products, particularly during periods of increased cooling demand.

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The academic and engineering communities honor the memory of Professor Emeritus Dr. Eng. Mircea Eremia, a distinguished educator, researcher, and leading figure in Romanian Power Engineering. His outstanding contributions to higher education, scientific knowledge, and professional development have left an enduring mark whose influence will remain an integral part of his legacy.

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REFERENCES

1. M. Eremia (Ed.), *Electric Power Systems. Electric Networks, AGIR Publishing House* (in Romanian), Technical Publishing House, Bucharest, (2002).
2. A. Hermina et al., *Power Quality. Contributions. Results, Perspectives* (in Romanian), AGIR Publishing House, Bucharest, (2013).
3. ****Voltage characteristics of electricity supplied to public distribution systems*, EN 50160:2023, (2023).
4. C. Săvescu, A. M. Morega, M. Roman, C. Nechifor, "Experimentally validated studies of thermoelectric generators installed on a compressor test bench", Rev. Roum. Sci. Techn. – Électrotechn. Et Énerg., **70**, *2*, pp. 193–198 (2025).
5. Y. Djeghader, C. Bousnoubra, S. Allele, "Mitigation of power quality problems in steel plants using static synchronous compensator", Rev. Roum. Sci. Techn. – Électrotechn. Et Énerg., **69**, *3*, pp. 293–297 (2024).
6. V. Ștefănescu, F. I. Hathazi, G. Rață, C. Ungureanu, "Technical losses caused by poor power quality in electrical networks with nonlinear consumers", Rev. Roum. Sci. Techn. – Électrotechn. Et Énerg., **70**, *3*, pp. 337–342 (2025).
7. L. C. Lipan, S. Dimitriu, "The cooling process modeling of a bar with variable properties in relation to temperature", University Politehnica of Bucharest Scientific Bulletin Series C – Electrical Engineering and Computer Science, **81**, *1*, pp. 261–270 (2019).
8. R. Elumalai, R. Varadhan, "Power quality evolution for wind energy conversion systems using embedded Z–source inverter and permanent magnet synchronous generator", Rev. Roum. Sci. Techn. – Électrotechn. Et Énerg., **70**, *4*, pp. 459–464 (2025).