Comprehensive Review of Power Quality Assessment, Monitoring, and Compensation in EHV Networks

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Abstract— Power Quality assessment is very important for Extra High Voltage networks. We need to make sure these networks are reliable, efficient and meet standards. Disturbances like harmonics, voltage surges, flicker and transients can move across transmission systems. This affects loads and distributed generation integration. This review looks at ways to monitor Power Quality measures to compare performance, strategies to fix problems and case studies that are relevant, to Extra High Voltage substations. These pictures show how to watch over systems they use numbers and payment plans and that helps us understand how to measure power quality in places with really high voltage, like power plants.

Keywords— Power Quality (PQ), Extra High Voltage (EHV) Networks, Harmonics, Voltage Sags and Swells, Reactive Power Compensation, Compound PQ Indices.

I. Introduction

The Extra High Voltage networks are really important for our power systems. They are like the roads that electricity uses to travel from one place to another. The Extra High Voltage networks help move a lot of electricity across areas and they connect the big power lines with the factories and the smaller power lines that people use in their homes and businesses. The Extra High Voltage networks are very good, at doing this job [1],[2]. Because of their scale and critical role, any disturbance in power quality (PQ) at this level can propagate widely, leading to increased technical losses, reduced equipment lifespan, and challenges in meeting contractual obligations within deregulated electricity markets [3],[4].

Assessing PQ in EHV systems requires more than basic monitoring; it demands integrated architectures that combine distributed sensing, advanced analytical indices, and corrective technologies [2],[5]. Standards such as IEEE 519 and IEC 61000 provide the frame work evaluating harmonics, voltage stability, and other PQ parameters, ensuring consistency and compliance across networks [5],[6].

This review brings together key contributions in PQ monitoring, analytic modelling, compensation methods, and Security linked Power Quality assessment is really important. This is shown in studies from [1] to [11]. When we look at all these studies together, we can see what we have done far with Power Quality and what we still need to work on. This helps us figure out what to do with Power Quality. Some things we can do are check Power Quality in time use Artificial Intelligence to find problems and include Power Quality measures, in our grid security plans [10] [11].

II. Monitoring Architectures in EHV Networks

Monitoring architectures in Extra High Voltage (EHV) networks are designed to ensure that power quality (PQ) disturbances are detected, classified, and mitigated before they propagate across the transmission system [1],[3]. Because EHV networks form the backbone of modern power systems, even minor PQ issues at this level can cascade into widespread. losses, equipment malfunctions, and contractual disputes in deregulated electricity markets [1],[2]. A robust monitoring architecture therefore integrates multiple layers of sensing, analysis, control, communication, and reporting.

This paper presents a comprehensive review of Power Quality (PQ) assessment in Extra High Voltage (EHV)networks, examining monitoring architectures, benchmarking indices, compensation strategies, loss modeling, industrial and utility case applications, distributed generation integration, and PQ -aware grid security frameworks, while highlighting applicable standards, implementation challenges, and future research directions.

A. Distributed Sensing

The basis of PQ monitoring is having sensors over the place like at substations and transmission nodes. These sensors are always checking the voltage, frequency and harmonic distortion. They do this in a detailed way, which helps us find out about problems that happen really quickly like when the voltage drops or goes up suddenly or when there are transients. This is really important for following the rules set by IEEE Std 1159 and IEC 61000 guidelines which're like the standards, for PQ monitoring. We need to follow these guidelines to make sure everything runs smoothly and safely with our PQ monitoring systems with the sensors that are always monitoring the voltage, current, frequency and harmonic distortion at substations and transmission nodes.

B. Local Analysis

Data captured by sensors are processed by local PQ analyzers. These devices classify disturbances into categories such as harmonics, flicker, or transients, and provide immediate diagnostic information [3],[4]. Local controllers can trigger corrective actions, including capacitor bank switching, transformer tap adjustments, or activation of static VAR compensators (SVCs) [4],[8]. This ensures that PQ issues are addressed at the source before they escalate.

