KSÜ Mühendislik Bilimleri Dergisi, 29(3), 2026
Araştırma Makalesi

KSU J Eng Sci, 29(3), 2023
Research Article

Kahramanmaras Sutcu Imam University
Journal of Engineering Sciences

Geliş Tarihi : 15.12.2025
Kabul Tarihi : 12.08.2026

Received Date : 15.12.2025
Accepted Date : 12.08.2026

POWER QUALITY CHALLENGES IN THE METAL INDUSTRY: AN IEEE AND IEC STANDARDS-BASED CASE STUDY

METAL ENDÜSTRİSİNDEKİ GÜÇ KALİTESİ SORUNLARI: IEEE VE IEC STANDARTLARINA DAYALI BİR VAKA ÇALIŞMASI

Ahmet NUR[1*] (ORCID: 0009-0006-5671-6923)

[1] Bitlis Eren Üniversitesi, Elektrik Elektronik Mühendisliği Bölümü, Bitlis, Türkiye

*Corresponding Author: Ahmet NUR, anur@beu.edu.tr

ABSTRACT

The rapid evolution of the types of loads used in electric power systems has made the concept of power quality a critical area of study. The use of nonlinear loads, semiconductor-based devices, renewable energy sources, and power electronics-based converters in modern power systems has led to power quality issues—such as harmonic distortion, voltage fluctuations, sudden voltage changes, frequency deviations, and imbalances—taking on a more complex nature. In this context, power quality is of strategic importance not only for the reliable operation of electronic devices but also in terms of grid integrity, energy efficiency, and system reliability. In this study, harmonic measurement data collected at a metal industry facility housing various industrial load groups were comprehensively evaluated within the framework of IEEE and IEC power quality standards. Data obtained from eighteen different measurement points were analyzed in terms of total current harmonic distortion (ITHD), total voltage harmonic distortion (UTHD), power factor, and the distribution of individual harmonic components. The study provides a comprehensive reference for industrial power quality assessment by integrating a comparative analysis of the IEEE and IEC standards ecosystems with real-world field data.

Keywords: Harmonic limits, power quality standards, IEEE, IEC, metal industry

ÖZET

Elektrik güç sistemlerinde kullanılan yük tiplerinin hızla değişmesi güç kalitesi kavramını kritik bir çalışma alanı hâline getirmiştir. Modern güç sistemlerinde doğrusal olmayan yüklerin, yarı iletken tabanlı cihazların, yenilenebilir enerji kaynaklarının ve güç elektroniği tabanlı dönüştürücülerin kullanılması, harmonik distorsiyonlar, gerilim dalgalanmaları, ani gerilim değişimleri, frekans sapmaları ve dengesizlikler gibi güç kalitesi sorunlarının daha karmaşık bir yapıya bürünmesine neden olmuştur. Bu bağlamda güç kalitesi, yalnızca elektronik cihazların güvenilir çalışması için değil, aynı zamanda şebekenin bütünlüğü, enerji verimliliği ve sistem güvenilirliği açısından da stratejik öneme sahiptir. Bu çalışmada, birbirinden farklı endüstriyel yük gruplarını bünyesinde barındıran bir Metal Sanayi tesisinde gerçekleştirilen harmonik ölçüm verileri, IEEE ve IEC güç kalitesi standartları çerçevesinde kapsamlı biçimde değerlendirilmiştir. On sekiz farklı ölçüm noktasından elde edilen veriler, akım toplam harmonik distorsiyonu (ITHD), gerilim toplam harmonik distorsiyonu (UTHD), güç faktörü ve bireysel harmonik bileşen dağılımı açısından analiz edilmiştir. Çalışma, IEEE ve IEC standart ekosisteminin karşılaştırmalı analizini gerçek saha verileriyle bütünleştirerek endüstriyel güç kalitesi değerlendirmesine yönelik kapsamlı bir referans sunmaktadır.

Anahtar Kelimeler: Harmonik sınırlar, güç kalitesi standartları, IEEE, IEC, metal sanayi

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INTRODUCTION

The widespread and indispensable use of electrical energy in modern society has led to problems related to power quality becoming increasingly important in both academic circles and industrial applications. In the past, problems encountered in electrical power systems were mostly evaluated within a singular and limited framework, such as frequency or voltage deviations. However, the concept of power quality is now addressed as a comprehensive technical issue (Shi et al., 2024). The development of technological infrastructure, changes in load characteristics, and the increasing complexity of power systems have made it necessary to address power quality from a broader perspective. The evolution of electrical power systems has brought significant innovations not only in production technologies but also in distribution and consumption-side hardware, control mechanisms, and automation infrastructure. With the widespread use of non-linear semiconductor-based components, fast-switching power electronics elements, and sensitive automation devices, the impact of such equipment on the power system has increased significantly. Today, a significant portion of modern loads used in a wide range of applications, from industrial facilities to commercial buildings and residences, exhibit characteristics that generate harmonics or distort the voltage waveform. This leads to a deterioration in power quality, directly affecting the operational reliability of sensitive devices (Sepasi et al., 2023; Michalec et al., 2021). In recent years, the scope of scientific research in the field of power quality has expanded significantly, encompassing multidimensional research areas such as monitoring technologies, data communication, data processing techniques, fault classification, and event management. Power quality monitoring activities require not only the development of measurement devices but also the reliable transmission, storage, and analysis of measured data. In this context, the creation of information platforms, the improvement of data communication infrastructure, and the development of methods to increase data materiality have become important research topics in the literature. Matrix completion methods, which are used to reduce deficiencies in data transmission, offer effective solutions, particularly in completing interrupted data sets in online monitoring systems (Farzin et al., 2021; Liang & Andalib-Bin-Karim, 2018; Liu et al., 2016).

As outlined in Figure 1, the amount of published literature and citations associated with Power Quality was on a continuous upward trend during the years 2013 through 2024, according to the information collected from the Web of Science database. The total published output as recorded by this database was approximately 450 in 2013 and over 1,100 in 2021; thus, showing steady growth from 2013 through 2020. According to data collected between 2013 and 2024, the number of citations in the field of Power Quality, which stood at less than 1,000 at the end of 2013, reached approximately 22,000 by the end of 2021, and by the end of 2024, the total number of citations related to the Power Quality literature had exceeded 26,000 (Rasoulnia et al., 2026). The amount of growth seen in the total citations associated with Power Quality illustrates that as more literature has been published on Power Quality over time, more researchers have become aware of and have utilized the published research.

