Integrating Unified Power Quality Conditioners with Renewable Energy Sources: A Review of Performance Enhancements in Hybrid Systems

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Abstract: The increasing integration of renewable energy sources (RES) such as solar and wind into modern power distribution systems has brought significant challenges to maintaining power quality (PQ). These intermittent sources induce disturbances like voltage sags, swells, harmonic distortions, and reactive power imbalances. This study explores the role of Unified Power Quality Conditioners (UPQC) as a comprehensive solution to these power quality challenges, especially in hybrid renewable energy systems. The UPQC, incorporating both series and shunt active filters, mitigates voltage- and current-related PQ disturbances by compensating for harmonics, unbalanced loads, and reactive power. The study classifies UPQC based on physical structure—converter type, system configuration, supply type—and compensation method, including UPQC-P, UPQC-Q, UPQC-S, and UPQC-VAmin. Furthermore, it discusses voltage stability issues in hybrid solar-wind systems and analyzes how UPQC enhances voltage regulation under varying load and fault conditions. Major implementation challenges such as control complexity, high cost, integration with legacy infrastructure, and DC-link voltage stability are also addressed. The study concludes by identifying research gaps and emphasizing the need for cost-effective, standardized, and scalable UPQC systems to ensure stable and efficient grid integration of renewable sources
Keywords: Unified Power Quality Conditioner (UPQC), Renewable Energy Sources (RES), Power Quality (PQ), Voltage Sag, Voltage Swell, Harmonic Distortion, Reactive Power, Power Electronics, Hybrid Systems, Active Power Filter (APF), Control Strategies, Voltage Regulation, Grid Integration, Intermittent Energy Sources, Voltage Stability, Power Distribution Systems, Smart Grid, Compensation Method

I. INTRODUCTION

The proliferation of the grid integrated renewable energy (RE) sources are increasing in the low and medium voltage utility grids to meet the energy demand. Renewable energy sources in the utility grid require power electronic-based converters which not only provide interfacing between these sources and utility grid but also allow higher levels of penetration. The higher level of RE penetration largely affects the power quality (PQ). It may lead to various PQ disturbances such as excess reactive power, transients, power factor collapse, large current and voltage fluctuations, sag, swell, notch, harmonics, and noise, etc [1]. Renewable power can reduce power losses, mitigate environmental pollution, defer or eliminate system upgrades, reduce operating costs, and improve voltage profile due to their nature and penetration at distribution level. The share of RES in total primary energy supply would rise from 14% in 2015 to 63% in 2050 [2]. The high penetration level of renewable energy (RE) sources into the utility grid led to PQ challenges and deteriorate the quality of electrical power significantly. PQ issues associated with the grid integration of RE sources include fluctuations in voltage, reactive power flow, harmonics, excessive neutral current, etc. The other important issues associated with RE placement, sizing and voltage ride-through in distribution systems [3]. By definition renewable energy sources, often called alternative sources, are those that can be used again and again to produce energy, eg, wind, solar, geothermal, or biomass.8 The total installed power generation using RESs is almost 2378 GW by the end of 2018 [4]. However, the integration of RESs with conventional power system brings several new challenges due to their intermittent nature. Some of them, eg, biomass, hydropower, and geothermal operate in the same way as traditional power plants do, but most of the available RESs like solar and wind are less predictable and more time variant [5]. The significance of power quality is something that cannot be compromised between customers and power utility companies because it dictates the benefits in the ever-competitive trade arena. The quality of power delivered to the customer is an asset for the utility company.