C. Compensation and Control

Monitoring architectures are closely linked with compensation technologies. Devices such as shunt capacitors, STATCOMs, and other FACTS controllers are integrated into the system to provide reactive power support and harmonic mitigation [4],[8]. These devices can be controlled either locally or through central commands, enabling both rapid response and coordinated system -wide PQ improvement.

D. Communication Infrastructure

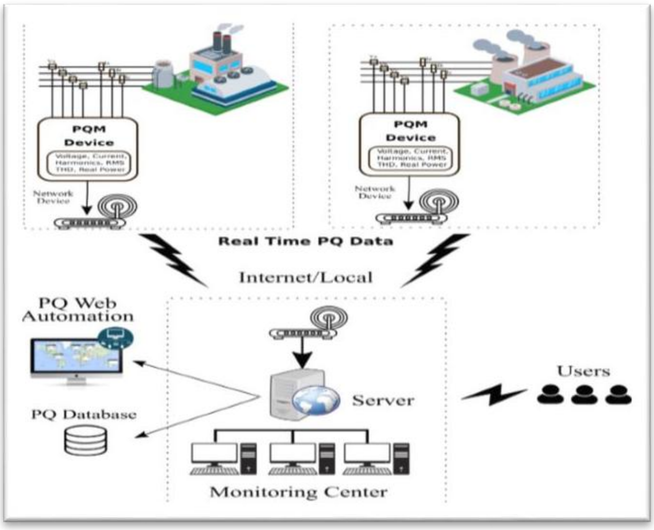
A dedicated communication network connects substations to central servers. Protocols such as IEC 61850 and SCADA systems ensure secure, time -synchronized data transfer [2],[9]. This communication layer aggregates PQ data across multiple substations, providing operators with a holistic view of system performance. Redundancy in communication channels is essential to guarantee reliability and resilience against failures.

E. Centralized Monitoring and Reporting

At the top of the architecture are centralized servers and monitoring centers. These systems collect PQ data from across the network, store it in databases, and apply advanced analytics to generate PQ indices and compliance reports [5],[10]. Dashboards provide operators with real-time visualization of PQ status, supporting operational planning, maintenance scheduling, and benchmarking against IEEE 519 harmonic limits [5],[6].

F. Compliance and Decision Support

Finally, monitoring architectures serve a compliance function, ensuring that utilities meet regulatory requirements and contractual obligations [1],[5]. PQ data is used to verify adherence to standards, support contingency planning, and provide transparency to regulators and market participants. This decision layer transforms raw PQ data into actionable insights for both operational reliability and market accountability.



III. Benchmarking and Compound Indices

Traditional approaches to power quality (PQ) assessment We have to look at the picture when it comes to Extra High Voltage networks. These networks are really complicated. They relied heavily on things like Total Harmonic Distortion and voltage sag duration. We also looked at severity. These things are useful for finding problems. When we are talking about Extra High Voltage networks they are not enough. The problems in these networks are complex. They involve a lot of things that are interacting with each other. We cannot just look at one thing. Think we know what is going on. So, when we try to figure out how the system is performing, just looking at parameters, like Total Harmonic Distortion or voltage sag duration is not enough. We need to look at the system to really understand what is happening with Extra High Voltage networks and the power quality disturbances that occur in them.