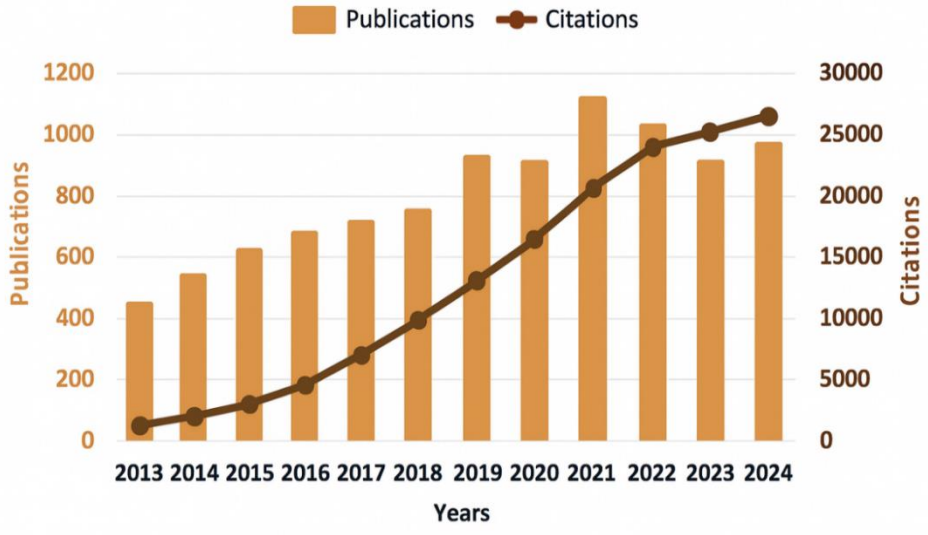

Figure 1. Graph Of Publication And Citation Counts Obtained From The Web of Science Database By Year (Rasoulnia et al., 2026)

Industrial organisations represent one of the primary areas in which power quality issues occur most intensely. The simultaneous operation of many different types of non-linear loads (including CNC machining centres, induction heat treaters, variable speed drives (VSDs), thermal processing equipment, and Light Emitting Diodes (LEDs)) within electrical distribution systems create complex harmonic interactions within those systems (Ashraf et al., 2021; de Oliveira et al., 2020). In this context, a metal industry can be considered a relevant and useful case study for analysing and improving power quality through the implementation of appropriate standards. This study presents a comprehensive power quality assessment of a metal industry based on field measurement data collected from 18 measurement points. The measured parameters — including ITHD, UTHD, individual harmonic orders (3rd through 21st), and power factor — are systematically evaluated against the limit values defined in IEEE 519-2022 and IEC 61000 series standards. The study thus integrates an up-to-date review of the global standards framework with a data-driven, real-world case study, contributing a novel and practically oriented perspective to the existing literature on industrial power quality (Jain et al., 2025; Ali et al., 2024).

POWER QUALITY DEVICES

In the past, the primary expectation of electricity consumers was "reliability," meaning the continuity of electricity supply. However, today, with the proliferation of power electronics-based devices and the increasing complexity of load characteristics, PQ monitoring has become a critical issue for the power industry in terms of protecting electronic and electrical equipment, determining the causes of failures, and maintaining energy continuity. Sensitive load groups such as air traffic control systems, life support and operating room systems in hospitals, sensitive database applications, textile, food, semiconductor processing plants, and bank security infrastructures require an uninterrupted and fault-free power supply. According to the European Power Quality Survey report, PQ-related problems cause approximately €150 billion in economic losses annually in the EU-25 countries. Therefore, even a small power quality disturbance must be detected quickly; accurate assessment of power quality extends equipment life and increases operational continuity (Jain et al., 2025). Power quality issues have emerged as a significant concern in energy systems due to their negative impact on the performance and reliability of electrical grids. These issues encompass various types of disturbances, including voltage dips and swells, short-term interruptions, harmonics, and flickers. Power quality standards serve as fundamental references for the safe, efficient, and reliable operation of electrical power systems and define acceptable limits for various PQ parameters. International standards organizations regularly update these standards to keep pace with technological developments and changing industrial requirements. Compliance with standards is mandatory for electrical utilities, manufacturers, and users to prevent equipment failures, guarantee power quality, and ensure compatibility between devices. Furthermore, standardization facilitates international trade and supports the development of innovative solutions in power system design (Arranz-Gimon et al., 2021; Li et al., 2021).

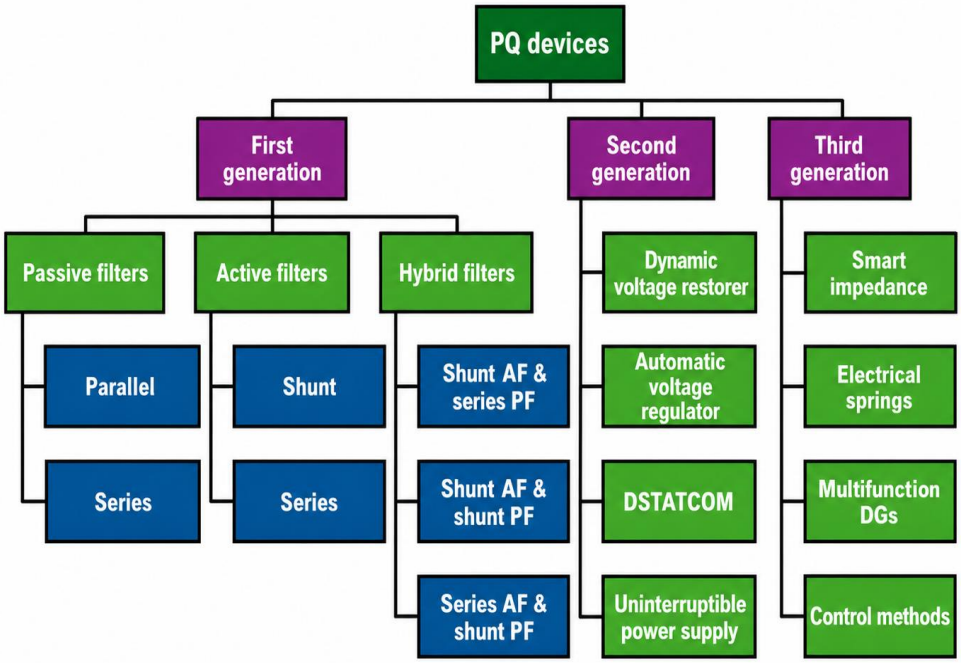

Figure 2. Types of Devices Used For Power Quality (Ali et al., 2024)

Figure 2 organizes the classification of PQ improvement devices developed to date into three distinct generations corresponding to their technological capabilities and usage. This classification operates as an indicator of the developments made in solving issues of PQ due to the ever-growing amount of non-linear loads, new power electronics equipment, and the growing use of renewable energy sources in electrical power systems (Buła et al., 2022; Khan et al., 2022).