Voltage disturbance and various power quality issues may cause damage to electrical and electronic appliances. Thus, many efforts have been considered to ensure that the quality of the voltage magnitude and frequency are within the allowable tolerance to deliver a viable quality of power to the user. There are various power quality issues that exist in the system, like voltage swelling, sagging, harmonic, and service interruption. Of all the voltage issues, voltage sag and swell are the critical kinds of disturbance because it affects the performance of the load in the system, especially the sensitive loads [6]. Power quality as a tool for describing the conditions at the interface of power sources and loads. To avoid misinterpretation of the term power quality, five different terms were defined voltage quality, current quality, power quality, quality of supply and quality of consumption. For ease of understanding, it may be said that power quality deals with the deviations in voltage and current waveforms from their respective ideal [7]. A unified power quality conditioner (UPQC) is a device that is similar in construction to a unified power flow conditioner (UPFC). The UPQC, like a UPFC, employs two voltage source inverters (VSIs) that are connected to a common dc energy storage capacitor. One of these two VSls is connected in series with the ac line while the other is connected in shunt with the same line. A UPFC is employed in a power transmission system to perform shunt and series compensation at the same time. Similarly, a UPQC can also perform both the tasks in a power distribution system. However, at this point the similarities in the operating principles of these two devices end. Since a power transmission line generally operates in a balanced, distortion (harmonic) free environment, a UPFC must only provide balanced shunt or series compensation. A power distribution system, on the other hand, may contain unbalance, distortion and even de components. Therefore, a UPQC must operate under this environment while providing shunt or series compensation [8]. UPQC consisted of a series and a shunt active power filter (APF), which were back-to-back connected through a common dc link capacitor. The APF in the UPQC is connected in parallel with the load and is used to compensate for the load current harmonics, while the APF connected in series with the power supply is used to regulate the voltage at the load terminals. The UPQC operates by injecting a compensating current in the system to cancel out the harmonics and regulate the voltage. It senses the voltage and current at the load terminals and uses a control algorithm to generate compensating currents [9]. UPQC is a very effective device for improving the power quality of the system, reducing power losses, and improving the efficiency of the system. It is commonly used in industrial and commercial applications where a stable and high-quality power supply is critical for the smooth operation of the equipment nowadays [10].

II. Unified Power Quality Conditioner (UPQC)

The UPQC has the capability of improving power quality at the point of installation on power distribution systems or industrial power systems. The UPQC, therefore, is expected to be one of the most powerful solutions to large capacity loads sensitive to supply voltage flicker/imbalance. As the UPQC is a combination of series and shunt active filters, two active filters have different functions. The series active filter suppresses and isolates voltage-based distortions. The shunt active filter cancels current-based distortions. At the same time, it compensates reactive current of the load and improves power factor. PQ issues is essential to guarantee the reliable and efficient operation of HRES within grid-connected systems. Because of its ability to handle various PQ problems in micro grid distribution systems, the UPQC was chosen. Unlike other FACTS devices [11], UPQC combines series and shunt compensators to manage voltage fluctuations, harmonic distortions, and unbalanced loads simultaneously, making it better suited for enhancing reliability and stability, especially in systems with variable renewable energy sources [12]

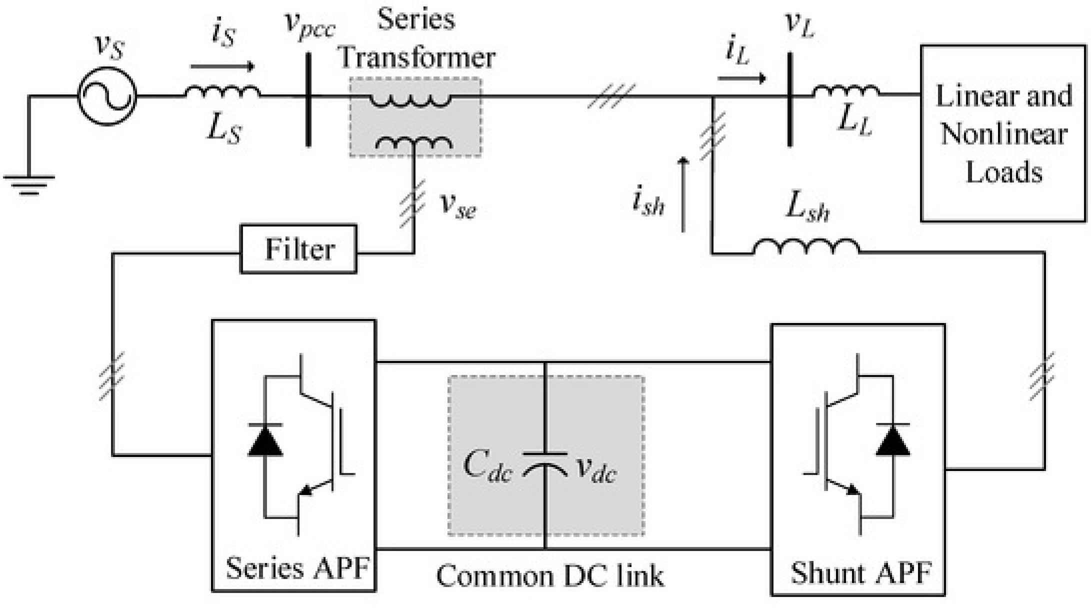

Fig 1 Schematic of a basic UPQC-based system [13].