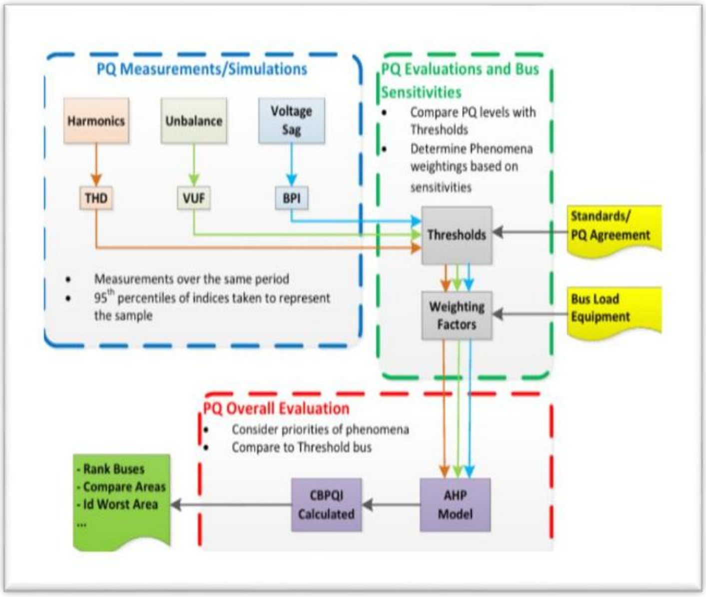
To address this limitation, researchers have proposed compound indices that integrate multiple PQ parameters into a single, unified score [5]. These indices combine measurements of harmonics, voltage sags, swells, flicker, and transients, producing a composite value that reflects overall PQ performance [5]. The advantage of compound indices lies in their ability to facilitate benchmarking across substations, transmission corridors, and even entire networks, enabling operators to compare PQ levels consistently and identify weak points in the system.

One widely explored methodology for developing compound indices is the Analytic Hierarchy Process (AHP) [2]. AHP The Power Quality framework helps us make decisions. It looks at Power Quality problems. Decides which ones are more important. For example, voltage sags are a deal because they can hurt the equipment used in factories.

So, we give voltage sags a score than flicker. This way utility companies can focus on the important Power Quality issues and use their resources in a better way.

We have seen this work in studies that compare Power Quality, around the world. These studies look at different things and give each region a score so we can see how they do compared to others. Despite these advances, standardized compound indices remain under development. There is no universally accepted formula or weighting scheme for integrating PQ parameters, and different studies often adopt context -specific models. Some indices emphasize harmonic distortion due to industrial sensitivity, while others prioritize voltage stability in transmission corridors. This lack of standardization poses challenges for cross -utility benchmarking and regulatory compliance.

Nevertheless, the concept of compound indices represents a significant step forward in PQ assessment. By moving beyond single -parameter evaluation, these indices provide a more holistic view of system performance, aligning with the requirements of IEEE 519 and IEC 61000 standards. Future research is expected to focus on developing universally accepted compound indices, integrating them with real -time monitoring systems, and applying machine learning techniques to dynamically adjust weighting factors based on operating conditions.



IV. Compensation Strategies in EHV Substations

Reactive power compensation plays a pivotal role in maintaining power quality (PQ) in Extra High Voltage (EHV) substations. Since these substations are responsible for transmitting bulk power and interfacing with industrial and distribution systems, even minor PQ disturbances can have widespread consequences. Compensation strategies are therefore designed to stabilize voltage, improve power factor, and mitigate harmonics, ensuring compliance with IEEE 519 and IEC 61000 standards.

A. Shunt Capacitor Banks

The thing that a lot of people do in EHV substations is they install shunt capacitor banks. These shunt capacitor banks are really good because they help with the power factor. They keep the voltage stable when the load is changing [4]. Shunt capacitor banks do this by giving the system some power, which is called reactive power. This reactive power from the shunt capacitor banks helps to balance out the loads that are using a lot of power which reduces the amount of power that is lost when it is being sent through the lines. This makes the whole system work better. It is more efficient.

B. Switched Capacitor Systems

While fixed shunt capacitors are effective, they lack flexibility under dynamic operating conditions. Switched capacitor systems address this limitation by enabling staged or automatic switching of capacitor units based on real -time PQ measurements [8]. This dynamic response allows substations to adapt to load variations, mitigate voltage fluctuations, and reduce harmonic distortion. Switched systems are often integrated with automated controllers that monitor PQ indices and trigger compensation actions as needed.

