

Power Quality in Sustainable Energy Systems: A Taxonomy-Driven Review Towards Achieving the Sustainable Development Goals (SDGs)

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ABSTRACT

Power quality is important to sustainable energy systems as renewable generation, energy storage and converter-based loads introduce disturbance and mitigation challenges. Yet the relationship between measured power quality improvements and Sustainable Development Goal (SDG) indicators remains limited. This taxonomy-driven review examines that relationship through four axes: disturbance class, mitigation locus, measurement and evidence class and SDG indicator linkage. Each axis contains five levels defined by observable tests. The synthesis codes 231 statements from engineering, mitigation technology and sustainable development literature to examine how evidence progresses from disturbance measurement towards indicator reporting. Four mechanisms limit traceability: disagreement over metrics and assessment boundaries, aggregation across sites and periods, uncertain attribution of outcomes to power quality and missing connections to indicator custodians. The coded evidence indicates stronger support for converter-level mitigation than for network-wide assessment or custodian-reportable SDG outcomes. Eight falsifiable research questions and a reporting checklist identify the measurements, comparison conditions and reporting definitions needed to strengthen studies. The taxonomy provides an auditable framework for evaluating claims and their relevance to sustainable development reporting.

Keywords: Power Quality; Sustainable Energy Systems; Sustainable Development Goals (SDGs); Taxonomy-Driven Review; Power Quality Mitigation

INTRODUCTION

Power quality is essential for reliable electricity delivery as renewable generation, energy storage and converter-based loads expand across electrical networks [1], [2]. These developments introduce challenges for sustainable energy integration [3]. Harmonic distortion affects transformer performance [4], while interharmonics require suitable frequency estimation methods [5]. Signal preprocessing influences disturbance classification [6]. Background voltage harmonics affect converter operation [7], while energy storage introduces modelling uncertainties [8].

Power quality mitigation involves filtering technologies [9], active disturbance rejection [10] and sliding-mode control [11]. Effective mitigation requires appropriate equipment placement [12] and filter tuning in wind power plants [13]. Renewable microgrids integrate power quality enhancement with energy management [14] and harmonic compensation [15].

Accurate diagnostics depend on harmonic estimation [16] and time-frequency analysis [17]. Improved Gabor transforms [18] and modified S-transform techniques [19], [20] strengthen disturbance classification. Spectrogram analysis identifies multiple harmonic sources [21], while periodogram methods support source localisation [22]. Frequency and phase analysis improve dominant disturbance identification [23]. Signal decomposition [24] and recurrent autoencoders [25] address measurement noise.

Artificial intelligence extends diagnostic capabilities through deep learning [26], convolutional autoencoders [27], shapelet methods [28] and hybrid architectures [29]. Non-intrusive identification [30], S-transform detection [31] and real-time monitoring [32] provide complementary approaches. Inverter switching faults are identified through time-frequency analysis [33], [34] and short-time Fourier transforms [35]. Periodogram verification [36] and time-frequency classification [37] provide further diagnostic evidence. Related investigations examine direct torque control [38], [39], [40], multilevel inverters [41], torque ripple [42], insulation leakage currents [43], electric vehicle drives [44] and real-time disturbance classification [45].

Renewable energy supports sustainable development objectives [46], [47]. Nevertheless, renewable expansion does not guarantee equitable energy access [48], [49]. Just transition research highlights distributional outcomes

[50]. Solar irradiation estimation [51] and wind-hydrogen energy management [52] support renewable integration. Sustainability assessments address environmental contributions [53] and development trade-offs [54]. Reliability research [55], energy poverty [56], rural electrification [57] and economic sustainability [58] provide complementary perspectives.

Despite these advances, connections between measured power quality improvements and Sustainable Development Goal (SDG) indicators remain insufficiently established. Existing studies demonstrate diagnostic and mitigation capabilities but provide limited evidence connecting engineering performance with development reporting. This review develops a four-axis taxonomy encompassing disturbance class, mitigation locus, measurement evidence and SDG indicator linkage. Analysis of 231 coded statements identifies four evidence attenuation mechanisms. Eight falsifiable research questions and a reporting checklist are proposed to strengthen methodological consistency, evidence validation and the integration of power quality research into sustainable development assessment.

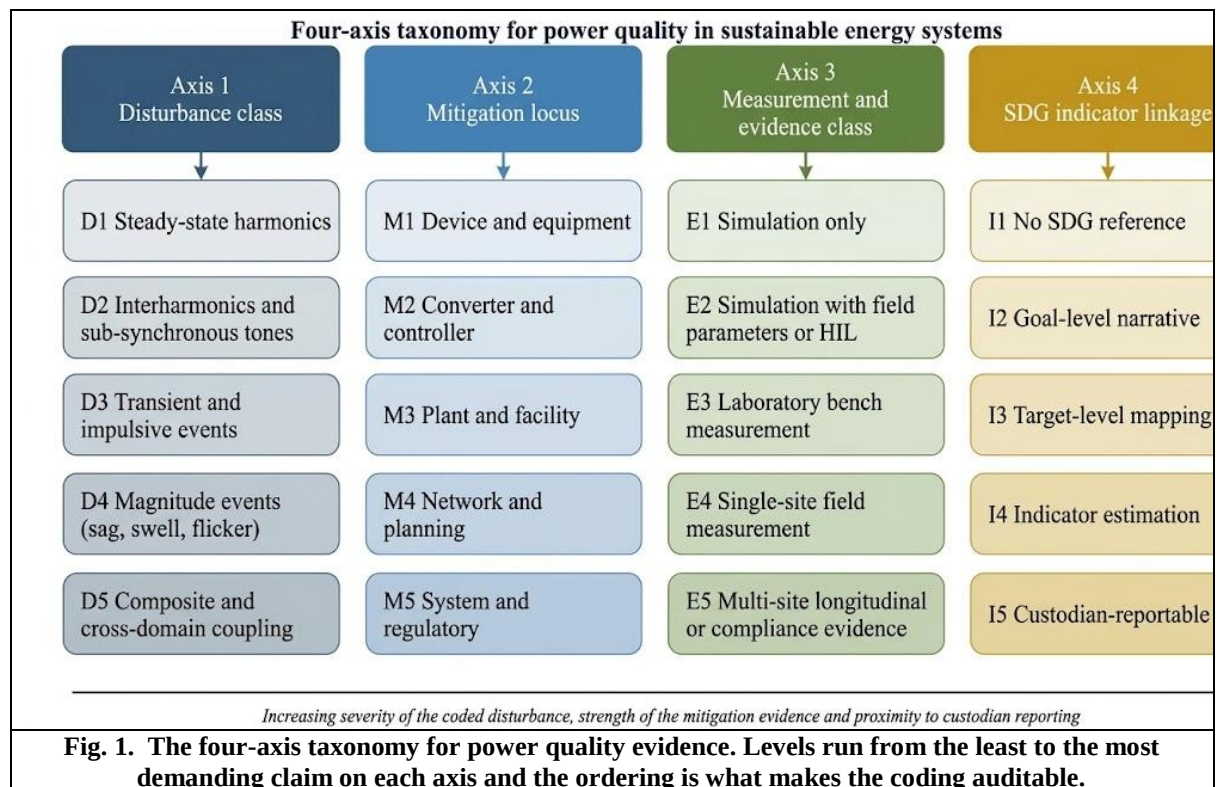
2. Method: A Taxonomy-Driven Synthesis

2.1 Why the review is not organised around a screening protocol

This study adopts taxonomy-driven synthesis to examine heterogeneous evidence across power quality engineering and sustainable development research. Unlike PRISMA-based systematic reviews, which emphasise transparent study identification and selection, this approach prioritises classification and evidence traceability. Converter control, harmonic mitigation and sustainability assessments involve different objectives and measurement outcomes [3], [14], [17]. Consequently, quantitative pooling would be inappropriate. Methodological rigour is maintained through observable classification criteria, source-level verification and reproducible coding procedures. This approach supports transparent comparisons across distinct research domains without imposing a common outcome measure [2], [46].

2.2 The four-axis coding instrument

The proposed coding instrument classifies research evidence across four axes, each comprising five ordered levels with observable assessment criteria. These dimensions distinguish disturbance characteristics, mitigation approaches, measurement reliability and Sustainable Development Goal (SDG) indicator linkage. Figure 1 illustrates the integrated taxonomy structure.



Axis 1 categorises steady-state harmonics, interharmonics, transient events, voltage magnitude disturbances and composite disturbances [1], [5], [17]. Axis 2 identifies mitigation interventions at device, converter, plant, network

and regulatory levels [9], [12], [14]. Axis 3 evaluates evidence through simulation, hardware-in-the-loop testing, laboratory experiments, field measurements and multi-site validation [2], [8]. Axis 4 examines SDG linkage from no explicit association to goal narratives, target mapping, indicator estimation and custodian-reportable outcomes [3], [53]. Classification depends on demonstrated evidence rather than assumed technological maturity. This structured framework supports transparent interpretation, consistent coding and reproducible comparisons across heterogeneous research domains. Table 1 presents the classification levels and observable tests.