This figure 1 depicts the configuration of a Unified Power Quality Conditioner (UPQC) system, which integrates both series and shunt active power filters (APF) to improve power quality in distribution systems. The series APF is used to mitigate voltage disturbances such as sags and swells, while the shunt APF compensates for current harmonics and reactive power. Both filters are connected via a common DC link, ensuring coordinated operation. The series transformer isolates the load from the power line disturbances, while the filters and common DC link work together to provide efficient compensation for both linear and nonlinear loads, improving the overall power quality and system stability.

A. Classification of Unified Power Quality Conditioners (UPQC)

The Unified Power Quality Conditioner (UPQC) is classified based on its physical structure into three main categories: converter type, configuration of DVR and DSTATCOM, and the type of supply system [14]. Converter-based classification includes Voltage Source Converters (VSC), which are most commonly used due to their high efficiency, compact size, and flexible control. Current Source Converters (CSC) are less common and are used in specific applications involving complex control strategies like neural networks or state-space methods. Configuration-based classification depends on how the DVR and DSTATCOM are connected [15]. The Right Shunt (UPQC-R) is preferred for its simplicity and low cost, while the Left Shunt (UPQC-L) is more complex. UPQC-DG integrates renewable sources like solar and wind with the grid, addressing synchronization and power quality issues. Modular (UPQC-MD) and Multilevel (UPQC-ML) designs are suitable for high-power applications due to their scalability [16]. Supply system-based classification considers the system's phase structure. Single-phase two-wire (1P2W) systems use isolated converters and phase-shift control. Three-phase three-wire (3P3W) systems are common in balanced loads, while three-phase four-wire (3P4W) systems address neutral current and load imbalances. Topologies like Split Capacitor (2C), Four-Leg (4L), and Three H-Bridge (3-HB) are used based on application size and power requirements, balancing performance, complexity, and cost [17].

Unified Power Quality Conditioners (UPQCs) can also be classified based on their compensation method, which determines how they address power quality (PQ) issues in the system [18]. The UPQC-P type focuses on active power control, where the DSTATCOM compensates for current issues while maintaining a unity power factor, and the DVR addresses voltage sags and swells. In this mode, the injected voltage is in phase with the supply current, meaning only active power is exchanged [19]. This configuration is often used with renewable energy systems like solar or wind, allowing them to not only improve PQ but also inject active power into the grid. The UPQC-Q type provides reactive power control, aimed at regulating system voltage and reducing the reactive power burden on the supply [20]. The UPQC-S configuration offers simultaneous control of both active and reactive power, providing comprehensive compensation for a wide range of PQ disturbances. Lastly, the UPQC-VAmin is optimized for minimal volt-ampere (VA) usage, ensuring effective compensation while keeping the converter size and power rating as low as possible, making it efficient for cost-sensitive applications [21].

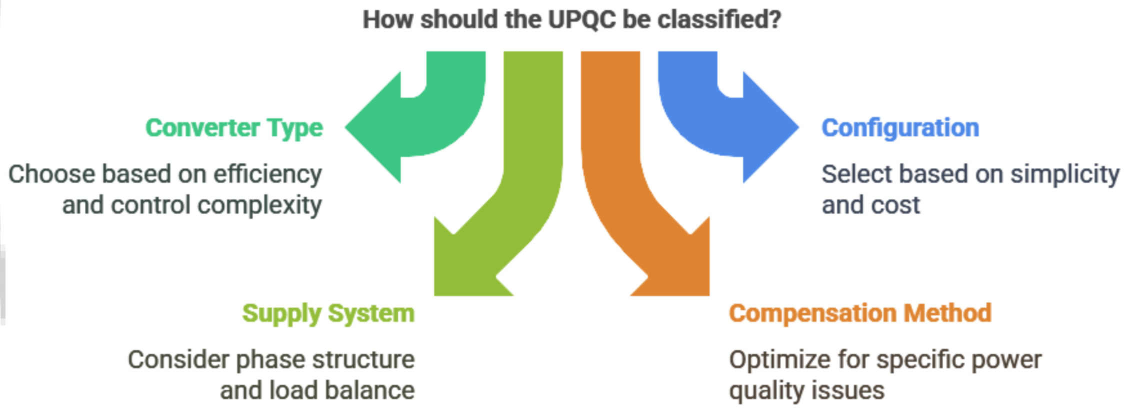

Fig 2 Classification of Unified Power Quality Conditioners

The figure 2 illustrates the four primary criteria for classifying a Unified Power Quality Conditioner (UPQC). These include Converter Type, chosen based on efficiency and control complexity; Configuration, selected considering simplicity and cost; Supply System, determined by the phase structure and load balance of the power system; and Compensation Method, which is optimized to address specific power quality issues like voltage sags, current harmonics, or reactive power. Each classification helps tailor the UPQC design for effective and efficient power quality enhancement in different applications.