C. FACTS Devices and Advanced Controllers

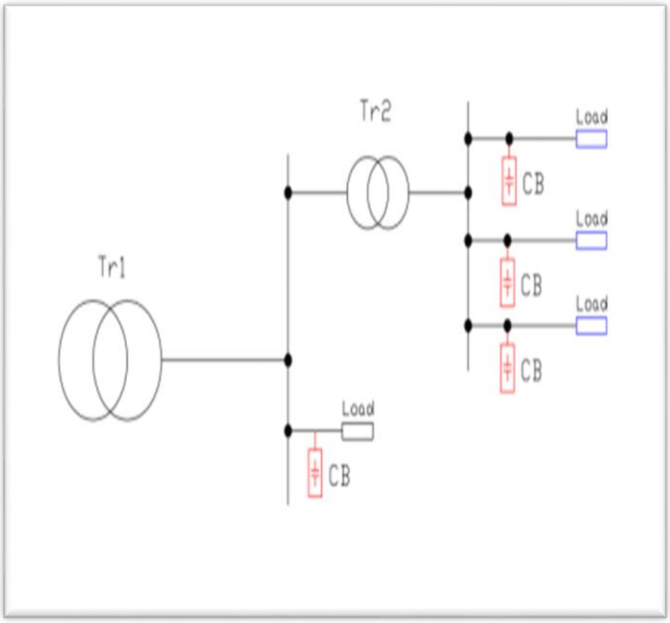
Beyond conventional capacitor banks, modern EHV substations increasingly employ Flexible AC Transmission Systems (FACTS) devices such as Static VAR Compensators (SVCs) and Static Synchronous Compensators (STATCOMs). These advanced controllers provide fast, continuous reactive power support and are highly effective in mitigating harmonics and stabilizing voltage during transient disturbances [3],[4]. FACTS devices also enhance system stability margins, making them valuable in networks with high penetration of renewable energy or distributed generation.

D. Harmonic Mitigation and Voltage Stability

Compensation strategies are not limited to reactive power support; they also contribute to harmonic mitigation [4],[8]. By reducing distortion levels, capacitor banks and FACTS devices help maintain compliance with IEEE 519 harmonic limits. Voltage stability is another critical benefit, as compensation ensures that voltage profiles remain within acceptable ranges even during peak demand or contingency events.

E. Integration with Monitoring Architectures

Effective compensation requires integration with PQ monitoring architectures. Sensors and analyzers detect disturbances, while communication networks relay data to controllers that activate compensation devices. This closed-loop system is really important because it makes sure that things get fixed on time and in the way. This helps prevent problems with power quality from happening all over the transmission network
[1],[3]. The closed-loop system is key, to stopping these problems from getting out of hand.



V. Control Technologies in Smart Grids

Smart grids represent the next generation of power systems, integrating advanced monitoring, communication, and control technologies to enhance reliability and power quality (PQ)[3],[10]. Unlike conventional transmission and distribution networks, smart grids are characterized by high penetration of inverter -based resources, distributed generation, and variable loads. These conditions introduce new PQ challenges such as voltage fluctuations, harmonic distortion, and transient disturbances. To address these issues, smart grid PQ control relies on a suite of advanced controllers capable of fast compensation, selective harmonic mitigation, and adaptive response.

A. FACTS Devices for Voltage and Reactive Power Control

Flexible AC Transmission Systems (FACTS) devices, including Static VAR Compensators (SVCs) and Static Synchronous Compensators (STATCOMs), are widely deployed in smart grids to provide dynamic reactive power support. These devices stabilize voltage profiles, improve power factor, and mitigate oscillations [3]. Their fast response times make them particularly effective in inverter-rich feeders where voltage variability is frequent. FACTS controllers also contribute to system stability margins, aligning PQ outcomes with IEEE 519 harmonic limits and IEC 61000 voltage standards.

