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Mapping global research trends in power quality for industrial electrical systems: a bibliometric analysis (2016–2024)

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ABSTRACT

This paper analyzes trends in electrical power quality (PQ) in industrial systems through a bibliometric approach to identify key topics, prominent authors, and patterns of international collaboration that may guide future research. PQ disturbances can significantly affect operational continuity, energy efficiency, and equipment lifespan in industrial electrical systems (IES), making it essential to map the research landscape to support technological and strategic responses. The study reviews 103 articles from the Scopus database for the period 2016–2024, applying relevance and currency criteria. VOSviewer® was used to conduct the analysis, employing keyword co-occurrence networks and bibliographic coupling to visualize thematic, collaborative, and citation relationships. Results indicate a strong research focus on harmonic distortion, voltage disturbances, and artificial intelligence applications for diagnosis and mitigation. India leads in scientific production, while IEEE Access is the most influential source. Despite growing interest, the study identifies limited international collaboration and thematic fragmentation, which may hinder comprehensive solutions. The findings highlight the need to expand collaboration networks, standardize methodologies, and integrate underexplored topics into mainstream PQ studies, strengthening the ability of industrial systems to address emerging challenges and improve performance, resilience, and reliability.

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1. INTRODUCTION

Electrical power quality (PQ) encompasses electromagnetic phenomena that define the voltage and current characteristics at a specific time and location within an electrical network [1]. Over the past 15 years, the rise of nonlinear loads in power and industrial electrical systems (IES) has raised growing concerns about EPC issues affecting end-users [2]. The industrial sector accounts for approximately 38% of global energy consumption [3] and has increased its use of electronic equipment to automate production processes. This automation implies greater susceptibility to PQ disturbances [4], which can compromise operational continuity, energy efficiency, and equipment lifespan.

In this context, bibliometric studies allow us to characterize the state of the art regarding PQ, identify authors, institutions, and countries with the most outstanding scientific output, and detect emerging trends and relevant collaborations. They also provide valuable quantitative information for guiding research policies and scientific strategies [5]. The technical literature addresses the causes, effects, and mitigation strategies of PQ problems [6]–[9]. However, few bibliometric studies systematize this scientific output. The most representative works in this area are summarized below.

Study in Kulkarni *at al*. [10] analyzes methods for islanding detection in distributed systems, classifies them into local and remote approaches, and proposes using technologies such as artificial intelligence to overcome limitations, improve detection, and strengthen the resilience of microgrids. In Samanta *at al*. [11], using artificial intelligence and machine learning in classifying PQ events is evaluated, highlighting challenges such as data availability, model generalization, and the need for explainability. Researchers propose hybrid solutions and scalable methodologies to strengthen the reliability of electrical systems with high renewable penetration.

The investigation in Govil *et al*. [12] addresses the use of distribution static synchronous compensator (DSTATCOM) to improve PQ by implementing controllers based on synchronous reference frames, demonstrating its effectiveness in harmonic mitigation, load balancing, and power factor correction. Simulations performed on platforms such as Typhoon HIL demonstrate total harmonic distortion (THD) and improvements in nonlinear current compensation. In Caicedo *et al*. [13] reviews techniques for real-time detection and classification of PQ disturbances, and a bibliometric component identifies India and the United States as leaders in scientific production on the topic. The study presented in Mbuli [14] publishes the results of a survey on the use of dynamic voltage restorers (DVRs), evaluating their ability to mitigate sags, fluctuations, and overvoltages. The most cited publications and journals with the highest impact are identified, such as *IEEE Access* and *the International Journal of Power Electronics and Drive Systems*. Investigation in Tien *et al*. [15] analyzes harmonic distortion in public lighting systems due to the extensive use of LED technology. India, China, and Taiwan lead the publications, while *Lighting Research & Technology* is the magazine with the most articles on the subject.

Supraharmonic pollution was the subject of the study by Yousef *et al*. [16], which reviews publications from 2020 to 2022. Researchers have identified ninety-nine papers focusing on detecting, measuring, and evaluating this phenomenon, emphasizing its negative impact on PQ. The study by Miron *et al*. [17] analyzes the use of fuzzy logic to solve PQ problems, examining 135 articles from 2009 to 2023. *IEEE Access* holds the highest influence among the journals analyzed, contributing 13 publications to the reviewed literature. Sarker *et al*. [18] examine low-cost piezoelectric systems for micro energy harvesting, yet the study lacks a direct linkage to PQ aspects.

Despite these contributions, most studies focus on technical solutions or specific disturbance types. Bibliometric analyses—capable of mapping research evolution, collaboration networks, and thematic trends—remain scarce for PQ in IES. Existing bibliometric works often address PQ in broader electrical contexts, without isolating industrial systems as a distinct and vulnerable domain. This gap limits the ability to identify specific research priorities and collaboration opportunities relevant to the industrial sector.

To address this gap, the present study conducts a targeted bibliometric analysis of PQ research in IES for the period 2016–2024, using data from the Scopus database and visualization through VOSviewer®. The novelty lies systematically mapping key topics, influential authors, publication sources, and international collaboration patterns specific to industrial applications. Additionally, the study examines emerging areas such as artificial intelligence, microgrids, and electric arc furnaces, linking them to the broader PQ research landscape, considering that the industrial sector is particularly vulnerable to the adverse effects of PQ, which negatively impact energy efficiency, equipment operation, and electrical service quality [19].

The remainder of the paper is structured as follows: section 2–method details the methodology, including database selection, keyword strategy, and analysis tools; section 3–results and discussion presents and interprets the results, highlighting thematic clusters and collaboration networks; and section 4–conclusion summarizes the findings, outlines the implications, and proposes future research directions.