The first generation of PQ devices deal primarily with issues of traditional power quality; they provide solutions to harmonic suppression and reactive power compensation. Those devices which fall under the Passive filter category are sometimes the simplest in structure and cost; Passive filter solutions can typically be configured to provide either tunable solutions (for specific harmonic frequencies) or fixed solutions (to mitigate or eliminate harmonic frequencies) using series or parallel filter configurations. Passive filters also have inherent limitations in the form of significant risk of resonance and little capability of adapting to changing load requirements (Bajaj & Singh, 2022; Shakeri et al., 2021). Active filters can be installed in either series or shunt configurations and provide dynamic compensation to eliminate harmonic currents or harmonic voltage distortion; thus, they generally will provide superior performance. Hybrid filters combine the advantages of passive and active filters, thereby providing a balanced solution from a cost and performance perspective (Gaiceanu et al., 2025; Melo et al., 2020).

The second generation of PQ devices consists of more extensive systems that provide better overall quality of voltage and power flow continuity to the user. To address this goal, two devices have been developed: Dynamic Voltage Regulators (DVR) and Automatic Voltage Regulators (AVR). Both devices respond quickly and effectively to voltage sags, voltage swells, and voltage imbalance conditions that are often encountered in a typical power system. DSTATCOMs improve the stability of distribution networks and provide reactive power control at the distribution level as well as voltage support at the distribution level. In contrast to DSTATCOMs, Uninterruptible Power Supplies (UPS) protect mission critical loads from short-term (momentary) and long-term (intermediate) interruptions. Both devices have power electronics based control structures with real-time measurement and rapid response capabilities and provide a more reliable and robust operation of the power system (Li et al., 2021).

The third generation of PQ devices offer a new, adaptive, multifunctional paradigm for PQ improvement. Smart impedances provide a mechanism for load-sided voltage regulation. Electric springs reduce the impact of fluctuations in the grid by providing a combined DSM or demand-side management option. Multifunctional distributed generation (DG) sources simultaneously conduct PQ functions, energy production, harmonic reduction or harmonic suppression, reactive power support, and voltage regulation. Advanced control methods and equipment available for this generation enable integration with advanced computer-based artificial intelligence, adaptive, and predictive control strategies while maximizing compatibility with the structural framework for smart grids (Khan et al., 2022; Shen et al., 2015).

MATERIALS AND METHODS

Power Quality Standards

The term Power Quality Disturbance (PQD) is used in the literature to describe any disruption occurring in the electrical grid. The increased use of switching elements, lighting control units, rectifiers and inverters, data processing devices, non-linear loads, and relaying equipment has led to a significant increase in PQ disturbances in modern power systems. Deviations of power quality parameters beyond acceptable limits lead to various problems such as voltage dips, flicker, voltage swells, transients, and harmonics, all of which negatively affect the quality of electrical energy. PQ disturbances are classified in the literature under three main categories: magnitude changes, steady-state harmonics, and transient events. Changes in voltage or current magnitude, such as interruptions, voltage surges, and dips, are frequently observed in real-time power systems as a result of power quality-related problems. Steady-state power quality disturbances include continuous deviations such as harmonics, notches, and flickers, and mostly arise from the use of power electronics converters and non-linear loads. Such PQ disturbances cause equipment failures and production losses, resulting in significant economic costs (Ali et al., 2024; Farzin et al., 2021). Power quality assessment heavily relies on technical standards to guide the development of science in this area. The technical standards as defined by global organisations like IEEE and IEC serve as a reference point for defining power quality parameters and how to measure, evaluate, and limit them. However, varying use and scope of standards around the world, within industry types, and even within particular applications of each standard make it difficult to conduct comparative analyses of power quality assessments across different countries, industries, and applications, and therefore require considerable time to collect literature reviews related to these types of standards. Although IEEE

standards are based on IEC standards, with many of the same basic concepts, they provide much more detail regarding how to implement and use these standards. Likewise, while IEC standards have established a general framework internationally for measuring power quality and defining allowable limits for those parameters, they are also developed to be used to support regional diversity and differences in technical requirements for energy companies, industrial users, and infrastructure providers (Shi et al., 2024; Arranz-Gimon et al., 2021).

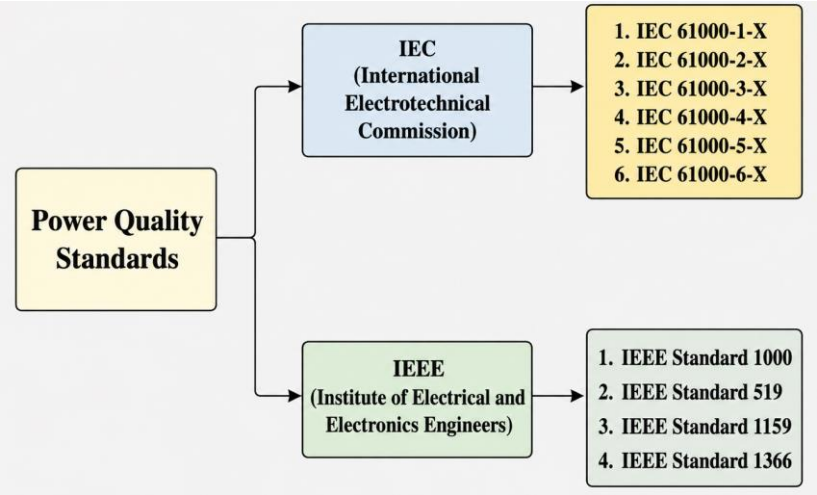

Figure 3. Power Quality Standards (Jain et al., 2025)