B. Dynamic Voltage Restorers (DVRs) for Series Compensation

Dynamic Voltage Restorers (DVRs) are series - connected devices designed to protect sensitive loads from voltage sags and swells [7]. By injecting a compensating voltage in series with the supply, DVRs restore the load voltage to acceptable levels during disturbances. They are especially valuable in industrial feeders where PQ compliance is critical to avoid equipment malfunctions. DVRs complement shunt -based FACTS devices by addressing PQ issues directly at the point of load connection.

C. Active Power Filters for Harmonic Mitigation

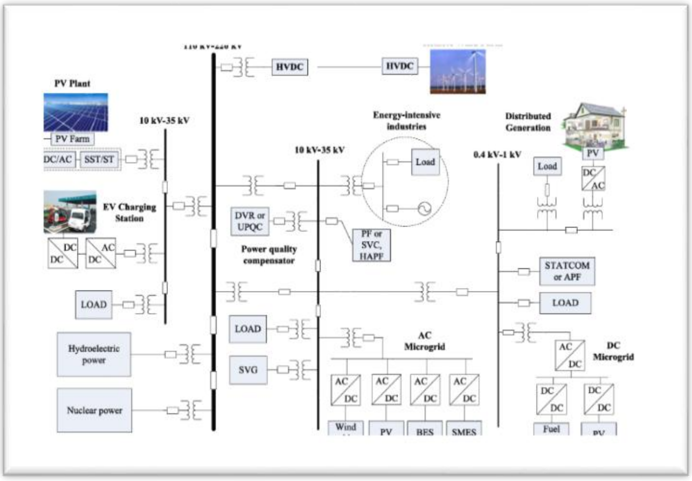
Active filters are employed to target specific harmonic components generated by nonlinear loads and inverter - based resources [3],[8]. Un like passive filters, active filters use power electronics to dynamically inject compensating currents, thereby cancel ling out harmonic distortion. This selective harmonic mitigation ensures compliance with IEEE 519 limits and improves overall system efficiency. Active filters can be deployed in both shunt and series configurations, depending on the nature of the PQ disturbance.

D. Closed -Loop Feedback and Adaptive Control

A defining feature of smart grid PQ control is the integration of closed -loop feedback systems. PQ analyzers continuously monitor disturbances and relay data to controllers, which adjust compensation devices in real time. This feedback loop enhances adaptability to load variability and ensures that corrective actions are proportional to the severity of PQ events [3],[10]. In inverter -rich feeders, closed -loop control is essential for maintaining voltage stability and minimizing harmonic distortion.

E. Integration and Compliance

The combined use of FACTS devices, DVRs, and active filters create a multi -layered PQ control topology. Each device addresses a specific aspect of PQ, while closed - loop feedback ensures coordination among controllers. This integrated approach aligns PQ outcomes with compliance standards, supports operational planning, and enhances resilience in smart grids with high renewable penetration.



VI. PQ IN DISTRIBUTED GENERATION INTEGRATION

The integration of distributed generation (DG), particularly inverter -based renewable sources such as solar photovoltaic (PV) and wind energy systems, has transformed the operational landscape of Extra High Voltage (EHV) networks [10]. While DG enhances sustainability and reduces dependence on centralized generation, it also introduces new power quality (PQ) challenges. These challenges stem from the inherent characteristics of inverter -based resources, which can generate harmonics, cause voltage fluctuations, and alter system dynamics at the point of common coupling (PCC).

A. Harmonics and Voltage Fluctuations

Inverter -based DG units are nonlinear in nature, and their switching operations often produce harmonic distortion [10]. When multiple DG sources are connected to EHV feeders, the cumulative harmonic content can exceed IEEE 519 limits, stress transformers and increasing system losses [5],[6]. In addition, the variability of renewable generation leads to frequent voltage fluctuations, particularly in feeders with high penetration of solar PV or wind turbines. These fluctuations can compromise voltage stability and affect sensitive industrial loads connected to EHV substations.