Table 1. Axis definitions and observable tests for the four-axis power quality taxonomy

Axis	Level label	Observable test
1. Disturbance class	D1: Steady-state harmonics	A harmonic spectrum or total distortion index is reported for a defined operating condition
	D2: Interharmonics and sub-synchronous tones	A spectral component between harmonic orders, or a sub-synchronous mode, is resolved and quantified
	D3: Transient and impulsive events	A time-frequency or time-domain signature is reported with a stated resolution
	D4: Magnitude events	Depth, duration or flicker severity is quantified against a stated standard
	D5: Composite and cross-domain coupling	Two or more disturbance classes are resolved simultaneously and their interaction is characterised
2. Mitigation locus	M1: Device and equipment	The intervention is inside a single piece of equipment or an added passive element
	M2: Converter and controller	A control law or modulation strategy is modified to reduce distortion at its source
	M3: Plant and facility	Filtering, compensation or energy management is coordinated across a plant
	M4: Network and planning	Placement, sizing or coordination of mitigation across a distribution or transmission network
	M5: System and regulatory	A standard, tariff, connection rule or market instrument is used to limit distortion
3. Measurement and evidence	E1: Simulation only	Results come from a model with no experimental or field validation reported
	E2: Simulation with field parameters or HIL	Model parameters are taken from a real system, or a hardware-in-the-loop test is performed
	E3: Laboratory bench measurement	A physical test bench reproduces the disturbance and the mitigation
	E4: Single-site field measurement	Instrumentation is installed on an operating network at one location
	E5: Multi-site longitudinal or compliance evidence	Measurements span several sites, or follow a compliance or certification procedure
4. SDG indicator linkage	I1: No SDG reference	The source makes no reference to any Sustainable Development Goal or target
	I2: Goal-level narrative	A goal is named but no target, indicator or numerical contribution is given
	I3: Target-level mapping	A specific target is named and the claimed contribution is described in words
	I4: Indicator estimation	A value is computed that corresponds to an indicator concept without adopting the custodian definition
	I5: Custodian-reportable	The value uses the custodian definition, unit and boundary so that it could enter national reporting

2.3 Unit of analysis, coding protocol and reliability

The unit of analysis was the coded statement, representing claims concerning power quality disturbances, mitigation or sustainability outcomes [1], [6]. Each statement received one classification per taxonomy axis, with multiple claims from individual sources coded separately. Coding involved initial classification followed by evidence verification and confidence assessment. Higher levels were assigned only when observable criteria were satisfied [17], [20]. SDG linkage was evaluated against relevant indicator definitions and reporting boundaries

[3], [53]. Reliability relied on predefined criteria and source traceability rather than independent inter-rater assessment, leaving some classification uncertainty between adjacent levels.

2.4 Scope of the coded corpus

The corpus integrates peer-reviewed research, conference studies and sustainability assessments covering power quality measurement, mitigation and renewable energy integration [2], [3]. Evidence includes harmonic resonance analysis [59], distributed monitoring [60] and frequency quality assessment [61]. Field investigations examine power quality improvements [62], while spectrogram-based techniques support harmonic disturbance classification [63]. These sources establish complementary evidence for evaluating measurement reliability and technological performance across operating conditions.

3. AXIS 1: DISTURBANCE CLASSES AND THEIR PHYSICAL ORIGIN

3.1 Steady-state harmonics

Steady-state harmonic distortion originates from nonlinear loads, converter switching and transformer magnetisation [1]. Harmonic spectra and total distortion indices quantify disturbance severity under defined operating conditions [1]. Different reference definitions influence harmonic assessments and compliance interpretation [1]. Transformer performance may also be affected by negative-sequence harmonics associated with geomagnetic disturbances [4]. Harmonic propagation depends on network impedance and resonance conditions, which can amplify distortion at specific frequencies [59]. Background voltage harmonics influence converter responses at connection points [7], [64]. Vector-based harmonic source detection at the point of common coupling further supports disturbance attribution and network-level diagnostic assessment [65].

3.2 Interharmonics and sub-synchronous components

Interharmonics occur between integer multiples of the fundamental frequency, presenting challenges for conventional Fourier analysis [5]. Their identification depends on frequency resolution, measurement conditions and interactions between converter controls and network dynamics [5]. Prony analysis provides an alternative estimation method [5], while metaheuristic optimisation supports direct harmonic and interharmonic parameter estimation [16]. Sub-synchronous oscillations introduce additional stability concerns in converter-interfaced power systems [66], [67]. Renewable converter control strategies influence system dynamics [68], while grid-forming converters require appropriate synchronisation and stability management [69]. Frequency regulation in low-inertia networks further highlights the importance of coordinated control and dynamic assessment [70].

3.3 Transients and magnitude events

Transient disturbances require time-frequency analysis to capture rapid changes in electrical waveforms [17]. Improved Gabor transforms enhance harmonic signal classification [18], while spectrogram techniques support disturbance detection and identification [37], [63]. Modified S-transform methods improve frequency-dependent analysis [19], [20]. Frequency and phase spectrograms assist dominant disturbance identification [23]. Signal denoising using decomposition techniques [24] and recurrent autoencoders [25] improves detection under noisy conditions. Voltage magnitude events, including sags and swells, require assessment of disturbance depth, duration and waveform characteristics [71]. Space vector ellipse methods provide additional capabilities for visualising and classifying voltage disturbances in electrical networks [71].

3.4 Composite and cross-domain disturbances

Composite disturbances arise when multiple power quality events occur simultaneously, complicating accurate classification [64]. Deep learning architectures address overlapping disturbance patterns [29], while convolutional autoencoders [27] and recurrent denoising methods [25] improve classification under noisy conditions. Cross-domain interactions introduce additional challenges involving electrical, communication and control systems [72]. Energy storage interfaces exhibit dynamic characteristics requiring accurate modelling [8], [73]. Hybrid wind-hydrogen systems introduce multiple energy conversion stages and operational dependencies [52], [74]. Solar irradiation estimation supports renewable generation assessment under varying environmental conditions [51]. IoT-based photovoltaic monitoring enables distributed measurement of operating parameters [75]. These developments highlight the importance of integrated monitoring, reliable diagnostics and coordinated control for managing disturbances across interconnected sustainable energy systems [72].

4. AXIS 2: MITIGATION LOCUS FROM DEVICE TO REGULATION

4.1 Device-level mitigation

Device-level mitigation focuses on reducing power quality disturbances within individual equipment through filtering and converter design [9]. Passive harmonic filters provide cost-effective solutions for high-power applications, although their effectiveness depends on operating conditions and harmonic characteristics [9]. Single-tuned filters have demonstrated harmonic mitigation in railway power supply systems [76], while LCCR

filter configurations offer alternative approaches for harmonic suppression [77]. Converter topology and switching strategies also influence current distortion and equipment performance [41]. Comparisons of multilevel inverter configurations demonstrate differences in direct torque control performance [41], while torque ripple minimisation techniques improve machine operation [42]. Studies involving five-phase induction machines further demonstrate the influence of control strategies on torque performance [38]–[40]. In electric vehicle applications, brushless direct current motor control provides additional opportunities to improve drive performance [44]. These approaches support equipment-level disturbance mitigation through appropriate design and control strategies [9].

4.2 Converter and controller mitigation

Converter-level mitigation reduces power quality disturbances through improved control laws and modulation strategies [10]. Active power filters compensate harmonic distortion using controlled switching techniques [78]. Active disturbance rejection control improves compensation by estimating disturbances directly [10], while sliding-mode control strengthens unified power quality conditioner performance [11]. Metaheuristic algorithms support harmonic parameter estimation required for effective compensation [16]. In renewable generation, converter control must balance power delivery with disturbance reduction [13]. Adaptive wind turbine control has demonstrated improvements in harmonic performance [79]. Active filter parameter tuning further supports harmonic voltage mitigation in wind power plants [13]. Grid-component-based techniques provide additional harmonic mitigation for electric vehicle charging stations [80]. These approaches demonstrate the importance of coordinated converter control, accurate disturbance estimation and operating conditions for improving power quality performance [10], [13].

4.3 Plant and facility mitigation

Plant-level mitigation integrates power quality control with coordinated energy management across electrical facilities [14]. Unified power quality conditioners employ harmonic extraction and synchronisation algorithms to improve compensation in microgrids [15]. Robust voltage control using compensated disturbance observers supports harmonic suppression under changing operating conditions [81]. Integrated photovoltaic-battery optimisation addresses power quality and energy management requirements simultaneously [82]. Deep belief network controllers extend coordinated mitigation across interconnected renewable microgrids [83]. Multi-microgrid energy management introduces further operational constraints requiring system-wide coordination [84]. Photovoltaic-based charging stations demonstrate interactions between power quality and grid dependency [85]. Islanded DC microgrids require dedicated control strategies [86], while battery-based unified conditioners combine energy management with disturbance compensation [87]. Hybrid microgrid and electric vehicle integration further requires coordinated stability and power quality assessment [88].