The global development of power quality standards has originated from two primary bodies representing different approaches, as depicted in Figure 3. IEC provides a wider-ranging set of technical rules that are accepted around the world, while IEEE emphasises more the operational processes, i.e., application, measurement, and harmonic control of power quality. Both of these paradigms provide an overall foundation for international harmonisation and the engineering practices employed in the power quality field. The International Electrotechnical Commission (IEC) published standards cover a large number of categories. These standards can be classified into six distinct category sections (IEC, 2002; IEC, 1992);

- IEC 61000–1-X: General provisions,
- IEC 61000–2-X: Environmental conditions,
- IEC 61000–3-X: Limit values,
- IEC 61000–4-X: Test and measurement techniques,
- IEC 61000–5-X: Installation and mitigation guidelines
- IEC 61000–6-X: General standard requirements.

The power quality standards published by the Institute of Electrical and Electronics Engineers (IEEE) are based on theoretical conceptual foundations; IEEE Std. 1100 (electronic power supply systems), IEEE Std. 519 (harmonic control), IEEE Std. 1159 (power quality monitoring), and IEEE Std. 1366 (reliability indices) are among the most frequently used standards (IEEE, 2012; IEEE, 1995; IEEE, 1992).

IEEE Standards

The standard development activities conducted by the IEEE are primarily coordinated by the Power Quality Subcommittee, which oversees various working groups and related technical activities concerning the monitoring and control of power quality. This subcommittee operates under the management structure of the Transmission and Distribution Committee, a unit of the IEEE Power and Energy Society (IEEE, 1992). In this context, the power quality standards developed by IEEE cover a wide range, including basic power quality indices, indices related to power quality equipment, economic evaluation criteria, and practical application principles. The general distribution of power quality standards created by IEEE is presented in Table 1 (Shi et al., 2024). The table shows that the standards developed by the Power Quality Subcommittee are classified into three main categories: fundamental standards, monitoring and transmission standards, and economic standards. Standards published by other IEEE subcommittees are also listed in the relevant sections of the table. Fundamental standards focus primarily on defining terms, establishing limit values, and evaluating power quality indices. In this context:

- Limit values for harmonics, measurement methods, and evaluation criteria are defined in detail (IEEE, 2022).
- Definitions of short-term and long-term indices for flicker have been established; procedures and limit values for evaluating flicker at the point of connection (PCC) in facilities supplied by fluctuating loads have been presented; technical recommendations for characterizing flicker levels have been developed (IEEE, 2022).
- Methods for quantifying single-event, field, and system performance indices have been defined (IEEE, 2014).
- Methods for determining power quality levels, evaluating power system performance factors, and improving power quality have been presented (IEEE, 2018).
- In addition, explanations regarding the structure and definitions of special power devices in distribution systems have been provided for the purpose of resolving power quality issues (IEEE, 2012).

The monitoring standards define the characteristic monitoring processes of AC power systems; they comprehensively address monitoring objectives, application techniques, and methods for interpreting the results related to power quality monitoring (IEEE, 2019). The transmission standard defines the PQDIF (Power Quality Data Interchange Format) file format, develops guidelines for data transfer, and aims to reduce transmission time (IEEE, 2019). The economic standards provide methods for evaluating economic losses incurred by sensitive consumers; this method has a multi-stage structure that includes data collection processes, the creation of performance indices, and the quantification of economic loss costs (IEEE, 2023). For the present study, IEEE 519-2022 serves as the primary reference standard for harmonic limit compliance assessment at the measurement point level.

Table 1. IEEE Power Quality Standards Classification

Category	Standard No.	Applicable Object / Scope
Basic	IEEE 519-2022	Harmonic control in electric power systems
	IEEE 1453-2022	Voltage fluctuations and light flicker measurement
	IEEE 1564-2014	Voltage sag indices and performance evaluation
	IEEE 1250-2018	Identifying and improving voltage quality
	IEEE 1409-2012	Power electronics application in distribution (1–38 kV)
Monitoring & Transmission	IEEE 1159-2019	Recommended practice for monitoring PQ
	IEEE 1159.3-2019	Power quality data interchange format (PQDIF)
Economic	IEEE 2938-2023	Economic loss evaluation for sensitive consumers
Other	IEEE 1100-2005	Powering and grounding sensitive electronic equipment
	IEEE 1459-2010	Measurement of electric power quantities
	IEEE 1668-2017	Voltage sag and short interruption testing for equipment

IEC Standards

Table 2 categorizes IEC power quality standards into the following categories: fundamental standards, assessment standards, distributed energy standards, management standards, and other standards (Shi et al., 2024). Fundamental standards focus primarily on defining basic indicators related to power quality:

- Voltage standards have been established for power source equipment, electrical appliances, electrical tools, batteries, and AC transmission, distribution, and utilization systems (IEC, 2021).
- Standards defining current values for electrical appliances have been developed (IEC, 2009).
- Frequency standardization has been carried out for single-phase and three-phase AC systems and other special systems such as ships, aircraft, and various industrial platforms (IEC, 2009).

- Planning principles and technical guidance have been provided to improve the interconnectivity of power systems, with the aim of increasing system reliability and reducing potential adverse effects (IEC, 2014).

Table 2. IEC Power Quality Standards — Part I: Core Standards

Category	Standard No.	Applicable Object / Scope
Basic	IEC 60038	Standard voltages for AC power supply systems
	IEC 60059	Standard current ratings for equipment
	IEC 60196	Standard frequencies for single- and three-phase AC systems
	IEC 62511	Guidelines for the design of interconnected power systems
Assessment	IEC 62749	Assessment of PQ at public network supply points
	IEC 63282	LVDC systems — voltage and PQ requirements
Distributed Energy	IEC 62786-1	Distributed energy resources — grid connection requirements
	IEC 62786-3	Battery energy storage systems — grid integration criteria
	IEC 62786-41	DER performance under steady-state and dynamic conditions
Management	IEC 63222-1	Power quality management — general guidelines
	IEC 63222-2	PQ monitoring system design and infrastructure
	IEC 63222-100	Impact of PQ disturbances on electrical equipment
Other	IEC 62559-2	Use case methodology for energy systems and smart grids
	IEC 63060	Maintenance of public network installations and equipment

Evaluation standards define the characteristics of power supply points (PCC) in electrical networks and outline power quality evaluation methods (IEC, 2020). Recommendations are also provided for measurement standardization regarding voltage levels, power quality parameters, EMC requirements, and LVDC systems (IEC, 2020). Three basic frameworks are presented to manage the effects of distributed energy resources on power systems:

- Technical requirements, control-monitoring methods, and test procedures for connecting distributed energy resources to the distribution grid have been determined (IEC, 2023a).
- Technical criteria and guidance are provided for Battery Energy Storage Systems integrated into the distribution network (IEC, 2023b).
- The performance levels of distributed energy systems under steady-state and dynamic conditions have been summarized; the parameters affecting this performance have been defined (IEC, 2023c).