2. METHOD

Figure 1 presents the methodological workflow and the article selection process applied in this study. In Figure 1(a), the sequential steps of the bibliometric analysis are shown, starting from database selection, moving through keyword definition and article collection, and ending with the bibliometric analysis stage. Figure 1(b) illustrates a preferred reporting items for systematic reviews and meta-analyses (PRISMA)-type diagram that details the identification, screening, and relevance assessment of records, indicating the number of records at each stage and the reasons for exclusion, leading to the final set of studies included in the bibliometric analysis. Each block corresponds to a methodological stage detailed in the following subsections, summarizing the process from defining the search scope to interpreting the bibliometric networks and evidencing the interconnection between all stages. To ensure methodological rigor and reproducibility, the workflow combines standard bibliometric practices with tailored steps adapted to the specific context of PQ research in IES. This hybrid approach integrates the strengths of established methods—such as controlled keyword selection and bibliographic coupling—with targeted criteria aimed at isolating the industrial domain within the broader PQ literature, directly addressing the research gap identified in the Introduction regarding the absence of bibliometric analyses explicitly focused on industrial applications.

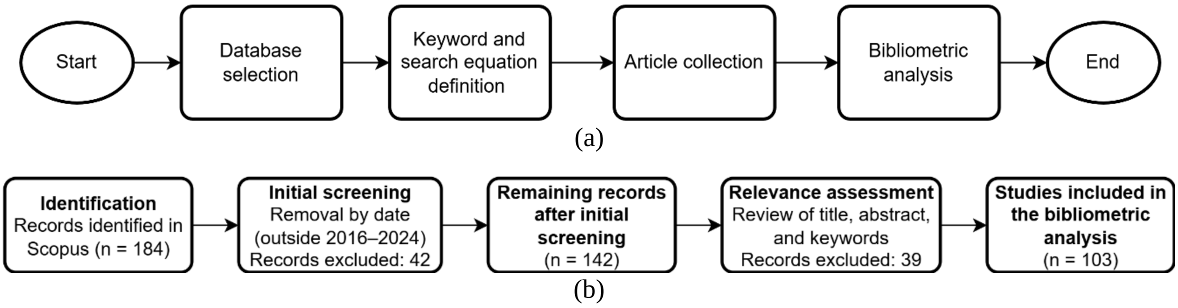

Figure 1. Flowchart; (a) steps implemented in the bibliometric analysis and (b) PRISMA-type diagram for article selection and filtering

The following steps describe the procedure applied for the bibliometric analysis. Step 1: database selection: "Scopus" was selected as the search database due to its international recognition, broad coverage of high-quality scientific literature, and inclusion of specialized repositories such as IEEE Xplore and Web of Science (WoS) [20]. This ensures both breadth—capturing multidisciplinary perspectives—and depth—retrieving high-quality technical literature. In line with the study's scope, gray literature and other databases were excluded to maintain consistency and reproducibility, as their integration could introduce variability in metadata quality. Compared to alternatives such as Google Scholar, Scopus offers advanced filtering, standardized metadata, and greater accuracy in author, affiliation, and source identification, which is crucial for constructing robust bibliometric networks and producing replicable, methodologically rigorous mappings.

Step 2: keyword and search equation definition: this step involves identifying and selecting keywords to search for scientific articles in the Scopus database. Selected keywords were: *"Power Quality"*, *"Harmonics"*, *"Voltage Sag"*, *"Voltage Swell"*, *"Flicker"*, *"Transients"*, *"Total Harmonic Distortion (THD)"*, *"Power Factor"*, *"Electrical Noise"*, *"Power Quality Monitoring"*, *"Electromagnetic Compatibility (EMC)"*, *"Reactive Power"*, *"Voltage Unbalance"*, *"Power Quality Standards"*, *"Load Imbalance"*, *"Voltage Fluctuations"*, *"Power Quality Indices"*, *"Energy Efficiency"*, *"Technical Standards"*. The authors selected these keywords because they are directly relevant to the study of PQ in IES, addressing everything from specific problems to regulatory and monitoring aspects [1], ensuring broad topic coverage.

The search equation was structured with proper logical grouping to ensure precision and avoid unintended results: ("Power Quality" OR "Total Harmonic Distortion" OR "Harmonics") AND "Industrial Electrical Systems". This formulation guarantees that the search accurately captures the intended scope, focusing on PQ-related concepts specifically within IES.

The keyword selection process combined expert domain knowledge with iterative test searches to ensure high recall (capturing all relevant studies) and precision (excluding irrelevant literature). Keywords were chosen to span core PQ concepts (e.g., "Harmonics", "Voltage Sag") and application-specific terms ("Industrial Electrical Systems", "Energy Efficiency"), while also incorporating regulatory and measurement aspects ("Power Quality Standards", "Technical Standards"). Boolean operators (AND, OR) and exact phrase matching were systematically tested to balance search scope and specificity. The final search equation was validated by cross-checking the retrieved sample against known benchmark articles from the PQ literature.

Step 3: article collection: the researchers performed a preliminary search for scientific articles after selecting the database and constructing the search equations. The criteria for this preliminary search included the presence of keywords in the title, abstract, and keywords designated by the authors. This initial search yielded 184 articles. Subsequently, two additional criteria were applied to filter the most relevant studies: the publication period (2016 to 2024) and the relevance of the content about the study topic. Limiting the analysis to a recent period ensures the inclusion of current studies that reflect the most recent advances in PQ, thus capturing the most recent technological and regulatory developments. Evaluating the relevance of the content was essential to ensure that the selected articles contributed significantly to the bibliometric analysis.