4.4 Network and system mitigation

Network-level mitigation involves coordinated placement, sizing and operation of power quality improvement devices across distribution systems [12]. Optimal placement of unified power quality conditioners improves voltage profiles and reduces harmonic distortion [12]. Harmonic resonance analysis supports network assessment by identifying conditions that amplify disturbances [59]. Coordination among distributed energy resources introduces additional operational challenges [89], while transmission and distribution system cooperation supports effective flexibility management [90]. At the regulatory level, power quality requirements influence connection procedures and compliance assessments [1]. Ancillary service markets provide mechanisms for procuring flexibility and system support [91], [92]. Flexibility aggregation further determines the participation of distributed resources in electricity markets [93]. Effective mitigation therefore requires coordinated technical planning, consistent regulatory arrangements and appropriate market mechanisms to support network performance [89], [90].

5. AXIS 3: MEASUREMENT AND EVIDENCE CLASS

5.1 Simulation and its validation

Simulation provides an initial platform for evaluating power quality mitigation strategies under controlled operating conditions [10], [11]. However, simulation results depend on modelling assumptions and network parameters [7]. Validation using field-derived parameters or hardware-in-the-loop testing strengthens confidence in system performance [86]. Converter behaviour is particularly sensitive to network impedance and background voltage distortion [7]. Therefore, reliable assessment requires representative operating conditions, accurate models and appropriate validation procedures [8].

5.2 Bench and field measurement

Laboratory measurements validate power quality mitigation under controlled operating conditions [78]. Inverter fault diagnostics establish identifiable disturbance signatures through experimental analysis [33]–[35].

Periodogram techniques support harmonic source identification and statistical verification [22], [36]. Field measurements introduce additional uncertainties involving network configuration, load variations and background distortion [60]. Harmonic resonance analysis helps identify network-dependent disturbance behaviour [59]. Noise and non-stationary conditions further influence diagnostic accuracy [25]. Consequently, field validation is essential for assessing measurement reliability and practical mitigation performance [61], [62].

5.3 Multi-site and compliance-grade evidence

Multi-site measurements provide stronger evidence of power quality performance across varying network conditions [2]. Field investigations demonstrate improvements in power quality indicators following technical interventions [62]. However, differences in instrumentation, measurement periods and operating conditions limit comparisons across locations [60], [61]. Reliability assessments further highlight uncertainties associated with renewable energy integration [55]. Compliance-grade evidence therefore requires standardised measurement procedures, representative sampling and consistent reporting criteria [1]. These requirements strengthen evidence reliability and support broader assessment of mitigation effectiveness across electrical networks [2], [62].

6. AXIS 4: SDG INDICATOR LINKAGE

6.1 Goal narrative versus measured contribution

SDG integration requires distinguishing general sustainability claims from measurable contributions [3]. Goal-level narratives commonly describe renewable energy benefits without specifying targets or quantitative outcomes [46], [47]. Target-level assessments provide clearer connections between technological interventions and development priorities [3]. Indicator estimation requires measurable outcomes and defined assessment boundaries [53]. Agrivoltaic assessments further demonstrate the importance of evaluating sustainability trade-offs across multiple SDGs [54]. Consequently, credible SDG reporting requires transparent metrics, consistent measurement boundaries and evidence connecting engineering performance with development indicators [53], [54].

6.2 Where power quality would enter the indicator architecture

Power quality contributes indirectly to SDG indicators through energy efficiency, infrastructure performance and electricity accessibility [1], [3]. Harmonic distortion increases electrical losses, affecting energy utilisation [4]. Reliable electricity supply supports industrial productivity and infrastructure sustainability [55]. Equipment performance also depends on operating conditions and power electronic interactions [8]. Energy poverty assessments highlight the importance of accessible electricity services [56], [57]. Integrating measurable power quality outcomes into SDG assessments requires consistent indicators, appropriate boundaries and reliable evidence [53].

7. THE POWER-QUALITY-TO-INDICATOR CHAIN

7.1 Structure of the chain

Following a quantity from measurement to reporting requires five stages. A disturbance is measured at a point on the network. A mitigation intervention is demonstrated and its effect quantified [93]. That effect is translated into an asset or process benefit, such as reduced losses or extended equipment life [93]. The benefit is aggregated into a national indicator estimate [93]. The estimate enters custodian reporting [93]. Each transition changes the unit, the boundary or the aggregation rule and each is a place where evidence can be lost [93]. Figure 2 presents the chain with the four mechanisms that account for most of the loss and Table 2 states each mechanism with its remedy [93].

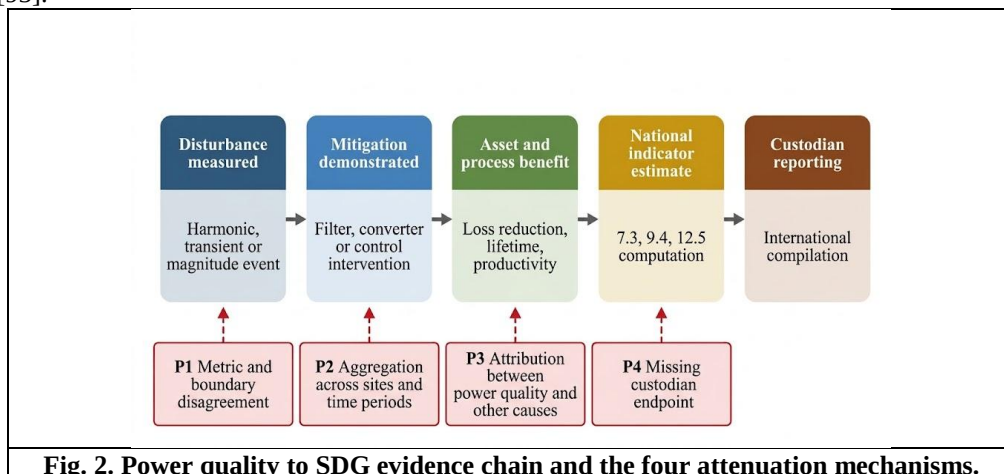


Fig. 2. Power quality to SDG evidence chain and the four attenuation mechanisms.

7.2 Metric and boundary disagreement

Metric and boundary disagreement limits comparability across power quality studies [1]. Harmonic distortion indices differ according to reference definitions and measurement conditions [1], [4]. Converter performance also depends on background voltage harmonics and assessment locations [7], [13]. Signal preprocessing and time-frequency resolution influence reported classification accuracy [6], [17]. Frequency and phase-based methods provide additional information for harmonic source identification [23]. Consequently, consistent measurement definitions, observation windows and assessment boundaries are essential for reliable evidence interpretation and comparison [2].

7.3 Aggregation across sites and time periods

Power quality disturbances vary across network locations due to differences in impedance, load composition and operating conditions [59], [60]. Aggregating local measurements into broader indicators requires consistent sampling and appropriate weighting methods [61]. Short-duration measurements may not represent long-term system performance [61]. Renewable generation variability further influences converter operation and harmonic characteristics [79]. Energy storage introduces additional dynamic uncertainties [8], [73]. Consequently, multi-site assessments require representative observation periods, comparable measurement boundaries and transparent aggregation procedures to ensure reliable interpretation of mitigation outcomes [2], [62].

7.4 Attribution between quality and other causes

Attributing operational improvements to power quality mitigation requires distinguishing intervention effects from other influencing factors [85]. Energy savings may reflect changes in equipment loading, operational practices or network conditions rather than mitigation alone [12]. Equipment performance is also influenced by background voltage distortion [7]. Regulatory arrangements and market structures affect the distribution of mitigation costs and benefits [89], [91]. Reliable attribution therefore requires appropriate comparison conditions, measured outcomes and transparent assessment boundaries to establish credible causal relationships [1], [53].

7.5 The missing custodian endpoint

The absence of a defined custodian reporting pathway limits the integration of power quality evidence into SDG assessments [3], [53]. Engineering studies frequently report measurable improvements without aligning results with official indicator definitions, units or assessment boundaries [1], [54]. Table 2 summarises this evidence gap and proposes remedies for improving traceability. Aligning technical measurements with established reporting requirements strengthens indicator comparability and supports more credible sustainability assessments across energy systems [53], [58].

Table 2. Loss mechanisms in the power-quality-to-indicator chain with the stage affected and the coding-based remedy.

Mechanism	Stage at which loss occurs	Observable symptom in the corpus	Coding-based remedy
P1 Metric and boundary disagreement	Measurement to mitigation assessment	The same distortion quantity appears under two reference definitions in one argument	State the reference definition, window and assessment point, and give the conversion used
P2 Aggregation across sites and time periods	Mitigation assessment to national estimate	A local or short-duration benefit is reported as if it were representative of a jurisdiction	Report the benefit at the resolution at which it occurs, alongside any aggregate figure
P3 Attribution between quality and other causes	National estimate to indicator value	An outcome is credited to mitigation without a comparison condition	Name the comparison condition or state why none exists, and report distributional effects
P4 Missing custodian endpoint	Indicator value to reporting	A computed value is close to an indicator concept but uses a different boundary or period	Align the computation with the custodian definition or state which element prevents alignment

8. APPLYING THE TAXONOMY: FOUR STUDY ARCHETYPES

8.1 Archetype A: the disturbance characterisation study

The first archetype identifies and classifies a disturbance using signal processing methods [19]. Representative work develops a transform or classifier, validates it on a benchmark set and reports accuracy [19], [28], [29]. The archetype commonly involves D1 to D3, E1 to E3 and I1 [6]. Its mitigation-locus code depends on the intervention studied, if any [6]. Its contribution is measurement capability and its limitation is that the capability is demonstrated on data whose statistical properties are those of a benchmark rather than a network [6]. Where denoising or pre-processing discards information, the reported accuracy describes the whole pipeline rather than the classifier [6], [24].