Management standards address methods, technical applications, and monitoring requirements related to power quality management:

- Technical specifications for power quality management in public supply networks have been presented (IEC, 2021).
- Design procedures and technical criteria for power system monitoring infrastructure have been defined (IEC, 2023d).
- The effects of power quality disturbances on electrical equipment have been explained, contributing to an analytical understanding of power quality management (IEC, 2023e).

Other standards include:

- A standardized framework for use in system development processes for energy systems and smart grids has been presented (IEC, 2015).

- Technical guidelines have been developed for equipment maintenance requirements for public networks, including high-voltage DC transmission (IEC, 2019).

The standards in Table 3 are classified as renewable energy, inverter dynamic characteristics, microgrids, virtual power plants, and other standards. These standards reflect the evolving landscape of power quality governance in the context of increasing penetration of power electronics-based generation and grid-interactive distributed resources (Sepasi et al., 2023; Liang & Andalib-Bin-Karim, 2018).

Table 3. IEC Power Quality Standards — Part II: Renewable Energy, Inverter, Microgrid, and VPP Standards

Category	Standard No.	Applicable Object / Scope
Renewable Energy	IEC 62934	Grid integration of renewable energy — terms and definitions
	IEC 63043	Renewable energy power forecasting technology
	IEC 63102	Grid code compliance assessment for wind and PV plants
Inverter Dynamic Characteristics	IEC 63401-1	Inverter-based resources — AC grid interconnection (low SCR)
	IEC 63401-2	Sub- and super-synchronous control interactions
	IEC 63401-3	Fast frequency response and frequency ride-through
	IEC 63401-4	IBR behavior in response to bulk grid faults
Microgrid	IEC 62898-1	Microgrid planning and specification guidelines
	IEC 62898-2	Microgrid operation guidelines
	IEC 62898-3-1	Microgrid protection and dynamic control requirements
	IEC 62898-3-3	Self-regulation of dispatchable loads in microgrids
	IEC 62898-3-4	Microgrid monitoring and control systems
	IEC 62898-4	Microgrid use cases and commercial applications
Virtual Power Plants	IEC 63189-1	VPP architecture, functional requirements, and operation
	IEC 63189-2	VPP use cases — energy storage, DG, controllable loads
Other	IEC 63410	Decentralized electrical energy systems roadmap
	IEC 63384-1	Power system stability control — framework design guideline

Renewable Energy Standards:

• Definitions and terminology related to grid-connected renewable energy generation have been established, power quality issues caused by renewable energy sources have been addressed (IEC, 2021a).
• Data requirements, estimation methods, and error evaluation criteria for photovoltaic and wind energy have been defined, and technical recommendations have been provided (IEC, 2020).
• Methods have been developed to evaluate grid connection compatibility by standardizing the power quality behavior of wind and PV power plants (IEC, 2021b).

Inverter Dynamic Characteristics Standards:

• A technological and standardization framework has been established for the connection of inverter-based generation sources to the AC grid (IEC, 2022a).
• Control interactions in converter-interfaced generators have been defined (IEC, 2022b).

• A comprehensive theoretical basis has been provided on frequency transition techniques and fast frequency response regarding the behavior of inverter-based generation sources in large power systems (IEC, 2023a).
• The fault behavior and fault current requirements of inverter-based sources have been defined in grid codes (IEC, 2022c).

Microgrid Standards:

• Guidance has been provided for the planning and technical specifications of microgrids in AC electrical systems (IEC, 2023b).
• Guidelines have been presented for the control, operating modes, monitoring methods, energy storage integration, protection principles, and maintenance–testing processes of microgrids (IEC, 2023c).
• Dynamic control and protection requirements to support stable operation of microgrids under fault conditions have been defined (IEC, 2023d).
• Focus has been placed on improving voltage and frequency stability in microgrids through the use of dispatchable loads, and self-regulating load behaviors such as synthetic inertia have been explained (IEC, 2023e).
• Architectural, functional, and performance requirements for microgrid monitoring and control systems have been standardized (IEC, 2023f).
• Definitions for commercial applications of microgrids have been established, and example development systems have been presented (IEC, 2023g).

Virtual Power Plant (VPP) Standards:

• VPP terminology and operational requirements have been defined, and application scenarios, roles, and procedures involving energy storage, distributed generation, and controllable loads have been described (IEC, 2023h; IEC, 2023i).

Other Standards:

• A method for classifying decentralized electricity systems has been provided, and deficiencies in existing standards have been identified (IEC, 2023j).
• A design framework for power system control failure management has been presented, along with technical guidance on its impact on power system security and stability (IEC, 2023k).

FINDINGS

Facility Description and Load Profile

Metal industry engages in metal processing/manufacturing and includes a fabrication/machining/heat treatment operation for structural steel. The electrical distribution infrastructure consists of a wide variety of non-linear and linear loads that simultaneously run on a highly heterogeneous load profile. The diversity of electrical loads presents an excellent opportunity to conduct a real-world multi-point power quality assessment in accordance with international standards.