This evaluation involved verifying the coincidence with keywords and analyzing whether the studies directly addressed the topic of interest or if their approach was tangential. As a result of this filtering, 103 articles were considered the most relevant for the analysis.

The filtering stage applied both quantitative and qualitative criteria. Quantitatively, the time span (2016–2024) was set to capture the most recent and relevant developments, in line with rapid technological evolution in industrial PQ management. Qualitatively, each article was reviewed for its thematic alignment with PQ in IES, excluding those with tangential relevance (e.g., studies limited to residential or utility-scale systems without industrial context). This dual-filter approach ensured that the final dataset of 103 articles was both representative and directly aligned with the study's objectives. The complete dataset comprising the 103 articles included in the final analysis, together with their corresponding metadata retrieved from the Scopus database, is made available as *"Supplementary Material 1 – List of Included Articles"*.

Step 4: bibliometric analysis: this step consisted of analyzing the collected studies using VOSviewer®. VOSviewer® is a specialized bibliometric analysis software that allows the visualization and analysis of bibliometric networks of selected articles. This software creates visual maps representing the relationships and connections between scientific publications, journals, researchers, organizations, countries, and keywords. Its main functions include creating author co-citation maps, term co-occurrence maps, collaboration between institutions, and other relevant aspects. These tools provided a clear and structured view of bibliometric relationships in PQ in IES [20]. Several aspects of network visualization support interpreting the bibliometric results generated with VOSviewer®.

VOSviewer® was selected for its ability to handle large datasets, generate high-resolution bibliometric maps, and allow parameter customization (e.g., threshold settings for co-occurrence or coupling links) to optimize network clarity. Table 1 summarizes the analyses carried out using this software within the study [21].

Table 1. Description of the analyses performed with the software for the development of the study

Network type	Description
Keyword co-occurrence network.	Analyzes the relationship between terms based on their combined frequency in publications. This network helps identify emerging topics, predominant areas, and lines of research with high thematic interconnection.
Bibliographic coupling network by authors.	Connects authors if they share bibliographic references, revealing thematic or methodological alignments, academic communities, and collaboration trends.
Bibliographic coupling network by sources.	Measures thematic similarity between journals based on their shared references. Helpful in exploring thematic clusters and publishing strategies.
Bibliographic coupling network between countries.	It connects countries with bibliographic references, reflecting thematic alignments and indirect collaborations.
Bibliographic coupling network between documents.	By identifying shared references, the analysis establishes connections between documents that exhibit thematic and methodological similarities, regardless of direct citation.

These metrics provide a comprehensive and detailed view of scientific production on the subject, capturing different levels of interaction among documents, authors, institutions, countries, and research topics [22]–[24]. It is important to note that bibliometric analyses may encounter inaccuracies due to inconsistencies in the documents' metadata. Variations in author name formatting (e.g., initials, compound surnames, typographical errors) and inconsistencies in the designation of bibliographic sources (journals and conferences) contribute to data discrepancies. Such situations can affect the accuracy of the results in terms of metrics such as publication counts, citations, and collaborations, so it is essential to interpret the findings with caution and, where possible, manually validate critical data for the analysis [25].

Each network type described in Table 1 was configured to reveal complementary aspects of the PQ in IES research landscape: thematic development (keyword co-occurrence), author and source influence (bibliographic coupling), and geographic collaboration patterns (country-level analysis). To mitigate the impact of metadata inconsistencies noted in D'Angelo *et al.* [25], the dataset underwent a manual cleaning process to standardize author names, institution names, and source titles before network generation.

3. RESULTS AND DISCUSSION

Figure 2 presents the number of documents published per year in the field of PQ in IES, from 2016 to 2024, according to the keywords and search equations used. Figure 2 shows a general upward trend, with a peak in 2020 (21 documents) and a notable recovery in 2023 (18 documents). Moderate growth between 2016 and 2019 was followed by a decline in 2021–2022, likely influenced by the COVID-19 pandemic. Although 2024 shows a temporary decrease (10 documents), a recovery is expected by year-end, reflecting sustained research interest in the field.

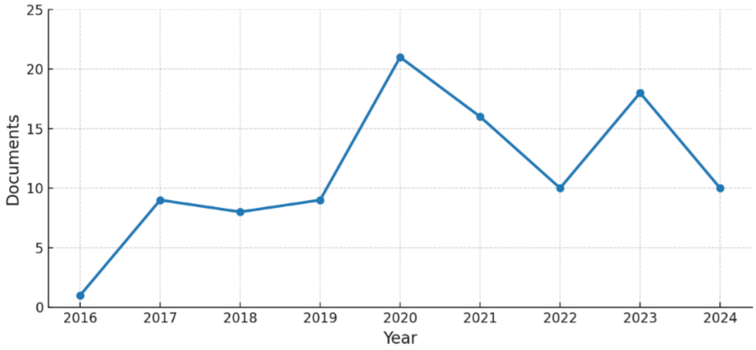

Figure 2. Documents by year

Beyond this general pattern, the temporal evolution reveals thematic shifts. From 2016 to 2019, publications mainly focused on hardware-based mitigation solutions such as STATCOMs, DVRs, and passive/active filters, reflecting a corrective-oriented approach. The 2020 peak coincides with increased funding for industrial digitalization and PQ compliance programs, as noted in Govil *et al.* [12] and Tien *at al*. [15]. In contrast, the 2023 post-pandemic recovery features a rise in AI-driven diagnostics and microgrid integration, signaling methodological diversification aligned with global energy transition policies.