B. Adaptive PQ Monitoring at PCC

To manage these disturbances, adaptive PQ monitoring systems are deployed at the PCC where DG sources interface with EHV feeders [9],[10]. PQ analyzers' continuously measure voltage, current, and harmonic spectra, enabling real -time classification of disturbances. Adaptive filters and controllers are then activated to mitigate harmonics and stabilize voltage. This closed -loop monitoring and compensation ensures that PQ indices remain within acceptable limits despite the variability of DG output.

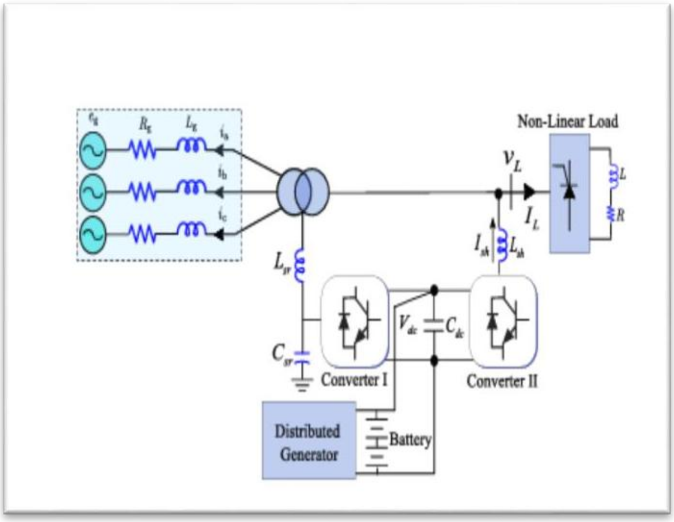
C. Sector -Specific Benchmarks

Different sectors impose unique PQ requirements. For example, industrial corridors connected to EHV substations demand stricter harmonic limits due to the sensitivity of equipment, while residential feeders may tolerate higher levels of distortion. Sector -specific benchmarking frameworks allow utilities to prioritize PQ issues based on load characteristics and contractual obligations [2],[5]. By integrating DG monitoring with sector benchmarks, operators can ensure compliance while optimizing resource allocation.

D. Continuous Monitoring Frameworks

Given the dynamic nature of DG output, continuous monitoring frameworks are essential. These frameworks combine distributed sensors, PQ analyzers, and centralized servers to provide system -wide visibility [9],[10]. Data aggregation enables benchmarking across feeders and substations, while predictive analytics support proactive maintenance and contingency planning.

Continuous monitoring also facilitates regulatory compliance, ensuring that utilities meet IEEE 519 and IEC 61000 standards in DG-rich environments.



VII. PQ & Grid Security

Static security assessment traditionally focuses on voltage stability, thermal limits, and system reliability under contingency scenarios [11]. By incorporating PQ indices such as voltage sag severity, harmonic distortion, and flicker into contingency models, operators can evaluate how disturbances affect both equipment reliability and contractual compliance [11]. For example, a line outage may not only reduce stability margins but also amplify harmonic distortion due to altered power flows. Integrating PQ metrics into contingency analysis therefore enhances the predictive capability of security studies [11].

A. PQ-Aware Contingency Analysis

A PQ -aware contingency analysis framework involves three key stages:

- Event Detection: Identification of potential contingencies such as line outages, transformer failures, or generator trips.
- PQ Metric Evaluation: Assessment of PQ indices under the contingency scenario, including harmonics, voltage sags, and flicker.
- Corrective Action Paths: Activation of compensation devices (STATCOMs, DVRs, active filters) or operational adjustments to restore PQ compliance [3],[7],[8].