The facility operates the following major load categories: (1) CNC Machining Centers (CNC.1, CNC.2, CNC.3) — each fed through 30 kVA isolation transformers (3×380/200 V), incorporating variable-frequency drives for spindle and axis control; (2) FICEP Structural Steel Processing Machines — four units (FICEP.3, FICEP.6, FICEP.10, FICEP.11) ranging from 26 kW to 58 kW, used for drilling, milling, and cutting operations on structural steel profiles; (3) Induction Heating System (INDUCTION.500) — a 50 kW resonant induction heater used for metal hardening and heat treatment processes; (4) Resistive Thermal Treatment Units (RETERM LSP27 and RETERM.200) — high-power thermal processing systems at 600 kW/960 A and 200 kW, respectively, operating across a wide frequency range (590–9500 Hz); (5) Spindle Drive Systems (SP58C1 and SP58C2) — 100 kW/250 A variable-speed spindle motor drives; (6) WORTMAN Drive Systems (V505 and V630M) — 112 kW/160 A and 45 kW/100 A variable-speed drives for heavy machining operations; and (7) LED Projector Lighting Systems — distributed across three hall sections, representing the facility's general lighting infrastructure.

Measurement Results

In accordance with IEC 61000-4-7 (2014), the Power Quality Parameters were measured at 18 different locations throughout the facility's electrical distribution system. For each location, the following key measurements were taken:

3-Phase Active Power (P1, P2, P3 in Watts); Reactive Power (Q1, Q2, Q3 in VARs), Apparent Power (S1, S2, S3 in VA); RMS Current (I1rms, I2rms, I3rms in Amperes); RMS Voltage at all 3 Phases (U1rms, U2rms, U3rms in Volts); Line Voltages (U12, U23, U13 in Volts); Neutral Current (Inull in Amperes); Individual Harmonics from the 3rd through the 21st order expressed as a percentage of the Fundamental; True Power Factor (PF); Displacement Power Factor (DPF); Total Equivalent Current Harmonic Distortion (ITHD %); Total Voltage Equivalent Harmonic Distortion (UTHD %).

All measurements were conducted using an IEC 61000-4-30 Class A 3-Phase Power Quality Analyzer adhering to IEC 61000-4-30 Edition 3 requirements. Table 4 summarizes all of the important power quality parameters which were measured at each of the eighteen measurement locations in the facility. The parameters measured include the ITHD for the three phases, UTHD, total power factor, the dominant harmonic components (3rd, 5th, 7th, and 11th), as well as the active power. The information in Table 4 will help to provide a complete overview of the harmonic environment for the various load types present in the facility.

Table 4. Power Quality Measurement Results of The Metal Industry

Measurement Point	P1 (kW)	ITHD1 (%)	ITHD2 (%)	ITHD3 (%)	UTHD1 (%)	PF (tot)	H3 (%)	H5 (%)	H7 (%)
LED Projector Hall-1 (1.1)	0.33	12.44	—	—	2.47	0.955	9	8	4
LED Projector Hall-2 (2.1)	0.21	15.06	—	—	2.64	0.807	9	4	7
LED Projector Hall-2 (2.2)	0.28	15.66	—	—	2.53	0.885	6	5	6
LED Projector Hall-3 (3.1)	0.14	12.89	—	—	2.36	0.888	4	6	6
CNC.1–30 kVA (3×380/200 V)	2.80	23.72	51.03	48.41	5.49	0.784	11	12	2
CNC.2–30 kVA (3×380/200 V)	0.42	22.55	54.29	50.12	6.47	0.779	13	5	6
CNC.3–30 kVA (3×380/200 V)	0.63	29.38	50.31	46.30	4.25	0.791	10	21	7
FICEP.3 (LAB.3)–40 kW/160 A	0.60	17.15	14.72	15.17	3.21	0.568	3	14	8
FICEP.6–30 kW/100 A	0.10	4.53	4.69	4.06	3.35	0.583	0	5	0
FICEP.10–58 kW/125 A	0.51	38.59	31.53	33.79	2.75	0.815	6	26	14
FICEP.11–26 kW/106 A	0.07	11.89	10.96	10.41	2.99	0.489	0	10	6
INDUCTION.500–50 kW	37.36	84.21	96.65	94.69	0.00	0.725	7	66	46
RETERM LSP27–600 kW/960 A	2.57	28.03	27.67	27.82	5.62	0.652	2	27	6
RETERM.200–200 kW	0.96	28.21	28.94	28.96	2.32	0.796	0	26	7
SP58C1–100 kW/250 A	0.28	35.99	45.22	37.23	4.85	0.826	12	38	18
SP58C2–100 kW/250 A	0.42	22.12	38.52	34.11	4.24	0.636	11	12	14
WORTMAN (V505)–112 kW/160 A	0.36	129.88	67.62	13.02	3.78	0.388	80	14	22
WORTMAN (V630M)–45 kW/100 A	0.25	53.49	50.71	37.81	3.72	0.847	10	37	30

Note: H3, H5, H7 = 3rd, 5th, and 7th harmonic current components as percentage of fundamental (Phase 1). ITHD2 and ITHD3 denote Phase 2 and Phase 3 current THD, respectively. "—" denotes single-phase measurement points. P1: Phase 1 active power. PF (tot): Total power factor averaged across phases. IEEE 519-2022 indicative ITHD threshold: 5% (for preliminary load-point assessment).

Harmonic Distortion Analysis

The findings in Table 4 show the power quality measurement results of the metal industry. The overall means for all 18 points were 32.5% for ITHD1, with a standard deviation of 30.51%. This shows the relatively high total distortion across all measurement points and also indicates a wide degree of variability across different types of loads. The mean value for UTHD1 (3.51%) is significantly lower than ITHD1. Thus, although the ITHD values are quite distorted, the corresponding UTHD values indicate that for individual points (voltage), the voltage distortion associated with that much more severe current distortion at that point is generally acceptable. The ITHD1 value of the induction heating system (INDUCTION.500, 50 kW) is 84.21%. The 5th harmonic reached 66% of the fundamental current, and the 7th harmonic reached 46% of the same. The high ITHD value and this pattern are characteristics of the rectifying inverter topology normally used in induction heating frequency converters. Typically, six-pulse rectification produces dominant 5th and 7th order harmonics. The ITHD2 value of 96.65% and ITHD3 value of 94.69% confirm the significant injection of harmonics at this measurement point; UTHD1 was 0.00%, which indicates that this particular measurement was performed on a dedicated supply circuit where voltage distortion had not yet propagated upstream.