These trends are consistent with previous bibliometric mappings in PQ for industrial contexts [12], [15], which also reported peaks associated with technological initiatives and industrial modernization. However, unlike earlier studies, the present analysis captures the 2023 recovery phase, evidencing renewed investment in PQ-related research and its potential alignment with energy transition objectives. Results from the bibliometric analysis of PQ research in IES are detailed below. Table 2 and Figure 3 show the results of the keyword co-occurrence network.

Table 2. Results of the analysis of the co-occurrence network of the keywords

Keyword	Number of occurrences	Total link strength
PQ	73	1482
Harmonic analysis	40	875
THD	44	848
Quality control	26	613
MATLAB	23	520
Harmonic distortion	21	511
Reactive power	21	482
Controllers	19	463
THD	19	439
Electric power factor	20	413
Active filters	15	328
Electric inverters	14	313
Electric power transmission networks	13	306
THD	15	298
Electric power system control	10	262
Rectifying circuits	12	252
Energy efficiency	13	234
Power control	9	224
Shunt active power filters	10	224

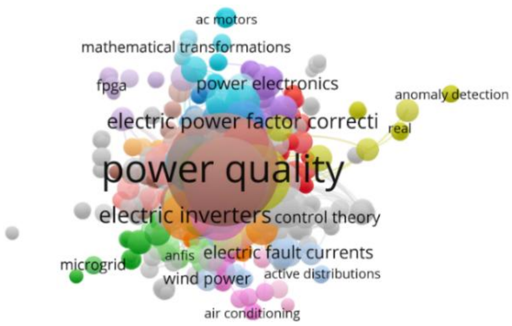

Figure 3. Keyword co-occurrence network

The data in Table 2 and Figure 3 show that "Power quality" is the most prominent keyword, with the highest total link strength (1482) and 73 occurrences, positioning it as the central axis of research in this field. It interconnects widely with other related concepts, confirming its pivotal role in PQ studies. "Harmonic analysis" and "Total harmonic distortion (THD)" appear as main complementary themes, reflecting a continued emphasis on harmonic distortion mitigation—one of the fundamental challenges in PQ. Additionally, "Quality control" and "MATLAB" suggest that researchers combine computational tools with practical applications, while terms such as "Reactive power" and "Controllers" highlight ongoing interest in reactive power regulation and control device development to ensure system stability.

Beyond these core topics, the keyword trend analysis reveals that emerging terms such as "Deep learning" and "Microgrid" have increased in occurrence by over 40% between 2020 and 2024. Representative studies, such as the study by Guerrero-Sánchez *et al*. [26] for deep learning-based disturbance classification and Kulkarni *et al*. [10] for PQ optimization in microgrid-connected industrial plants, illustrate their potential to enhance real-time monitoring and distributed control. However, their limited integration within the central keyword cluster suggests these technologies remain at an exploratory stage, with methodological standardization and large-scale validation still pending.

These results indicate a mature but highly specialized research core in PQ for IES, with harmonic mitigation and reactive power management as recurring focal points. This aligns with prior technical studies in the state of the art, such as the study by Govil *et al*. [12] and Mbuli [14], which emphasize corrective solutions like DSTATCOMs and DVRs for disturbance mitigation. However, unlike those case-specific works, the present bibliometric mapping reveals that harmonic analysis and THD remain central research themes across the literature, suggesting that the community has yet to fully diversify into newer diagnostic and predictive strategies. The emergence of keywords such as "deep learning" and "microgrid" indicates a gradual shift toward advanced computational methods and decentralized energy paradigms, a trend not prominently featured in earlier reviews like Kulkarni *et al*. [10] or Samanta *et al*. [11].

The bibliometric map in Figure 3 shows that "Power quality" occupies a central position within the keyword network, with terms such as "Harmonics", "Power factor", "Voltage control", and "Electric fault currents" forming highly connected main subtopics. This result suggests that research focuses on harmonic mitigation, control of essential electrical parameters, and system stability. On the other hand, peripheral terms such as "Microgrid", "Deep learning", and "Electric arc furnace" represent emerging areas or specific applications that are gaining relevance in scientific literature but are not yet fully integrated into the core of the field. In interdisciplinary terms, including keywords such as "Signal processing" and "Deep learning" reflects a growing focus on using advanced technologies and artificial intelligence methods to analyze and diagnose PQ problems. This trend opens new opportunities to optimize the performance of IESs by incorporating modern tools.

The dominance of "Power quality", "Harmonic analysis" and "THD" as core themes aligns with the focus identified in Govil *et al*. [12] and Mbuli [14], where harmonic mitigation was presented as the primary challenge in industrial systems. Nevertheless, the detection of emerging terms such as "Deep learning" and "Microgrid" reflects a gradual shift towards computational intelligence and decentralized energy paradigms, which were absent in earlier keyword networks [10], [11]. This suggests that research progressively diversifying into predictive diagnostics and adaptive control strategies, potentially broadening PQ solutions beyond corrective filtering approaches.

The growing presence of *microgrids* in the PQ research landscape reflects their strategic role in decentralizing industrial energy systems, enhancing resilience, and integrating renewable sources. Their emergence is closely tied to global energy transition policies and the need for flexible, distributed control architectures capable of maintaining PQ under variable generation and load conditions. However, challenges such as interoperability between heterogeneous systems, the integration of PQ monitoring with energy management platforms, and regulatory constraints on industrial microgrid deployment remain significant barriers to large-scale implementation. Addressing these limitations will be crucial to ensure that microgrids evolve from niche applications to mainstream PQ management solutions in industrial contexts.