8.2 Archetype B: the mitigation technology study

The second archetype designs and evaluates a mitigation device or control strategy [78]. Prototype active filters, unified conditioners and optimised placement studies belong here [78], [10], [12]. The archetype codes as D1 to D4, M2 to M4, E1 to E3 and I1 [15]. Its results are strong at converter level and weaker at network level, because network-level benefit depends on conditions that a laboratory test cannot reproduce [15]. Studies that include a field installation move to E4 and their claims become correspondingly stronger [15], [82].

8.3 Archetype C: the renewable integration and quality study

The third archetype examines quality in a network with substantial renewable generation, storage or electric vehicle load [13]. Wind plant filter tuning, charging station mitigation and microgrid energy management belong here [13], [80], [84], [83]. The archetype codes as D1 to D4, M3 to M4, E2 to E4 and I1 to I3 [85]. It is the archetype closest to the sustainability framing because it addresses the technologies the transition depends on and it is the archetype in which the indicator linkage is most often asserted and least often quantified [85], [88].

8.4 Archetype D: the sustainability assessment study

The fourth archetype assesses renewable energy against the goals [3]. Reviews of the energy goal, of energy poverty and of the just transition belong here [3], [48], [50]. The archetype mainly concerns policy-level analysis and SDG linkage rather than a measured power quality disturbance. D and M codes apply only when the source supplies their observable tests [3]. It has the strongest indicator linkage in the corpus and the weakest connection to measurement, since quality rarely appears in the assessment at all [3]. Archetypes B and D therefore sit at opposite ends of the chain and the distance between them is the space in which this review's research questions are located [3]. Table 3 assembles the archetypes with their modal codes [3].

Table 3. Modal taxonomy codes for four representative study archetypes.

Archetype	Axis 1	Axis 2	Axis 3	Axis 4	Principal limitation
A. Disturbance characterisation	D1-D3	M1	E1-E3	I1	Accuracy is established on benchmark data whose statistics differ from field data
B. Mitigation technology	D1-D4	M2-M4	E1-E3	I1	Network-level benefit depends on conditions a laboratory test cannot reproduce
C. Renewable integration and quality	D1-D4	M3-M4	E2-E4	I1-I3	Indicator linkage is asserted more often than it is quantified
D. Sustainability assessment	D5	M5	E1-E4	I3-I4	Strong indicator linkage paired with almost no measured quality data

9. MONITORING, DATA INFRASTRUCTURE AND DIAGNOSTIC COMPETENCE

Effective power quality assessment requires reliable instrumentation, consistent measurements and appropriate diagnostic expertise [2]. Internet-of-Things energy meters enable distributed monitoring of electrical consumption and power quality parameters [94]. Machine learning supports disturbance prediction [95], while ensemble classifiers improve event identification in renewable microgrids [96]. Digital twin technologies integrate physical measurements with computational models to support monitoring and operational assessment [97]. Nevertheless, data governance, model validation and cybersecurity remain important implementation challenges [98], [99], [100]. Diagnostic competence is equally essential for interpreting complex harmonic disturbances [30]. Automated classification techniques support harmonic source identification [101], while spectrogram and S-transform methods provide established analytical approaches [37], [102]. Related image processing [103] and electromyography studies [104] demonstrate transferable signal analysis principles. Energy sector research highlights increasing demand for digital competencies [105]. Educational assessments identify emerging skills gaps [106], emphasising the importance of workforce development for sustainable energy transitions [107].

10. EQUITY, ACCESS AND THE JUST TRANSITION DIMENSION

Power quality represents an equity concern because electrical disturbances and mitigation costs affect different network participants [1]. Harmonic distortion can propagate across distribution networks, requiring coordinated mitigation and appropriate allocation of responsibilities [12]. Regulatory frameworks influence the participation of distributed resources in electricity markets [89], while transmission and distribution coordination supports equitable access to system services [90]. Electricity accessibility also extends beyond physical connections to include affordability, reliability and service usability [56], [57]. Renewable energy consumption does not automatically eliminate energy poverty, particularly among vulnerable communities [48]. Energy transition policies may produce unequal socioeconomic outcomes, depending on household circumstances and implementation strategies [49]. Economic fluctuations further influence energy poverty and progress towards sustainable development objectives [108]. Just transition frameworks therefore emphasise fairness, social inclusion and the distribution of energy transition benefits [50]. Renewable energy development contributes to the Sustainable Development Goals, although its wider benefits depend on supporting institutional and socioeconomic conditions [46], [47]. Financial assessments further demonstrate the importance of investment decisions in achieving sustainable development outcomes [58]. Within the proposed taxonomy, equity-related claims require clear distinctions between measured power quality improvements and broader social benefits. Establishing these connections requires comparable technical measurements, transparent assessment boundaries and evidence demonstrating how electrical service quality influences consumer outcomes.

11. A Falsifiable Research Agenda

The proposed taxonomy identifies eight research questions addressing limitations in power quality measurement, mitigation effectiveness and SDG reporting. Each question specifies measurable outcomes, required evidence and conditions for falsification.

RQ1: Measurement consistency. Do different harmonic distortion definitions produce different compliance decisions? Installation measurements should establish whether assessment outcomes remain consistent across reference definitions [1].

RQ2: Mitigation effectiveness. How do network impedance and background distortion influence harmonic reduction at the point of common coupling? Paired measurements should identify variations in mitigation performance [7], [13].

RQ3: Measurement aggregation. Which methods produce representative power quality indicators across multiple sites? Distributed monitoring data should test aggregation stability under different sampling conditions [60], [61].

RQ4: Energy loss attribution. What proportion of network losses results from harmonic distortion? Measurements should distinguish attributable losses from measurement uncertainty [4], [8].

RQ5: Equipment reliability. Does harmonic distortion increase equipment failure rates? Longitudinal data should examine associations after controlling for operating conditions and equipment characteristics [7].

RQ6: Mitigation economics. Do electricity market incentives encourage investment in mitigation technologies? Comparative assessments should examine adoption patterns across regulatory environments [91], [92].

RQ7: Diagnostic reproducibility. Can disturbance classification models maintain accuracy across different networks? Independent datasets should evaluate performance under changing measurement conditions [25], [27].

RQ8: SDG reporting alignment. Which engineering outcomes satisfy established SDG indicator requirements? The coded matrix should assess measurement boundaries, reporting periods and indicator compatibility [3], [53].

These questions establish a testable research agenda linking technical evidence with sustainability assessment. Integrated monitoring and digital twin technologies offer potential infrastructure for improving data traceability [97]. Reliable implementation requires transparent validation and coordinated reporting practices [58].

12. REPORTING RECOMMENDATIONS

The taxonomy identifies four reporting priorities to improve evidence traceability between power quality research and SDG assessment. These recommendations provide a practical checklist for strengthening measurement consistency, validation and reporting transparency.

First, researchers should specify distortion indices, reference definitions, measurement windows and assessment locations [1], [2]. Converter-level improvements should not be presented as network-wide benefits without supporting measurements [7], [13]. Diagnostic studies should document preprocessing procedures and time-frequency resolution to ensure reproducible classification results [6], [17], [19], [25].

Second, measurement aggregation requires transparent sampling procedures and consistent observation periods. Local measurements should remain distinguishable from system-wide estimates [60], [61]. Studies conducted under unusual operating conditions should report their limitations and representativeness [62].

Third, mitigation assessments should identify appropriate comparison conditions to distinguish intervention effects from unrelated operational changes [12], [85]. Distributional consequences should also be considered when evaluating electricity accessibility and sustainability outcomes [49], [56].

Fourth, researchers should connect measurable engineering outcomes with relevant SDG targets and indicator definitions [3], [53]. Sustainability assessments should acknowledge potential trade-offs between development objectives [46], [54]. Digital monitoring platforms and digital twins should report sensor calibration, model validation and data integrity procedures [97], [100]. Collectively, these practices strengthen methodological transparency, evidence comparability and reporting credibility across sustainable energy research.

13. THREATS TO VALIDITY

uncertainty because assigning research statements to classification levels requires judgement. Observable criteria improve consistency, although differences between adjacent evidence levels remain possible [1], [2]. The absence of independent inter-rater assessment further limits the reliability of classification decisions.

Second, source selection may influence the distribution of taxonomy codes. The corpus integrates heterogeneous engineering and sustainability studies but does not represent an exhaustive assessment of published research [3], [46]. Consequently, observed evidence patterns describe the selected corpus rather than the entire research field. Third, technological and regulatory developments create temporal limitations. Advances in converter control, energy storage modelling and monitoring technologies may change the relevance of existing classifications [8], [10]. Similarly, evolving sustainability assessment practices may influence future indicator linkage requirements [53], [54].