The WORTMAN V505 (112 kW/160 A) had a very high ITHD1 of 129.88% and included an extremely high 3rd harmonic component of 80%. This value is the highest third harmonic component measured across all points. This particular pattern is not found in standard three-phase six-pulse drives, which normally have very low triplen harmonic contributions. A third harmonic component at such a high value suggests other types of problems, including asymmetric phase loading, single-phase input operation, or a malfunction of the rectifier system during the measurement. The total power factor (0.388) is very low and indicates a severe reactive power burden on the distribution network, with the potential for transformer overloading. CNC machines have been installed with isolation transformers, but their ITHD1 values ranged from 22.5% to 29.4%. Their respective ITHD2 and ITHD3 values (46%–54%) were significantly higher than that of ITHD1. This indicates very high phase asymmetry in the injection of current harmonics. This asymmetry can result from the interaction of the leakage inductance of the isolation transformers with the non-linear load of the CNC drive. The 5th harmonic is dominant in CNC.3 (21%), which again confirms six-pulse rectifier behavior. The FICEP structural machines show a broad variation within the FICEP measurements: FICEP.10 had ITHD1 = 38.59%, with a dominant 5th harmonic (26%) and also had a significant 7th harmonic (14%), while FICEP.6 had the only measurement point of less than ITHD1 = 4.53%, which is consistent with the limit recommended in IEEE 519-2022. For LED lighting systems, measurements were conducted for all three sections in the hall. ITHD1 values for LED systems ranged from 12.4% to 15.7%, with relatively balanced contributions from the 3rd and 5th orders. These values exceed the 5% indicative level but are less than the levels measured for the power electronics intensive machine loads. The 3rd harmonic contribution (4%–9%) in LED systems is indicative of switch mode power supply drivers, which inject triplen harmonics into the neutral conductor in three-phase applications. Table 5 shows the statistical summary of key power quality parameters of the metal industry.

Table 5. Statistical Summary of Key Power Quality Parameters of The Metal Industry

Parameter	Minimum	Maximum	Mean	Std. Dev.	Median
ITHD1 (%)	4.53	129.88	32.54	30.48	22.34
ITHD2 (%)	4.69	96.65	40.92	24.17	38.52
ITHD3 (%)	4.06	94.69	34.42	22.59	33.79
UTHD1 (%)	0.00	6.47	3.50	1.51	3.28
Total Power Factor (PFtot)	0.388	0.955	0.734	0.151	0.787
5th Harmonic—Phase 1 (%)	4.0	66.0	18.7	14.7	14.0
3rd Harmonic—Phase 1 (%)	0.0	80.0	10.7	16.4	8.5
7th Harmonic—Phase 1 (%)	0.0	46.0	11.6	12.0	7.0

Power Factor Analysis

Table 6 shows load category power factor classification of the metal industry. The power factor analysis indicates that the overall average total (PFtot) of the facility is 0.734, which falls well below the acceptable minimum range of 0.90 to 0.95 required by industry. The WORTMAN drive (V505) shows the lowest PF of 0.388, while the FICEP (11 and 3) drives have a PF of 0.489 and 0.568, respectively. The low PF values reflect a substantial amount of reactive power being used, and that reactive power cannot be compensated for adequately by conventional shunt capacitors alone because of harmonics resonance amplification — a phenomenon that has been well documented in many high harmonic generating facilities.

The factors (PF) in terms of the LED-based lighting systems, ranging from 0.807 to 0.955, demonstrate that modern LED driver circuits with active power factor correction (PFC) circuits can manage reactive power much better than traditional power electronics-intensive industrial drives. RETERM thermal units, as a result of their inductive-resistive characteristics, demonstrate reasonably PFs, ranging from 0.65 to 0.80. SP spindle motors, as indicated by the range of PFs from 0.636 to 0.826, and FICEP drives, ranging from 0.489 to 0.815, exhibit considerable variation in PFs, probably reflective of the instantaneous load of the equipment at the time of measurement.

Table 6. Load Category Power Factor Classification of The Metal Industry

Load Category	Representative Points	PF Range	Mean PF	Dominant Harmonic	Primary Standard
LED Lighting	Hall 1–3 (4 points)	0.807 – 0.955	0.884	3rd/5th	IEC 61000-3-2
CNC Machining Centers	CNC.1, 2, 3	0.779 – 0.784	0.785	5th/3rd	IEEE 519-2022
FICEP Machines	FICEP.3, 6, 10, 11	0.489 – 0.815	0.614	5th/7th	IEEE 519-2022
Induction Heating	INDUCTION.500	0.725	0.725	5th/7th	IEEE 519-2022 / IEC 61000-3-12
Thermal Treatment	LSP27, RETERM.200	0.652 – 0.796	0.724	5th	IEEE 519-2022
Spindle Drives (SP)	SP58C1, SP58C2	0.636 – 0.826	0.731	5th/7th	IEEE 519-2022
Variable-Speed Drives	WORTMAN V505, V630M	0.388 – 0.847	0.618	3rd/5th/7th	IEEE 519-2022

Note: Mean PF values are calculated from available three-phase measurements. Dominant harmonic orders are ranked by magnitude of Phase 1 harmonic components. Primary standards indicate the most applicable IEEE/IEC limit framework for each load category.

IEEE 519-2022 Compliance Assessment

IEEE 519-2022 evaluates harmonic limits based on total demand distortion (TDD) at the point of common coupling PCC. Compliance depends on system parameters such as Isc/IL ratio and aggregated harmonic currents. Since measurements in this study were taken at load terminals, a direct compliance assessment is not possible. Table 7 shows the IEEE 519-2022 harmonic summary of the metal industry.

Using the ITHD measurements taken from the facility, we can classify the harmonic pollution level of the various loads as follows, listed in descending order of severity: (1) WORTMAN variable speed drive (53.5%–129.9% ITHD1) — critical violation of standards, requires immediate action; (2) Induction heating system (84.2% ITHD1) — severe violation of standards, primarily due to 5th and 7th harmonics; (3) SP series spindle drive (22.1%–36.0% ITHD1) — significant violation of standards; (4) FICEP structural machine — FICEP.10 at 38.6% (non-compliant), FICEP.6 at 4.53% (compliant); (5) CNC machining centers (22.5%–29.4% ITHD1) — non-compliant; significant phase asymmetry; (6) RETERM heater (28.0%–28.2% ITHD1) — non-compliant; (7) LED lighting system (12.4%–15.7% ITHD1) — non-compliant, but considered the lowest impact.