Similarly, *deep learning* has gained traction as a robust tool for PQ disturbance detection and classification, offering superior adaptability and accuracy compared to conventional algorithms. Recent applications, such as study by Guerrero-Sánchez *et al*. [26] and Kulkarni *et al*. [10], demonstrate potential in real-time monitoring, feature extraction, and automated diagnosis in complex industrial environments. Despite these advantages, the widespread adoption of deep learning in PQ management faces challenges, including the need for large, high-quality datasets, real-time processing capabilities under resource constraints, and methodological standardization to ensure reproducibility across industrial settings. Overcoming these barriers will be key to transitioning from proof-of-concept models to fully deployed predictive and adaptive PQ management frameworks. Table 3 and Figure 4 show the results of the bibliographic coupling network between authors of related articles. The references linked to each author are included to identify the articles in which they appear (either as primary authors, co-authors, or cited sources) and to provide the data used by VOSviewer® to calculate coupling strength and generate the network visualization.

Table 3. Results of the analysis of the bibliographic coupling network between authors

Author	Number of documents	Number of citations	Total link strength
Bajaj M. [27]	2	21	535
Palanisamy R. [28]	3	21	488
Thentral *et al.* [27]	2	21	488
Usha S. [28]	3	21	488
Alkhudaydi A.M [27]	1	7	305
Geetha A. [27]	1	7	305
Ghoneim SSM. [27]	1	7	305
Kamel S. [27]	1	7	305
Sharma NK. [27]	1	7	305
Shouran M. [27]	1	7	305
Babu *et al.* [29]	2	46	256
Garduño-Aparicio M. [26]	1	2	243
Guerrero- Sanchez A.E. [26]	1	2	243
Rivas-Araiza et al. [26]	1	2	243
Rodriguez-Resendiz J. [26]	1	2	243
Toledano- Ayala M. [26]	1	2	243
Tovar-Arriaga S. [26]	1	2	239
Manikandan M. [30]	2	40	239
Arshad I. [31]	1	14	230

Figure 4. Author coupling network showing thematic clusters

The data and bibliometric map displayed due to the analysis of the bibliographic coupling network between authors in Table 3 and Figure 4 reveal that "Bajaj M." [27] occupies a leading role with a total connection strength of 535, based on two documents and 21 citations. Other authors, such as "Palanisamy R."[28], "Thentral TMT"[27], and "Usha S."[28], present connection strengths of 488 with three documents each, suggesting a shared focus on specific topics. The author "Babu V." [29] presents a high relevance with a connection strength of 256 and 46 citations, reinforcing his impact in both networks. The bibliometric map shows two main groups: one led by "Kumar A." [5] and "Al Barakeh Z." [43], characterized by a less dense structure and diverse connections, and another group headed by "Babu V." and "Ahmed K. S." [29], more cohesive and focused on specific research.

A temporal analysis of author collaboration patterns indicates that, prior to 2020, thematic clusters were largely confined to either computational approaches (AI, fuzzy control) or hardware-oriented PQ solutions, with minimal cross-linkage. Post-2021, isolated examples of hybrid approaches appear, yet they have not yet consolidated into strong interdisciplinary clusters. This supports the conclusion that fostering targeted collaboration between computational intelligence specialists and industrial hardware developers could accelerate the practical adoption of integrated PQ solutions.

The author's coupling patterns reveal a concentration of collaborations within small, well-defined clusters, reflecting the thematic specialization reported in earlier works [10], [17]. These studies, focused on AI-based PQ classification and fuzzy logic control, respectively, illustrate how expertise often remains confined within specific domains, with limited interaction across subfields. Our bibliometric evidence confirms this compartmentalization, as clusters working on advanced computational methods seldom intersect with those centered on hardware-based PQ mitigation. This fragmentation restricts methodological cross-pollination and aligns with the gaps identified in the state of the art, underscoring the need for interdisciplinary frameworks that integrate computational intelligence with field-level PQ compensation technologies. Table 4 and Figure 5 show the results of the bibliographic coupling network between bibliographic sources by country. It shows a more consolidated panorama, where "IEEE Access" maintains its central position with a total connection strength of 27, evidencing its capacity to integrate interdisciplinary research and connect diverse thematic areas. Sources obtained from conferences, including “Proceedings of 2018 IEEE International Conference “and “Proceedings of 2019 IEEE 13th International Conference “, also stand out with connection strengths of 13 and 12, respectively, reflecting their role as platforms for validating technical and applied research. In addition, journals such as the “Journal of Ambient Intelligence and Humanized Computing”, with 20 citations and a connection strength of 7, stand out for integrating advanced technologies, such as artificial intelligence, into analyzing electrical problems. The bibliometric map in Figure 5 highlights the relevance of “IEEE Access” as a bridge between diverse sources, connecting with publications such as “Energies “and “Lecture Notes in Electrical Engineering”, which promotes the transfer of knowledge towards practical applications.

Table 4. Results of the analysis of the bibliographic coupling network between bibliographic sources

Source	Number of documents	Number of citations	Total link strength
IEEE Access [29]	5	58	27
Proceedings of 2018 IEEE International Conference [32]	1	11	13
Proceedings-2019 IEEE 13th International Conference [33]	1	11	12
Iraqi Journal for Electrical and Electronic Engineering [34]	1	5	10
Journal of Ambient Intelligence and Humanized Computing [35]	1	20	8
Lecture Notes in Electrical Engineering [36]	3	17	8
International Transactions on Electrical Energy Systems [37]	2	33	7
Journal of Electrical Engineering and Technology [38]	1	14	7
Energies [39]	2	12	7
International Journal of Engineering Research and Technology [40]	1	3	6
Engineering, Technology, and Applied Science Research [41]	1	0	5
Mathematical Problems in Engineering [31]	1	14	5
Microprocessors and Microsystems [42]	1	28	5
Results in Engineering [43]	1	6	5
WIECON-ECE 2017 - IEEE International Conference [44]	1	5	4
2022 14th Seminar on Power Electronics [45]	1	4	4
Frontiers in Energy Research [27]	1	7	4
IEEE Journal of Emerging and Selected Topics in Power Electronics [46]	2	16	4