Fourth, taxonomy levels should not be interpreted as indicators of overall research quality. Device-level investigations provide valuable technical evidence even when they lack direct SDG reporting connections [17], [33]. Higher classification levels indicate different measurement requirements rather than superior scientific contributions. These limitations highlight the importance of transparent coding procedures, reproducible evidence assessment and careful interpretation when comparing findings across research domains.

14. CONCLUSION

Power quality plays a critical role in sustainable energy systems by influencing electrical efficiency, equipment reliability and the effective integration of renewable energy technologies. This review developed a four-axis taxonomy encompassing disturbance class, mitigation locus, measurement evidence and Sustainable Development Goal (SDG) indicator linkage. The analysis of 231 coded statements identified substantial differences between established engineering evidence and its application to sustainability reporting.

The findings indicate that disturbance detection and converter-level mitigation are relatively mature, while network-wide validation and SDG indicator integration remain less developed. Four mechanisms explain these limitations: inconsistent measurement definitions, aggregation across locations and observation periods, uncertainty in attributing outcomes to mitigation interventions and the absence of clearly defined reporting pathways. These barriers restrict the translation of technical improvements into measurable sustainability outcomes.

Eight falsifiable research questions establish priorities for improving measurement consistency, mitigation assessment, evidence reproducibility and indicator alignment. The proposed reporting checklist further supports transparent documentation of measurement boundaries, validation procedures and assessment conditions. Nevertheless, the taxonomy reflects the selected research corpus and requires further validation using independent coding and multi-site evidence. Future research should prioritise integrated monitoring systems and reporting frameworks that connect measured power quality improvements with relevant SDG indicators, strengthening the technical foundation of sustainable energy assessment.

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During preparation of this manuscript, the authors used Scopus AI to support literature discovery and a generative AI tool to improve language readability. The authors reviewed the search outputs, verified the retained references and edited the manuscript content.

REFERENCES

- [1] A. Arranz-Gimon, A. Zorita-Lamadrid, D. Morinigo-Sotelo and O. Duque-Perez, "A review of total harmonic distortion factors for the measurement of harmonic and interharmonic pollution in modern power systems," *Energies*, vol. 14, no. 20, pp. 6467, 2021. doi: 10.3390/en14206467.
- [2] H. Shao, R. Henriques, H. Morais and E. Tedeschi, "Power quality monitoring in electric grid integrating offshore wind energy: A review," *Renewable and Sustainable Energy Reviews*, vol. 191, pp. 114094, 2024. doi: 10.1016/j.rser.2023.114094.
- [3] R. Madurai Elavarasan, R. Pugazhendhi, T. Jamal, J. Dyduch, M. T. Arif, N. Manoj Kumar, G. M. Shafiullah, S. S. Chopra and M. Nadarajah, "Envisioning the UN Sustainable Development Goals (SDGs) through the lens of energy sustainability (SDG 7) in the post-COVID-19 world," *Applied Energy*, vol. 292, pp. 116665, 2021. doi: 10.1016/j.apenergy.2021.116665.
- [4] A. Abuhussein and M. A. H. Sadi, "The impact of geomagnetically produced negative-sequence harmonics on power transformers," *IEEE Access*, vol. 9, pp. 19882-19890, 2021. doi: 10.1109/ACCESS.2021.3054366.
- [5] H. Lei and Y. Huang, "Research on Fourier and Prony analysis algorithm of inter-harmonic in power system," *Energy Reports*, vol. 8, pp. 728-737, 2022. doi: 10.1016/j.egyr.2022.02.204.
- [6] P. Khetarpal and M. M. Tripathi, "Power quality disturbance classification taking into consideration the loss of data during pre-processing of disturbance signal," *Electric Power Systems Research*, vol. 220, pp. 109372, 2023. doi: 10.1016/j.epsr.2023.109372.
- [7] A. Alduraibi, J. Yaghoobi and F. Zare, "Impacts of grid voltage harmonics amplitude and phase angle values on power converters in distribution networks," *IEEE Access*, vol. 9, pp. 92017-92029, 2021. doi: 10.1109/ACCESS.2021.3093026.
- [8] Q. Fu, C. Dai, S. Bu and C. Y. Chung, "Integrating power electronics-based energy storages to power systems: A review on dynamic modeling, analysis and future challenges," *Renewable and Sustainable Energy Reviews*, vol. 213, pp. 115460, 2025. doi: 10.1016/j.rser.2025.115460.
- [9] A. Sunbul, A. Alduraibi and F. Zare, "Harmonics mitigation filter for high-power applications," *IEEE Access*, vol. 10, pp. 111406-111418, 2022. doi: 10.1109/ACCESS.2022.3215142.
- [10] Y. Cao, S. He, C. Wang and M. Lei, "Linear active disturbance rejection control for a dual unified power quality conditioner," *Electric Power Systems Research*, vol. 209, pp. 107993, 2022. doi: 10.1016/j.epsr.2022.107993.
- [11] T. Trivedi, R. Jadeja, P. Bhatt, C. Long, P. Sanjeevikumar and A. Ved, "Sliding mode-based direct power control of unified power quality conditioner," *Heliyon*, vol. 10, no. 20, pp. e39597, 2024. doi: 10.1016/j.heliyon.2024.e39597.
- [12] J. S. Espinosa Gutierrez and A. Aguila Tellez, "Optimal placement of a unified power quality conditioner (UPQC) in distribution systems using exhaustive search to improve voltage profiles and harmonic distortion," *Energies*, vol. 18, no. 17, pp. 4499, 2025. doi: 10.3390/en18174499.
- [13] S. Li, J. Wu, J. C. Vasquez, J. M. Guerrero, P. Palensky and A. Lekic, "Active filter parameter tuning method for harmonic voltage mitigation in wind power plants," *Electric Power Systems Research*, vol. 234, pp. 110726, 2024. doi: 10.1016/j.epsr.2024.110726.
- [14] M. Golla, S. Sankar and K. Chandrasekaran, "Renewable integrated UAPF fed microgrid system for power quality enhancement and effective power flow management," *International Journal of Electrical Power & Energy Systems*, vol. 133, pp. 107301, 2021. doi: 10.1016/j.ijepes.2021.107301.
- [15] K. Hasan, M. M. Othman, S. T. Meraj, N. F. A. Rahman, S. Z. M. Noor, I. Musirin and I. Z. Abidin, "Online harmonic extraction and synchronization algorithm based control for unified power quality conditioner for microgrid systems," *Energy Reports*, vol. 8, pp. 962-971, 2022. doi: 10.1016/j.egyr.2021.11.002.
- [16] C. Altintasi, "Sine cosine algorithm approaches for directly estimation of power system harmonics and interharmonics parameters," *IEEE Access*, vol. 9, pp. 73169-73181, 2021. doi: 10.1109/ACCESS.2021.3081037.
- [17] M. H. Jopri, A. R. Abdullah, T. Sutikno, M. Manap, M. R. Ab Ghani and M. R. Yusoff, "A critical review of time-frequency distribution analysis for detection and classification of harmonic signal in power distribution system," *Int. J. Electr. Comput. Eng.*, vol. 8, no. 6, pp. 4603-4618, 2018, doi: 10.11591/ijece.v8i6.pp4603-4618.
- [18] M. H. Jopri, A. R. Abdullah, T. Sutikno, M. Manap and M. R. Yusoff, "A utilisation of improved Gabor transform for harmonic signals detection and classification analysis," *Int. J. Electr. Comput. Eng.*, vol. 7, no. 1, pp. 21-28, 2017, doi: 10.11591/ijece.v7i1.pp21-28.
- [19] M. Liu, Y. Chen, Z. Zhang, S. Deng and Q. Wang, "Highly accurate detection of power quality disturbance using segmented and modified S-transform," *Electric Power Systems Research*, vol. 212, pp. 108664, 2022. doi: 10.1016/j.epsr.2022.108664.