Table 7. IEEE 519-2022 Harmonic Summary of The Metal Industry

Measurement Point	ITHD1 (%)	Harmonic Source Severity	Potential Impact at PCC	Recommended Mitigation
WORTMAN (V505)– 112 kW	129.88	Very High	Critical contribution to TDD; high risk of exceeding IEEE 519 limits	12-pulse rectifier / Active Power Filter (APF)
INDUCTION.500– 50 kW	84.21	Very High	Strong harmonic injection; significant PCC distortion risk	Passive tuned filter (5th–7th) + APF
WORTMAN (V630M)– 45 kW	53.49	Very High	Likely dominant contributor to harmonic current aggregation	Multi-pulse rectifier / APF
SP58C1– 100 kW	35.99	High	Significant harmonic source; may elevate TDD under high loading	Line reactor + Passive filter
FICEP.10– 58 kW	38.59	High	Strong 5th harmonic contribution; local distortion risk	Tuned passive filter (5th)
CNC.3– 30 kVA	29.38	High	Phase asymmetry + harmonic injection; PCC contribution probable	AC reactor + harmonic filter
RETERM LSP27– 600 kW	28.03	High	Continuous harmonic emission under load	High-pass passive filter
RETERM.200– 200 kW	28.21	High	Similar harmonic pattern; cumulative effect expected	High-pass passive filter
CNC.1– 30 kVA	23.72	Moderate–High	Moderate harmonic injection; cumulative effect at PCC	AC reactor
CNC.2– 30 kVA	22.55	Moderate–High	Similar harmonic behavior	AC reactor
SP58C2– 100 kW	22.12	Moderate–High	Variable harmonic emission depending on load	Line reactor
FICEP.3– 40 kW	17.15	Moderate	Local harmonic contribution	Passive filter
LED Hall-2 (2.2)	15.66	Moderate	Triplen harmonics; neutral current risk	Shared 3rd harmonic filter
LED Hall-2 (2.1)	15.06	Moderate	Same pattern; cumulative neutral loading	Shared filter
LED Hall-3 (3.1)	12.89	Moderate	Limited impact individually; cumulative effect possible	Shared filter
LED Hall-1 (1.1)	12.44	Moderate	Distributed harmonic sources	Shared filter
FICEP.11– 26 kW	11.89	Low–Moderate	Minor contribution	Line reactor (optional)
FICEP.6– 30 kW	4.53	Low	Negligible impact on PCC	No action required

Note: The classification presented in this table is based on ITHD measurements at individual load terminals and is intended for indicative assessment of harmonic source severity. IEEE 519-2022 compliance requires evaluation at the Point of Common Coupling (PCC) using TDD and system short-circuit ratio (Isc/IL).

Mitigation Recommendations

Harmonic analysis results and IEEE 519-2022, IEC 61000-3-12, and PQ improvement literature provide technical guidance for the following prioritized solutions for the metal industry facility. The WORTMAN variable speed drives (V505 and V630M) are, overall, the strongest harmonic sources in use. Therefore, there is a recommendation for installing either 12 pulse rectifier front end or dedicated shunt active power filters (APF). APF dynamically compensates for harmonics from the 2nd through the 50th order and also improves power factor. As a result, APF is the preferred option for variable/harmonic loads of significant magnitude. The induction heating system (INDUCTION.500) should have both passive tuned filters for 5th and 7th harmonic orders and an active or hybrid filter to address residual higher order harmonics and load variability. This configuration follows the hybrid filtering method of PQ literature, which can be applied to high power, frequency variable and industrial loads. For CNC machining centers, it is recommended to install three-phase line reactors, with 3%–5% impedance, on the input side

of drives before other methods to reduce 5th harmonic injection and increase power factor. Single tuned passive filters for the 5th harmonic order may be added at the motor control center (MCC) level to achieve additional reductions. In regard to LED lighting systems, it is recommended that they be fitted with shared 3rd harmonic filters at the distribution panel level to mitigate triplen accumulation of harmonics in the neutral conductor, thus minimizing the risk of overcurrent in the neutral conductor of a three-phase four-wire distribution system.

CONCLUSION

This research fills an essential void in the body of knowledge by offering a detailed classification and comparative evaluation of standards devised by the IEEE and IEC, considering the growing complexity of technology and interdisciplinary exchange within the domain of power quality To alleviate concerns about the increasing number of power quality issues that exist as a result of the growing number of non-linear loads and power electronic converters, the introduction of renewables, and the heightened sensitivity of electronic devices in today's power systems, the concept of using standards is not limited strictly to informing us of technical limit values, but additionally demonstrates the range of impacts that the application of standards has on areas such as measurement methodology and engineering practice.

The comparative assessment of IEEE and IEC standards presented in this research article reflects an important opportunity to systematically organise information regarding power quality standards that is otherwise dispersed throughout the literature. Unlike IEC standards, which delineate internationally accepted definitions of techniques and structures for measurement, evaluation, and establishing limit values, IEEE standards provide an application-oriented and operational touch, while additionally providing detailed explanations of technical concepts. It is essential to recognize the fundamental differences between the standard-setting organizations discussed, as this awareness will assist in identifying compliance issues related to the design and operation of energy systems that are governed by the various standards and regulatory frameworks.

In summary, this study has developed a comprehensive and up-to-date resource that holistically reviews power quality standards applicable to energy systems. The presented work is intended to serve as a reference for future research in this field. It is supported by real-world, on-site power quality measurements obtained from a heavy metal manufacturing facility. The recommendations provided for mitigating harmonic distortion—such as the use of active power filters, 12-pulse rectifiers, passive tuned filters, and line reactors—are consistent with both IEEE and IEC standards, which were employed to evaluate the facility’s performance and to guide improvement efforts.

Future research may focus on extending this analysis to different industrial sectors and operating conditions, as well as examining the impact of increasing renewable energy integration on power quality performance. Additionally, the development of advanced monitoring and mitigation strategies, including data-driven and intelligent approaches, could further enhance compliance with evolving standards and improve overall system reliability.

Artificial Intelligence Contribution Statement

Artificial intelligence is used in the creation of shapes and in the verification of English text.

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