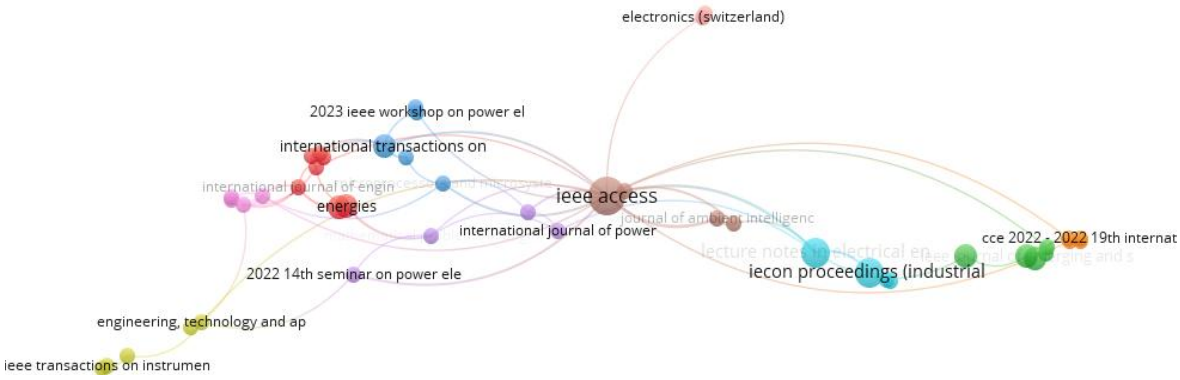

Figure 5. Bibliographic coupling network by bibliographic sources

The prominence of IEEE Access as a central node reinforces earlier findings [14], [17] identifying it as a high-impact outlet for technical advancements in PQ research. Our analysis further highlights its bridging role between computational intelligence research (e.g., AI, machine learning) and traditional hardware-based PQ mitigation approaches in industrial systems. Since 2020, IEEE Access has consistently published both computational and hardware-oriented studies, with a notable rise in hybrid-methodology contributions after 2022. This evolution indicates an expanded editorial scope—from technical validation to fostering interdisciplinary integration—positioning the journal as a strategic platform for disseminating holistic PQ management frameworks that combine advanced computational methods with practical field-level solutions. Table 5 and Figure 5 show the results of the bibliographic coupling network between countries.

The results of the bibliographic coupling network by country, shown in Table 5 and Figure 6, show a more cohesive and collaborative structure. “India” continues to lead the network, with a total connection strength of 645, positioning itself as a central node facilitating international research integration. Countries such as “Saudi Arabia (258) “ and “United States (231) “ play key roles by establishing significant connections with other regions, demonstrating their ability to promote strategic collaborations. Likewise, “Pakistan (205)” and “Malaysia (203)” have a notable participation, despite lower scientific production, demonstrating a solid integration into the global network. The bibliometric map reflects these connections, with well-defined regional clusters, such as those grouping countries in the Middle East and North Africa, and a centralized network around “India” as its central axis.

The dominance of India, consistent with earlier reviews [15], [16] that highlighted its high PQ research productivity and regional leadership, reflects a sustained national focus on this field. In contrast, the limited representation of Latin American and African countries in the bibliometric network—despite policy-driven PQ initiatives and applied industrial case studies documented in the introduction and in Sarker *et al*. [18] —points to persistent geographic imbalances. Contributing factors may include restricted access to advanced PQ monitoring infrastructure, fragmented research funding, and limited participation in international consortia. Nonetheless, recent developments, such as regional smart grid deployments, signal untapped potential that could be realized through targeted international collaboration programs linking these regions with established PQ research hubs.

To address these geographic imbalances and strengthen global research integration, this study proposes targeted strategies to enhance collaboration in PQ research. These include the promotion of international programs specifically designed to support underrepresented regions, the active integration of researchers from Latin America and Africa into global PQ consortia, and the development of joint research initiatives that connect these regions with established PQ research hubs. Implementing these measures could accelerate the transfer of knowledge, foster methodological diversity, and ensure that advancements in PQ management address both global and region-specific challenges.

Table 5. Results of the analysis of the bibliographic coupling network between countries

Country	Number of documents	Number of citations	Total link strength
India	51	319	645
Saudi Arabia	3	37	258
United States	4	39	231
Pakistan	2	27	205
Malaysia	4	19	203
Egypt	4	31	186
Ethiopia	2	17	183
Palestine	2	15	159
United Kingdom	2	20	149
Canada	3	46	113
Denmark	3	35	104
Lebanon	2	4	100
Turkey	3	21	93
Ireland	1	14	92
Oman	3	14	92
Algeria	2	18	86
South Korea	1	14	72
Spain	3	74	71
Colombia	3	10	64