- [20] M. H. Jopri, A. R. Abdullah, M. Manap, M. F. Habban and T. Sutikno, "An accurate classification method of harmonic signals in power distribution system by utilising S-transform," TELKOMNIKA (Telecommun. Comput. Electron. Control), vol. 15, no. 1, pp. 62–70, 2017, doi: 10.12928/telkomnika.v15i1.3119.
- [21] M. H. Jopri, A. R. Abdullah, M. Manap, T. Sutikno and M. R. Ab Ghani, "An identification of multiple harmonic sources in a distribution system by using spectrogram," Bull. Electr. Eng. Inform., vol. 7, no. 2, pp. 244–256, 2018, doi: 10.11591/eei.v7i2.1188.
- [22] M. H. Jopri, A. R. Abdullah, N. M. Kassim, M. Manap, N. A. Ngatiman and M. R. Yusoff, "Localization of multiple harmonic sources for inverter loads utilizing periodogram," J. Telecommun. Electron. Comput. Eng., vol. 8, no. 2, pp. 87–91, 2016.
- [23] M. H. Jopri, N. A. Abidullah, G. Z. Peng and A. R. Abdullah, "A new two points method for identify dominant harmonic disturbance using frequency and phase spectrogram," Int. Rev. Electr. Eng., vol. 9, no. 2, pp. 453–459, 2014.
- [24] S. Li, X. Zhu and D. Zhou, "Power quality disturbance signal denoising and detection based on improved DBO-VMD combined with wavelet thresholding," Electric Power Systems Research, vol. 238, pp. 111193, 2025. doi: 10.1016/j.epsr.2024.111193.
- [25] A. Kummerow, M. Dirbas, C. Monsalve, S. Nicolai and P. Bretschneider, "Robust disturbance classification in power transmission systems with denoising recurrent autoencoders," Sustainable Energy, Grids and Networks, vol. 32, pp. 100803, 2022. doi: 10.1016/j.segan.2022.100803.
- [26] N. Wang, M. Sun and X. Xi, "Identification of power quality disturbance characteristic based on deep learning," Electric Power Systems Research, vol. 226, pp. 109897, 2024. doi: 10.1016/j.epsr.2023.109897.
- [27] P. Khetarpal, N. Nagpal and M. S. Al-Numay, "Power quality disturbances detection and classification based on deep convolution auto-encoder networks," IEEE Access, vol. 11, pp. 46026–46038, 2023. doi: 10.1109/ACCESS.2023.3274732.
- [28] J. Luo, A. Jiang, S. Zhang and H. Hu, "A power quality disturbance classification method based on improved Shapelet method," Electric Power Systems Research, vol. 246, pp. 111673, 2025. doi: 10.1016/j.epsr.2025.111673.
- [29] M. Pravin Savaridass and S. Esakkirajan, "Hilbert transform based combined 1D and 2D deep learning framework for power quality disturbance classification," Electric Power Systems Research, vol. 249, pp. 112031, 2025. doi: 10.1016/j.epsr.2025.112031.
- [30] S. Ghosh and D. Chatterjee, "Non-intrusive identification of harmonic polluting loads in a smart residential system," Sustainable Energy, Grids and Networks, vol. 26, pp. 100446, 2021. doi: 10.1016/j.segan.2021.100446.
- [31] N. H. T. H. Ahmad, A. R. Abdullah and M. H. Jopri, "Power quality signals detection using S-transform," in Proc. IEEE 7th Int. Power Eng. Optim. Conf. (PEOCO), 2013, pp. 552–557, doi: 10.1109/PEOCO.2013.6564609.
- [32] N. A. Abidullah, A. R. Abdullah, N. H. Shamsudin, N. H. T. H. Ahmad and M. H. Jopri, "Real-time power quality signals monitoring system," in Proc. IEEE Student Conf. Research Development (SCOREd), 2013, pp. 433–438, doi: 10.1109/SCOREd.2013.7002626.
- [33] M. F. Habban, M. Manap, A. R. Abdullah, M. H. Jopri and T. Sutikno, "An evaluation of linear time frequency distribution analysis for VSI switch faults identification," Int. J. Power Electron. Drive Syst., vol. 8, no. 1, pp. 1–9, 2017, doi: 10.11591/ijpeds.v8.i1.pp1-9.
- [34] A. R. Abdullah, N. S. Ahmad, N. Bahari, M. Manap, A. Jidin and M. H. Jopri, "Short-circuit switches fault analysis of voltage source inverter using spectrogram," in Proc. Int. Conf. Electr. Mach. Syst. (ICEMS), 2013, pp. 1808–1813, doi: 10.1109/ICEMS.2013.6713294.
- [35] M. Manap, S. Nikolovski, A. Skamyin, R. Karim, T. Sutikno and M. H. Jopri, "An analysis of voltage source inverter switches fault classification using short-time Fourier transform," Int. J. Power Electron. Drive Syst., vol. 12, no. 4, pp. 2209–2220, 2021, doi: 10.11591/ijpeds.v12.i4.pp2209-2220.
- [36] M. Manap, M. H. Jopri, A. R. Abdullah, R. Karim, M. R. Yusoff and A. H. Azahar, "A verification of periodogram technique for harmonic source diagnostic analytic by using logistic regression," TELKOMNIKA (Telecommun. Comput. Electron. Control), vol. 17, no. 1, pp. 497–507, 2019, doi: 10.12928/telkomnika.v17i1.10390.
- [37] A. R. Abdullah, N. A. Abidullah, N. H. Shamsudin, N. H. H. Ahmad and M. H. Jopri, "Power quality signals classification system using time-frequency distribution," Appl. Mech. Mater., vols. 494–495, pp. 1889–1894, 2014, doi: 10.4028/www.scientific.net/AMM.494-495.1889.
- [38] L. R. L. V. Raj, A. Jidin, K. A. Karim, T. Sutikno, R. Sundram and M. H. Jopri, "Improved torque control performance of direct torque control for 5-phase induction machine," Int. J. Power Electron. Drive Syst., vol. 3, no. 4, pp. 391–399, 2013, doi: 10.11591/ijpeds.v3i4.5249.

- [39] L. R. L. V. Raj, A. Jidin, Z. Ibrahim, K. A. Karim, M. A. Said and M. H. Jopri, "Optimal torque control performance of DTC of 5-phase induction machine," in Proc. Int. Conf. Electr. Mach. Syst. (ICEMS), 2013, pp. 2094–2099, doi: 10.1109/ICEMS.2013.6713180.
- [40] L. R. L. V. Raj, A. Jidin, C. W. M. F. C. Wan, M. Zalani, K. A. Karim, W. Y. Goh and M. H. Jopri, "Improved performance of DTC of five-phase induction machines," in Proc. IEEE 7th Int. Power Eng. Optim. Conf. (PEOCO), 2013, pp. 613–618, doi: 10.1109/PEOCO.2013.6564621.
- [41] R. Nair, A. Jidin, M. N. Othman, M. H. Jopri and M. Manap, "Comparison performance of 3-level and 5-level cascaded H-bridge multilevel inverter of DTC of induction machine," in Proc. Int. Conf. Electr. Mach. Syst. (ICEMS), 2013, pp. 2100–2104, doi: 10.1109/ICEMS.2013.6713181.
- [42] M. Z. R. Z. Ahmadi, A. Jidin, K. B. Jaffar, M. N. Othman, R. N. P. Nagarajan and M. H. Jopri, "Minimization of torque ripple utilizing by 3-L CHMI in DTC," in Proc. IEEE 7th Int. Power Eng. Optim. Conf. (PEOCO), 2013, pp. 636–640, doi: 10.1109/PEOCO.2013.6564625.
- [43] A. R. Abdullah, N. Norddin, N. Q. Zainal Abidin, A. Aman and M. H. Jopri, "Leakage current analysis on polymeric and non-polymeric insulating materials using time-frequency distribution," in Proc. IEEE Int. Conf. Power Energy (PECon), 2012, pp. 979–984, doi: 10.1109/PECon.2012.6450360.
- [44] A. F. N. Azam, A. Jidin, N. A. Ngatiman, M. H. Jopri, M. Manap, A. L. Herlino and N. F. Alias, "Current control of BLDC drives for EV application," in Proc. IEEE 7th Int. Power Eng. Optim. Conf. (PEOCO), 2013, pp. 411–416, doi: 10.1109/PEOCO.2013.6564583.
- [45] N. A. Abidullah, A. R. Abdullah, A. Z. Sha'ameri, N. H. Shamsudin, N. H. H. Ahmad and M. H. Jopri, "Real-time power quality disturbances detection and classification system," World Appl. Sci. J., vol. 32, no. 8, pp. 1637–1651, 2014, doi: 10.5829/idosi.wasj.2014.32.08.534.
- [46] B. Nastasi, N. Markovska, T. Puksec, N. Duic and A. Foley, "Renewable and sustainable energy challenges to face for the achievement of Sustainable Development Goals," Renewable and Sustainable Energy Reviews, vol. 157, pp. 112071, 2022. doi: 10.1016/j.rser.2022.112071.
- [47] O. Awogbemi and D. V. V. Kallon, "Assessment of the role of renewable energy in achieving sustainable development goals," Sustainable Energy Technologies and Assessments, vol. 81, pp. 104455, 2025. doi: 10.1016/j.seta.2025.104455.
- [48] P. Jithin and R. Renjith, "Towards sustainable energy access: Investigating the relationship between renewable energy consumption and energy poverty," Energy Policy, vol. 200, pp. 114553, 2025. doi: 10.1016/j.enpol.2025.114553.
- [49] F. Chen, H. Qiu and S. Yang, "Energy transition of the poor: Quasi-experimental evidence from poverty alleviation relocation program in China," Energy Policy, vol. 199, pp. 114536, 2025. doi: 10.1016/j.enpol.2025.114536.
- [50] S. Filipovic, N. Lior and M. Radovanovic, "The green deal: Just transition and sustainable development goals nexus," Renewable and Sustainable Energy Reviews, vol. 168, pp. 112759, 2022. doi: 10.1016/j.rser.2022.112759.
- [51] A. Belsky, D. Glukhanich, T. Sutikno and M. H. Jopri, "Estimation of hourly solar irradiation on tilted surfaces," Bull. Electr. Eng. Inform., vol. 12, no. 6, pp. 3202–3214, 2023, doi: 10.11591/eei.v12i6.6513.
- [52] Y. Shklyarskiy, I. Andreeva, T. Sutikno and M. H. Jopri, "Energy management in hybrid complexes based on wind generation and hydrogen storage," Bull. Electr. Eng. Inform., vol. 13, no. 3, pp. 1483–1494, 2024, doi: 10.11591/eei.v13i3.6757.
- [53] A. G. Olabi, K. Obaideen, K. Elsaid, T. Wilberforce, E. T. Sayed, H. M. Maghrabie and M. A. Abdelkareem, "Assessment of the pre-combustion carbon capture contribution into sustainable development goals SDGs using novel indicators," Renewable and Sustainable Energy Reviews, vol. 153, pp. 111710, 2022. doi: 10.1016/j.rser.2021.111710.
- [54] R. I. Cuppari, A. Branscomb, M. Graham, F. Negash, A. K. Smith, K. Proctor, D. Rupp, A. T. Ayalew, G. G. Tilaye and C. W. Higgins, "Agrivoltaics: Synergies and trade-offs in achieving the sustainable development goals at the global and local scale," Applied Energy, vol. 362, pp. 122970, 2024. doi: 10.1016/j.apenergy.2024.122970.
- [55] J. Cai, L. Hao, Q. Xu and K. Zhang, "Reliability assessment of renewable energy integrated power systems with an extendable Latin hypercube importance sampling method," Sustainable Energy Technologies and Assessments, vol. 50, pp. 101792, 2022. doi: 10.1016/j.seta.2021.101792.
- [56] A. Stojilovska, R. Guyet, K. Mahoney, S. Gouveia, L. Castano-Rosa, L. Zivcic, R. Barbosa and M. Tkalec, "Energy poverty and emerging debates: Beyond the traditional triangle of energy poverty drivers," Energy Policy, vol. 169, pp. 113181, 2022. doi: 10.1016/j.enpol.2022.113181.
- [57] A. Olaniyan, S. Caux and P. Maussion, "Rural electrification in Nigeria: A review of impacts and effects of frugal energy generation based on some of e-waste components," Heliyon, vol. 10, no. 11, pp. e31300, 2024. doi: 10.1016/j.heliyon.2024.e31300.