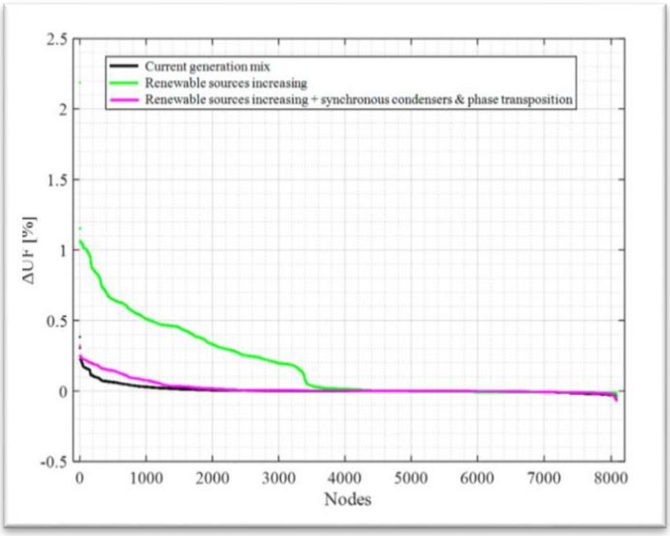
This process ensures that corrective actions are not only stability -oriented but also PQ -oriented, aligning operational outcomes with IEEE 519 and IEC 61000 standards.

B. Cyber -Physical Risks and Renewable Variability

Cyber -Physical Risks and Renewable Variability While contingency analysis provides a structured framework, emerging challenges such as cyber -physical risks and renewable variability remain underexplored. Cyber intrusions can compromise PQ monitoring and control systems, leading to undetected disturbances. Similarly, the variability of inverter -based renewable generation introduces dynamic PQ issues that traditional static models may not capture [10],[11]. Future research must therefore integrate cyber -security protocols and probabilistic renewable models into PQ -aware contingency frameworks.

C. Benefits of PQ -Integrated Security

- Enhances grid resilience by addressing both stability and PQ disturbances.
- Provides compliance assurance with IEEE/IEC standards under contingency conditions.
- Supports operational planning by identifying weak points in both PQ and stability margins.
- Facilitates regulatory transparency by integrating PQ indices into security reports [11].



VIII. CONCLUSION

Power quality (PQ) assessment in Extra High Voltage (EHV) networks is a multidimensional challenge that requires integrated monitoring, advanced benchmarking, and dynamic compensation strategies [1]-[11]. Traditional single -parameter indices such as THD or voltage sag duration provide useful insights but are insufficient to capture the complexity of PQ disturbances in large transmission systems [3],[5]. The evolution of compound indices and analytic models, supported by frameworks such as the Analytic Hierarchy Process (AHP), has enabled more holistic benchmarking across substations and transmission corridors [2],[5]. These approaches allow utilities to prioritize PQ concerns and align operational outcomes with IEEE 519 and IEC 61000 standards.

Industrial case studies demonstrate the practical relevance of PQ management, particularly in sectors such as steel and glass manufacturing where nonlinear loads impose significant harmonic and reactive power burdens [6],[9]. Similarly, utility - level investigations highlight how disturbances in low -voltage feeders can propagate upstream into EHV substations, underscoring the need for coordinated monitoring across voltage levels [9],[10].

The integration of distributed generation (DG), especially inverter -based renewables, further complicates PQ management by introducing harmonics and voltage variability at the point of common coupling [10]. These real-world applications emphasize that PQ assessment cannot remain isolated at the transmission level but must incorporate industrial, utility, and DG perspectives into unified framework.

Looking ahead, future research must focus on three critical directions. First, the development of standardized compound indices is essential to ensure consistency in PQ benchmarking across utilities and regions. Second, the adoption of predictive PQ analytics, leveraging machine learning and AI, will enable proactive identification of disturbances and optimization of compensation strategies. Third, the design of cyber -resilient PQ security frameworks are increasingly important as monitoring and control systems become more digitized and vulnerable to cyber -physical risks. By advancing these areas, EHV networks can maintain reliability, efficiency, and compliance in the face of growing complexity, renewable integration, and evolving market structures.

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