TABLE 1 Comparative Classification of UPQC Based on Structure and Compensation Method

Classification Type	Category	Key Features	Application Area	Ref. No.
Based on Converter Type	VSC, CSC	VSC: High efficiency, compact, flexible control; CSC: Advanced control (neural networks, state-space models)	General use (VSC), specialized systems (CSC)	[14]

According to System Configuration	UPQC-R, UPQC-L, UPQC-DG	UPQC-R: Simple, low cost; UPQC-L: Complex structure; UPQC-DG: RES integration and grid synchronization	General PQ improvement, renewable energy systems	[15]
By Application Scalability	UPQC-DG, UPQC-MD, UPQC-ML	DG: RES integration; MD/ML: Modular, scalable for high-power needs	Renewable integration, high-power systems	[16]
Related to Supply Structure	1P2W, 3P3W, 3P4W (2C, 4L, 3-HB)	1P2W: Phase-shift control; 3P3W: Ripple filtering; 3P4W: Neutral current handling using various topologies	Single-phase, balanced and unbalanced three-phase	[17]
Based on Power Control Strategy	UPQC-P, UPQC-S	P: Active power control, in-phase injection, used with RES; S: Combined active and reactive power compensation	PQ improvement, renewable integration, wide PQ range	[18]
For Active Compensation Focus	UPQC-P	Injects only active power; integrated with wind/solar to enhance PQ and supply power to grid	Renewable energy and PQ support	[19]
For Reactive Compensation Focus	UPQC-Q	Manages reactive power, regulates voltage, reduces burden on the source	Reactive load conditions	[20]
Optimized for Efficiency	UPQC-VAmin	Minimal VA rating design, efficient for low-cost systems	Cost-sensitive, low to medium power applications	[21]

III. Power Quality Disturbances in Hybrid Solar-Wind Systems

In power distribution systems, maintaining voltage stability is crucial for ensuring uninterrupted and reliable electricity supply to consumers. Voltage stability refers to the ability of the system to maintain voltage levels within acceptable limits, preventing disruptions in electrical equipment operation and safeguarding against potential damage. It plays a pivotal role in sustaining the efficiency and safety of power distribution systems, as consistent voltage levels are essential for the optimal performance of electrical equipment, ranging from sensitive electronic devices to heavy machinery used in industrial processes. Fluctuations in voltage can lead to equipment malfunctions, premature wear and tear, and even catastrophic failures, endangering both personnel and property [22]. Moreover, voltage stability ensures the quality of electrical supply, which is indispensable for various sectors, including manufacturing, healthcare, telecommunications, and residential utilities [23]. Voltage swell and sag represent significant challenges to voltage stability in power distribution systems. Swells manifest as short-term increases in voltage magnitude, often lasting for a few cycles, and can result from events such as capacitor switching or load disconnection. Conversely, voltage sags entail temporary reductions in voltage magnitude, typically caused by faults, motor starting, or sudden changes in load demand [24]. Understanding the characteristics and causes of these phenomena is crucial for identifying their root causes and implementing effective mitigation strategies. Voltage variations, particularly swells and sags, can have detrimental effects on electrical equipment and industrial processes, leading to equipment malfunctions, production downtimes, and potential safety hazards. Therefore, comprehensive knowledge of voltage swells and sag phenomena is essential for maintaining the reliability and stability of power distribution networks.