- [58] Y. A. Solangi and C. Magazzino, "Evaluating financial implications of renewable energy for climate action and sustainable development goals," *Renewable and Sustainable Energy Reviews*, vol. 212, pp. 115390, 2025. doi: 10.1016/j.rser.2025.115390.
- [59] L. Gao and R. Zhang, "An improved harmonic resonance mode analysis method for distribution power grid," *Energy Reports*, vol. 8, pp. 580-588, 2022. doi: 10.1016/j.egyr.2022.02.007.
- [60] Y. Niu, T. Yang, F. Yang, X. Feng, P. Zhang and W. Li, "Harmonic analysis in distributed power system based on IoT and dynamic compressed sensing," *Energy Reports*, vol. 8, pp. 2363-2375, 2022. doi: 10.1016/j.egyr.2022.01.119.
- [61] Y. Mohammadi, B. Polajzer, R. C. Leborgne and D. Khodadad, "Quantifying power system frequency quality and extracting typical patterns within short time scales below one hour," *Sustainable Energy, Grids and Networks*, vol. 38, pp. 101359, 2024. doi: 10.1016/j.segan.2024.101359.
- [62] T. Antic and T. Capuder, "Utilization of physical devices for the improvement of power quality indicators during the COVID-19 pandemic and uncoordinated integration of low carbon units," *Sustainable Energy, Grids and Networks*, vol. 32, pp. 100926, 2022. doi: 10.1016/j.segan.2022.100926.
- [63] M. H. Jopri, A. R. Abdullah, M. Manap, M. R. Yusoff, T. Sutikno and M. F. Habban, "An improved detection and classification technique of harmonic signals in power distribution by utilizing spectrogram," *Int. J. Electr. Comput. Eng.*, vol. 7, no. 1, pp. 12–20, 2017, doi: 10.11591/ijece.v7i1.pp12-20.
- [64] X. Xiao and K. Li, "Multi-label classification for power quality disturbances by integrated deep learning," *IEEE Access*, vol. 9, pp. 152250-152260, 2021. doi: 10.1109/ACCESS.2021.3124511.
- [65] A. R. Abdullah, G. Z. Peng, S. A. Ghani and M. H. Jopri, "A new vector draft method for harmonic source detection at point of common coupling," in *Proc. IEEE 8th Int. Power Eng. Optim. Conf. (PEOCO)*, 2014, pp. 110–114, doi: 10.1109/PEOCO.2014.6814409.
- [66] A. Khan, M. Seyedmahmoudian, A. Raza and A. Stojcevski, "Analytical review on common and state-of-the-art FR strategies for VSC-MTDC integrated offshore wind power plants," *Renewable and Sustainable Energy Reviews*, vol. 148, pp. 111106, 2021. doi: 10.1016/j.rser.2021.111106.
- [67] L. F. Normandia Lourenco, A. Louni, G. Damm, M. Netto, M. Drissi Habti, S. Grillo, A. J. Sguarezi and L. G. Meegahapola, "A review on multi-terminal high voltage direct current networks for wind power integration," *Energies*, vol. 15, no. 23, pp. 9016, 2022. doi: 10.3390/en15239016.
- [68] A. Lunardi, L. F. Normandia Lourenco, E. Munkhchuluun, L. Meegahapola and A. J. Sguarezi Filho, "Grid-connected power converters: An overview of control strategies for renewable energy," *Energies*, vol. 15, no. 11, pp. 4151, 2022. doi: 10.3390/en15114151.
- [69] R. Rosso, X. Wang, M. Liserre, X. Lu and S. Engelken, "Grid-forming converters: Control approaches, grid-synchronization and future trends, a review," *IEEE Open Journal of Industry Applications*, vol. 2, pp. 93–109, 2021. doi: 10.1109/OJIA.2021.3074028.
- [70] K. Yan, G. Li, R. Zhang, Y. Xu, T. Jiang and X. Li, "Frequency control and optimal operation of low-inertia power systems with HVDC and renewable energy: A review," *IEEE Transactions on Power Systems*, vol. 39, no. 2, pp. 4279-4295, 2024. doi: 10.1109/TPWRS.2023.3288086.
- [71] M. R. Alam, F. Bai, R. Yan and T. K. Saha, "Classification and visualization of power quality disturbance-events using space vector ellipse in complex plane," *IEEE Transactions on Power Delivery*, vol. 36, no. 3, pp. 1380-1389, 2021. doi: 10.1109/TPWRD.2020.3008003.
- [72] J. Hou, C. Hu, S. Lei and Y. Hou, "Cyber resilience of power electronics-enabled power systems: A review," *Renewable and Sustainable Energy Reviews*, vol. 189, pp. 114036, 2024. doi: 10.1016/j.rser.2023.114036.
- [73] P. H. A. Barra, W. C. de Carvalho, T. S. Menezes, R. A. S. Fernandes and D. V. Coury, "A review on wind power smoothing using high-power energy storage systems," *Renewable and Sustainable Energy Reviews*, vol. 137, pp. 110455, 2021. doi: 10.1016/j.rser.2020.110455.
- [74] A. Risco-Bravo, C. Varela, J. Bartels and E. Zondervan, "From green hydrogen to electricity: A review on recent advances, challenges and opportunities on power-to-hydrogen-to-power systems," *Renewable and Sustainable Energy Reviews*, vol. 189, pp. 113930, 2024. doi: 10.1016/j.rser.2023.113930.
- [75] T. Sutikno, H. S. Purnama, A. Pamungkas, A. Fadlil, I. M. Alsofyani and M. H. Jopri, "Internet of things-based photovoltaics parameter monitoring system using NodeMCU ESP8266," *Int. J. Electr. Comput. Eng.*, vol. 11, no. 6, pp. 5578–5587, 2021, doi: 10.11591/ijece.v11i6.pp5578-5587.
- [76] K. Kritsanasuwan, U. Leeton and T. Kulworawanichpong, "Harmonic mitigation of AC electric railway power feeding system by using single-tuned passive filters," *Energy Reports*, vol. 8, pp. 1116-1124, 2022. doi: 10.1016/j.egyr.2022.05.276.
- [77] Y. Fang, Z. Wang, J. Miao and J. Wang, "A LCCR filter based harmonic suppression method for power quality improvement," *Energy Reports*, vol. 9, pp. 549-557, 2023. doi: 10.1016/j.egyr.2023.03.062.
- [78] M. Gaiceanu, S. Epure, R. C. Solea and R. Buhosu, "Power quality improvement with three-phase shunt active power filter prototype based on harmonic component separation method with low-pass filter," *Energies*, vol. 18, no. 3, pp. 556, 2025. doi: 10.3390/en18030556.