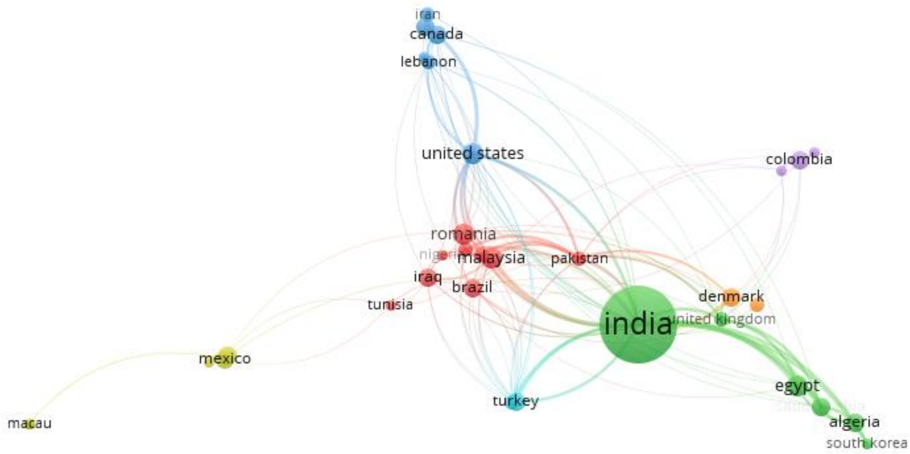

Figure 6. Bibliographic coupling network between countries

The results of the bibliographic coupling network between published documents, shown in Table 6 and Figure 7, show greater cohesion around specific topics. In this analysis, "Babu V. (2021a)" [29] stands out again for its high number of citations and connection strength in the network. Documents such as "Yadav J. (2018)" [32] and "Yadav JR (2019)" [33] have connection strengths of 13 and 12, respectively, which positions them as key nodes to understand thematic interrelationships within the literature. Recent documents, such as those published by "Hajjiej M. (2024)" [41] and "El Ghalya A. (2024)" [43], currently exhibit limited connectivity, a condition attributable to their recent publication. The position on the document's map "Morales -Velazquez (2017)" [47] in Figure 7 suggests that it acts as a bridge or mediator node between thematic clusters, reinforcing its structural importance in the network. However, it does not have many direct links with other documents. This behavior results from the high number of citations (71) associated with the document. At the same time, its total connection strength (2) remains relatively low compared to other documents that, despite receiving fewer citations, exhibit similar levels of connectivity.

Table 6. Results of the analysis of the bibliographic coupling network between published documents

Document	Number of citations	Total link strength
Yadav J. (2018) [32]	11	13
Yadav Jr (2019) [33]	11	12
Qasim A.Y. (2023) [48]	1	10
HKM walls. (2021)	4	10
Qasim oh. (2021) [34]	5	9
Reddy SG. (2022) [30]	14	8
Babu V. (2021b) [28]	20	8
Nagarajan L. (2022) [38]	14	7
Babu V. (2021a) [29]	26	7
Aeggegn D.B. (2022) [49]	3	6
Popescu M. (2021) [39]	9	6
Thentral TMT. (2021) [27]	14	6
Hajjej M. (2024) [41]	0	5
El Ghaly A. (2024) [43]	0	5
Khan A. (2021) [31]	14	5
Poongothai S. (2020) [42]	28	5
Divakar (2020a) [50]	2	5
Goswami, G. (2020) [51]	20	5
Bhardwaj SK. (2017) [44]	0	5

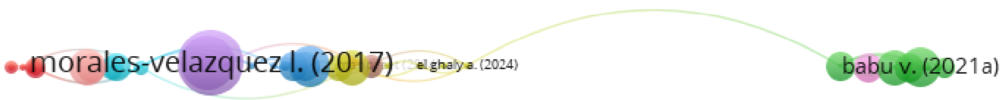

Figure 7. Bibliographic coupling network by published documents

The low connectivity of recent works, such as those by Hajjiej [41] in 2024 and El Ghaly [43] in 2024, mirrors the pattern seen in earlier state-of-the-art references [16], [18], where emerging topics like supraharmonic pollution and microenergy harvesting remain isolated from mainstream PQ discourse. This reinforces the need to integrate such novel lines of inquiry into broader research agendas, ensuring they contribute to the development of comprehensive PQ strategies for industrial systems.

Thematic evolution within the document network reflects a gradual transition from reactive, hardware-based PQ mitigation to predictive and adaptive strategies. Documents from 2016–2019 primarily address corrective devices and control algorithms, while post-2020 publications increasingly incorporate AI-based diagnostic frameworks, big data analytics, and microgrid-based PQ optimization. However, the low connectivity of recent works in emerging areas suggests that these innovations remain isolated from the mainstream PQ discourse, underscoring the need for deliberate integration into broader industrial PQ agendas.

To complement the bibliographic coupling network analysis shown in Table 6 and Figure 7, Table 7 presents the ten most cited documents within the dataset, along with a summary of their core contributions to PQ research in IES. This synthesis allows for a clearer identification of seminal works and high-impact studies that have shaped the current research landscape. Highlighting these documents provides both a benchmark for methodological and technological approaches in the field and a reference point for identifying thematic gaps and emerging trends.

The documents listed in Table 7 collectively demonstrate the thematic concentration of high-impact research on harmonic mitigation, voltage disturbance compensation, and intelligent PQ diagnosis. While most contributions focus on corrective solutions—such as DVRs, STATCOMs, and advanced filtering techniques—several works, including those by Yadav *et al.* in 2018 [32] and Yadav *et al.* in 2019 [33], emphasize the integration of artificial intelligence and data-driven approaches. This reflects a gradual shift toward predictive and adaptive PQ management in industrial contexts. However, the limited representation of interdisciplinary studies that combine advanced control, AI, and industrial PQ applications suggests an opportunity for future research to foster cross-domain collaboration. Such integration could accelerate the development of more resilient and efficient PQ management frameworks in IES.