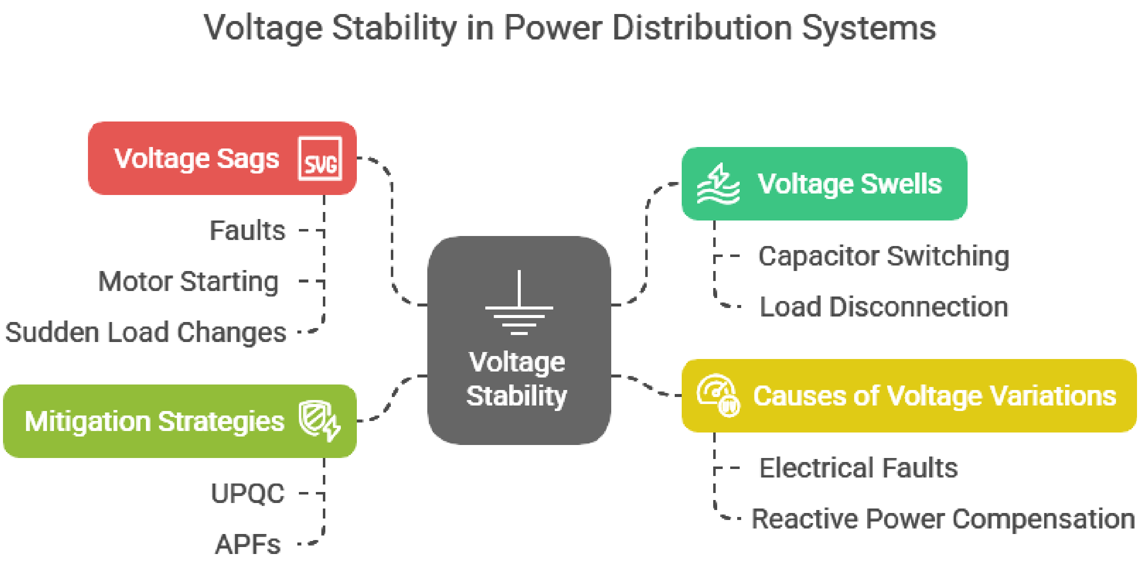

Fig. 3 Voltage Stability in Power Distribution Systems and Associated Mitigation Strategies

This figure 2 illustrates the key components and factors associated with voltage stability in power distribution systems. It highlights the two primary voltage disturbances—voltage sags and voltage swells—and their respective causes. Voltage sags are typically caused by faults, motor starting, and sudden load changes, while voltage swells often result from capacitor switching and load disconnections. The figure also outlines the causes of voltage variations, which include electrical faults and issues related to reactive power compensation. To address these challenges, effective mitigation strategies such as the integration of Unified Power Quality Conditioners (UPQC) and Active Power Filters (APFs) are employed to stabilize voltage and improve overall power quality within the system. These strategies play a crucial role in ensuring the reliability and stability of power distribution networks.

Voltage swell and sag are transient disturbances in power distribution systems characterized by temporary deviations from nominal voltage levels. Swells refer to short-term increases in voltage magnitude, typically lasting for a few cycles, while sags entail temporary reductions in voltage magnitude. These phenomena can have significant impacts on electrical equipment and industrial processes, making it essential to understand their characteristics for effective mitigation [25]. Voltage variations are typically measured and quantified using parameters such as magnitude, duration, and frequency. The magnitude of a voltage swells or sag is the difference between the peak or trough voltage level and the nominal voltage level [26]. Electrical faults, such as short circuits or ground faults, are another significant cause of voltage variations in distribution systems. These faults can disrupt the normal flow of electricity and result in sudden changes in voltage levels. Faults may occur due to equipment failures, insulation breakdown, or environmental factors such as lightning strikes. For instance, a short circuit in an underground cable network can cause a voltage sag, affecting nearby industrial facilities and residential areas connected to the same distribution network. Inadequate reactive power compensation or improper operation of compensation devices can also contribute to voltage variations [27]. UPQC combines two converters shunt and series working as APFs with common dc capacitor. A shunt APF can inject reactive current to correct the power factor, inject harmonic current to address load current harmonics and balance supply currents via injecting negative and zero-sequence components as required by the load. It can also control the DC bus voltage. A series APF regulates the voltages at the load bus by injecting negative and zero sequence voltages to compensate for those in the source, controls the magnitude of the load voltage by injecting the active power components that are necessary, and isolates the load bus from harmonics in the source voltages by injecting harmonic voltages [28].