- [79] A. M. Shawqran, A. El-Marhomy, M. A. Sameh and M. A. Attia, "Reduction of total harmonic distortion of wind turbine active power using blade angle adaptive PI controller," *Energies*, vol. 14, no. 20, pp. 6798, 2021. doi: 10.3390/en14206798.
- [80] A. Mehmood and F. Yang, "Improvement of power quality of grid-connected EV charging station using grid-component based harmonic mitigation technique," *Energies*, vol. 18, no. 11, pp. 2876, 2025. doi: 10.3390/en18112876.
- [81] H. Safamehr, I. Izadi and J. Ghaisari, "Robust voltage control for harmonic suppression in islanded microgrids using compensated disturbance observer," *IEEE Transactions on Power Delivery*, vol. 38, no. 2, pp. 1208-1218, 2023. doi: 10.1109/TPWRD.2022.3210596.
- [82] Z. Reguieg, I. Bouyakoub and F. Mehedi, "Integrated optimization of power quality and energy management in a photovoltaic-battery microgrid," *Renewable Energy*, vol. 241, pp. 122358, 2025. doi: 10.1016/j.renene.2025.122358.
- [83] N. Sivakumar, J. Selvaraj, K. Jayaprakash and K. A. Fante, "Optimized DBN-based control scheme for power quality enhancement in a microgrid cluster connected with renewable energy system," *IET Renewable Power Generation*, vol. 18, no. 12, pp. 1926-1947, 2024. doi: 10.1049/rpg2.13058.
- [84] X. Xing and L. Jia, "Energy management in microgrid and multi-microgrid," *IET Renewable Power Generation*, vol. 18, no. 15, pp. 3480-3508, 2023. doi: 10.1049/rpg2.12816.
- [85] K. K. Nandini, N. S. Jayalakshmi and V. K. Jadoun, "A combined approach to evaluate power quality and grid dependency by solar photovoltaic based electric vehicle charging station using hybrid optimization," *Journal of Energy Storage*, vol. 84, pp. 110967, 2024. doi: 10.1016/j.est.2024.110967.
- [86] H. Anum, M. A. Hashmi, M. U. Shahid, H. M. Munir, M. Irfan, A. S. Veerendra, M. Kanan and A. Flah, "Backward neural network (BNN) based multilevel control for enhancing the quality of an islanded RES DC microgrid under variable communication network," *Heliyon*, vol. 10, no. 12, pp. e32646, 2024. doi: 10.1016/j.heliyon.2024.e32646.
- [87] R. H. Yang, J. X. Jin, S. Mu and M. S. Zhang, "Battery-energy-storage-based triple-active-bridge DC unified power quality conditioner for energy management and power quality enhancement of DC renewable sources," *International Journal of Electrical Power & Energy Systems*, vol. 143, pp. 108442, 2022. doi: 10.1016/j.ijepes.2022.108442.
- [88] B. Sahoo, S. K. Routray, P. K. Rout and M. M. Alhaider, "Power quality and stability assessment of hybrid microgrid and electric vehicle through a novel transformation technique," *Sustainable Energy Technologies and Assessments*, vol. 51, pp. 101927, 2022. doi: 10.1016/j.seta.2021.101927.
- [89] F. Gulotta, E. Dacco, A. Bosisio and D. Falabretti, "Opening of ancillary service markets to distributed energy resources: A review," *Energies*, vol. 16, no. 6, pp. 2814, 2023. doi: 10.3390/en16062814.
- [90] Y. Ruwaida, J. P. Chaves-Avila, N. Etherden, I. Gomez-Arriola, G. Gurses-Tran, K. Kessels, C. Madina, A. Sanjab, M. Santos-Mugica, D. N. Trakas and M. Troncia, "TSO-DSO-customer coordination for purchasing flexibility system services: Challenges and lessons learned from a demonstration in Sweden," *IEEE Transactions on Power Systems*, vol. 38, no. 2, pp. 1883-1895, 2023. doi: 10.1109/TPWRS.2022.3188261.
- [91] G. Rancilio, A. Rossi, D. Falabretti, A. Galliani and M. Merlo, "Ancillary services markets in Europe: Evolution and regulatory trade-offs," *Renewable and Sustainable Energy Reviews*, vol. 154, pp. 111850, 2022. doi: 10.1016/j.rser.2021.111850.
- [92] N. E. Koltsaklis and J. Knappek, "Assessing flexibility options in electricity market clearing," *Renewable and Sustainable Energy Reviews*, vol. 173, pp. 113084, 2023. doi: 10.1016/j.rser.2022.113084.
- [93] P. Crespo del Granado, J. Rajasekharan, S. V. Pandiyan, A. Tomasgard, G. Kara, H. Farahmand and S. Jaehnert, "Flexibility characterization, aggregation and market design trends with a high share of renewables: A review," *Current Sustainable/Renewable Energy Reports*, vol. 10, pp. 12-21, 2023. doi: 10.1007/s40518-022-00205-y.
- [94] T. Karthick, S. Charles Raja and P. Venkatesh, "Design of IoT based smart compact energy meter for monitoring and controlling the usage of energy and power quality issues with demand side management for a commercial building," *Sustainable Energy, Grids and Networks*, vol. 26, pp. 100454, 2021. doi: 10.1016/j.segan.2021.100454.
- [95] L. Zjavka, "Power quality multi-step predictions with the gradually increasing selected input parameters using machine-learning and regression," *Sustainable Energy, Grids and Networks*, vol. 26, pp. 100442, 2021. doi: 10.1016/j.segan.2021.100442.
- [96] A. Vinayagam, V. Veerasamy, M. Tariq and A. Aziz, "Heterogeneous learning method of ensemble classifiers for identification and classification of power quality events and fault transients in wind power integrated microgrid," *Sustainable Energy, Grids and Networks*, vol. 31, pp. 100752, 2022. doi: 10.1016/j.segan.2022.100752.

- [97] A. Mansour, A. Ismail, M. H. Ahmed and M. S. Bakr, "Applications of IoT and digital twin in electrical power systems: A comprehensive survey," *IET Generation, Transmission & Distribution*, vol. 17, no. 10, pp. 4457-4479, 2023. doi: 10.1049/gtd2.12940.
- [98] S. Al-Rubaye, G. Tsourdos and A. Tsourdos, "The applications and challenges of digital twin technology in smart grids: A comprehensive review," *Applied Sciences*, vol. 14, no. 23, pp. 10933, 2024. doi: 10.3390/app142310933.
- [99] N. Kumari, A. P. Sharma, B. Tran, N. Chilamkurti and D. Alahakoon, "A comprehensive review of digital twin technology for grid-connected microgrid systems: State of the art, potential and challenges faced," *Energies*, vol. 16, no. 14, pp. 5525, 2023. doi: 10.3390/en16145525.
- [100] J. B. Heluany and V. Gkioulos, "A review on digital twins for power generation and distribution," *International Journal of Information Security*, vol. 23, no. 2, pp. 1171-1195, 2024. doi: 10.1007/s10207-023-00784-x.
- [101] M. H. Jopri, M. R. Ab Ghani, A. R. Abdullah, M. Manap, T. Sutikno and J. Too, "K-nearest neighbor and naïve Bayes based diagnostic analytic of harmonic source identification," *Bull. Electr. Eng. Inform.*, vol. 9, no. 6, pp. 2650-2657, 2020, doi: 10.11591/eei.v9i6.2685.
- [102] N. H. T. Ahmad, A. R. Abdullah, N. A. Abidullah and M. H. Jopri, "Analysis of power quality disturbances using spectrogram and S-transform," *Int. Rev. Electr. Eng.*, vol. 9, no. 3, pp. 611-619, 2014.
- [103] N. H. Ali, A. R. Abdullah, N. M. Saad, A. S. Muda, T. Sutikno and M. H. Jopri, "Brain stroke computed tomography images analysis using image processing: A review," *IAES Int. J. Artif. Intell.*, vol. 10, no. 4, pp. 1048-1059, 2021, doi: 10.11591/ijai.v10.i4.pp1048-1059.
- [104] T. N. S. Tengku Zawawi, A. R. Abdullah, M. H. Jopri, T. Sutikno, N. M. Saad and R. Sudirman, "A review of electromyography signal analysis techniques for musculoskeletal disorders," *Indones. J. Electr. Eng. Comput. Sci.*, vol. 11, no. 3, pp. 1136-1146, 2018, doi: 10.11591/ijeecs.v11.i3.pp1136-1146.
- [105] M. Kacprzak, A. Krol, I. Wielewska, A. Milewska and Z. Ciekanowski, "Employment and competencies of employees in the energy sector in Poland," *Energies*, vol. 15, no. 19, pp. 6941, 2022. doi: 10.3390/en15196941.
- [106] R. Vakulchuk and I. Overland, "The failure to decarbonize the global energy education system: Carbon lock-in and stranded skill sets," *Energy Research & Social Science*, vol. 110, pp. 103446, 2024. doi: 10.1016/j.erss.2024.103446.
- [107] R. N. Bray, A. Mejia-Montero and R. Ford, "Skills deployment for a just net zero energy transition," *Environmental Innovation and Societal Transitions*, vol. 42, pp. 395-410, 2022. doi: 10.1016/j.eist.2022.02.002.
- [108] R. Yasmeen and W. U. H. Shah, "Impact of business cycles on energy poverty: Exploring the significance with sustainable development goals in newly industrialized economies," *Applied Energy*, vol. 378, pp. 124777, 2025. doi: 10.1016/j.apenergy.2024.124777