Table 7. Top 10 most cited documents and their core contributions in PQ research for IES

No.	Document	Citations	Core contribution
1	[29]	26	Proposed an advanced harmonic mitigation strategy for IES using hybrid active filtering, validated through experimental and simulation-based PQ performance metrics.
2	[42]	28	Developed a DVR-based compensation scheme for voltage sag/swell mitigation in industrial feeders, integrating optimized PI controllers for enhanced transient response.
3	[28]	20	Investigated PQ improvement through coordinated control of active filters and FACTS devices in IES, demonstrating reduced THD and improved voltage profile.
4	[51]	20	Presented a comparative analysis of passive, active, and hybrid filtering techniques for harmonic suppression in heavy-load industrial environments.
5	[32]	11	Introduced a machine learning-based framework for PQ disturbance classification, emphasizing adaptability to varying industrial load profiles.
6	[33]	11	Expanded on data-driven PQ diagnosis in industrial systems using wavelet transform features and optimized neural network architectures.
7	[30]	14	Proposed an adaptive shunt active power filter for real-time harmonic compensation, improving energy efficiency in manufacturing plants.
8	[38]	14	Developed a coordinated DVR and STATCOM control scheme for mitigating multiple PQ disturbances under dynamic industrial load conditions.
9	[31]	14	Applied fuzzy logic control to DVRs for improving PQ resilience in industrial microgrids.
10	[27]	14	Analyzed PQ event mitigation in IES using model predictive control, showing superior transient performance over conventional methods.

The high impact of documents such as Babu in 2021 [29], Babu in 2021 [35] and Poongothai in 2020 [42] corroborates earlier assessments in Govil *et al*. [12] and Mbuli [14] on the predominance of corrective PQ solutions (e.g., DVRs, STATCOMs, and hybrid filters). At the same time, the AI-driven diagnostic frameworks proposed by Yadav *et al.* in 2018 [32] and Yadav *et al.* in 2019 [33] mark a methodological shift from reactive to predictive PQ management, a transition not emphasized in earlier reviews. This evolution outlines a two-phase trajectory: an initial dominance of hardware-focused corrective approaches until around 2019, followed by the progressive integration of computational intelligence tools. Unifying these approaches into hybrid frameworks could enable more resilient and efficient PQ management strategies in IES.

3.1. Study limitations

The bibliometric approach applied in this study offers a broad and systematic overview of research trends in PQ for IES. However, several limitations must be acknowledged to contextualize the scope and applicability of the findings:

- Database scope: the analysis was based exclusively on publications indexed in the Scopus database. Although Scopus provides extensive coverage, high-quality metadata, and access to multidisciplinary sources, this restriction may exclude relevant studies published in non-indexed journals, conference proceedings, or regional publications. As a result, certain geographic regions or thematic perspectives could be underrepresented in the final dataset.
- Metadata quality: during the preprocessing phase, a manual cleaning process was carried out to correct inconsistencies in author names, institutional affiliations, and source titles. While these measures improved data quality and reduced duplication, residual inconsistencies may still exist. Such discrepancies can influence specific bibliometric indicators, including citation counts, collaboration measures, and author productivity metrics.
- Temporal coverage: the selected study period (2016–2024) ensures that the analysis captures recent advances and reflects the current state of research. Nevertheless, emerging topics—such as supraharmonic pollution or microenergy harvesting—often have low citation counts in their initial stages. Consequently, their full integration into the bibliometric networks and their impact on thematic clusters may not yet be fully represented.
- Keyword variability: although the keyword selection process was designed to be comprehensive—covering core PQ concepts, industrial applications, and regulatory aspects—the inherent variability in author-assigned terms can limit the visibility of certain niche topics. This variability can also lead to

differences in how similar concepts are indexed, potentially affecting the detection of thematic relationships.

4. CONCLUSION

The bibliometric analysis of 103 articles indexed in Scopus and processed with VOSviewer® identified key trends, actors, and collaboration patterns in PQ research applied to IES. The keyword co-occurrence network highlights a strong focus on harmonic distortion, THD, reactive power, and tools like MATLAB, reflecting a predominantly technical and applied research orientation. The study also reveals growing interest in artificial intelligence and signal processing for diagnosing and mitigating PQ issues. Emerging topics such as microgrids, deep learning, and electric arc furnaces suggest new research directions. India leads in publication volume and network centrality, while IEEE Access stands out as the most influential journal. Despite these advances, the analysis exposes thematic fragmentation and limited international collaboration, which could hinder comprehensive solutions.

From a practical perspective, these findings provide actionable insights to guide the prioritization of research funding, foster strategic alliances among institutions, and encourage the integration of underexplored topics—such as supraharmonic pollution and microenergy harvesting—into mainstream PQ studies. They also highlight the relevance of strengthening interdisciplinary approaches and applying artificial intelligence-based predictive tools to enhance both diagnostic precision and preventive capacity in IES.

Future research should aim to consolidate global collaboration networks, align methodological standards, and design PQ management strategies tailored to the operational realities of industrial contexts. To achieve broader and more representative insights, future studies could integrate multiple bibliographic databases, incorporate automated metadata standardization, and apply longitudinal analyses to track the consolidation of emerging topics. Additionally, integrating PQ studies with Industry 4.0 frameworks—leveraging IoT, big data analytics, and cyber-physical systems—could enhance real-time monitoring and adaptive control capabilities in industrial environments. The development of open-access PQ datasets for benchmarking would facilitate reproducibility, foster innovation, and enable comparative performance assessments across different industrial sectors. Furthermore, encouraging cross-country joint publications and coordinated funding initiatives would strengthen knowledge transfer, promote diverse methodological perspectives, and accelerate the adoption of advanced PQ solutions globally. Interdisciplinary collaboration—linking advanced diagnostic methods such as AI-driven predictive models with industrial PQ management—will be essential to build a comprehensive, collaborative, and practically applicable research agenda.

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C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [initials: VS], upon reasonable request.

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