TABLE 2 Comparative Analysis of Voltage Stability and UPQC in Power Systems

Ref No.	Focus Area	Key Contributions	Challenges Discussed	Insights/Recommendations
[14]	Voltage Stability in Power Distribution Systems	Voltage stability ensures uninterrupted supply and safeguards electrical equipment	Fluctuations can lead to malfunctions, premature wear, and failures	Maintaining stable voltage is crucial for safety and efficiency in various sectors

[15]	Impact of Voltage Stability on Quality of Electrical Supply	Voltage stability ensures optimal performance across industries	Unstable voltage affects sensitive equipment, manufacturing, healthcare, etc.	Stable voltage is essential for smooth operation in critical sectors
[16]	Voltage Swell and Sag in Power Distribution Systems	Describes the causes and effects of voltage swells and sags	Voltage swells and sags can cause equipment malfunctions and safety hazards	Understanding the phenomena is key to effective mitigation
[17]	Understanding Voltage Variation Causes	Highlights electrical faults, such as short circuits, as major causes	Faults can disrupt power flow and cause voltage variations	Mitigation strategies must address faults and their impact on voltage levels
[18]	Measurement of Voltage Variations	Discusses parameters like magnitude, duration, and frequency of voltage variations	Need for precise measurement and control of voltage variations	Implementing comprehensive monitoring tools can help mitigate issues
[19]	Role of Reactive Power Compensation in Voltage Stability	Explores inadequate reactive power compensation as a cause for voltage variations	Improper compensation devices contribute to unstable voltage levels	Reactive power management is essential for voltage regulation and stability
[20]	UPQC's Role in Voltage Regulation and Power Quality	Explains UPQC's role in mitigating voltage variations and compensating for power quality issues	UPQC helps address power factor correction, harmonics, and load voltage compensation	UPQC is effective in maintaining stable voltage and improving system performance

IV. Challenges in the Integration of Unified Power Quality Conditioner (UPQC)

Power System applications of Unified Power Quality Conditioners (UPQC) provide great advantages in terms of better voltage regulation, increasing power quality, and disturbance compensating for various types. However, there are many challenges that shall be addressed for the successful implementation. One of the major challenges relates to the complexity involved in control strategies [29]. UPQC systems require extensive control algorithms so that series and shunt compensators operation does not get overly complicated. Developing and implementing efficient solutions to ensure seamless operation and optimal performance under various conditions becomes a challenge. UPQC systems may be very expensive, which discourages their usage to a greater extent. These systems use specialized components of power electronics, transformers, or controllers, and therefore expensive to install, operate, or maintain. Because of this cost factor, the integration of UPQC can become economically unfeasible for some utilities or industries, especially in developing countries [30]. UPQC systems can be used to solve some of the problems associated with power quality, such as voltage fluctuations, but harmonic distortion is still a challenge. Designing and tuning the harmonic filters in UPQC to suppress disturbances is cumbersome, and sizing and designing the system are other problems. Proper sizing of the UPQC system is crucial for adequate compensation. Over-sizing is tantamount to unnecessary expense, while under-sizing results in insufficient correction of power quality issues [31].

Integrating UPQC with an existing power grid poses another challenge. Old grid infrastructure must be modified with retrofitting or more additional components to be modern UPQC systems compatible. This integration process might lead to disruptions of operation or large redevelopments within the grid, making it more difficult to adopt this system. Another important consideration in ensuring stable UPQC operation is the stabilization of DC link voltage-involving series and shunt compensators. DC link fluctuations would adversely affect system performance, compromising stability in the compensation. Thermal and overload problems are also serious. Devices associated with UPQC belonging to power electronics generate heat and demand proper cooling solutions to avoid overheating and to ensure their reliability. Moreover, UPQC will be very complex in their maintenance and operation skill workers will be required to monitor, test, and maintain cost and time-consuming. The absence of standardized regulations for UPQC systems in various industries and across regions does not help in their application as well. It becomes a challenge to adopt these systems without generally recognized guidelines for their implementation and integration in different regulatory environments. These issues would be made to wane through advanced control strategies and cost-effective designs. Proper integration can make UPQC a viable. It can clearly be observed that since the introduction of UPQC for PQ enhancement, researchers have attempted to implement it in various applications with the objective of mitigating PQ problems and integrating RES with the main grid. However, the UPQC is still in the research phase and has not yet been extensively applied. The main reason for this is that the UPQC includes two sets of PE converters and a series transformer. This raises the overall cost dramatically along with production and marketing expenses, etc. The main challenge to the researcher is reducing the VA rating of the UPQC without compromising on performance. Many studies have been conducted to identify the features of the UPQC for its application in a balanced environment. However, the power system is unbalanced with both single-phase and three-phase loads. The major PQ problems occurring in an unbalanced power system are an excessive neutral current, harmonics, a reactive power burden, etc [32].

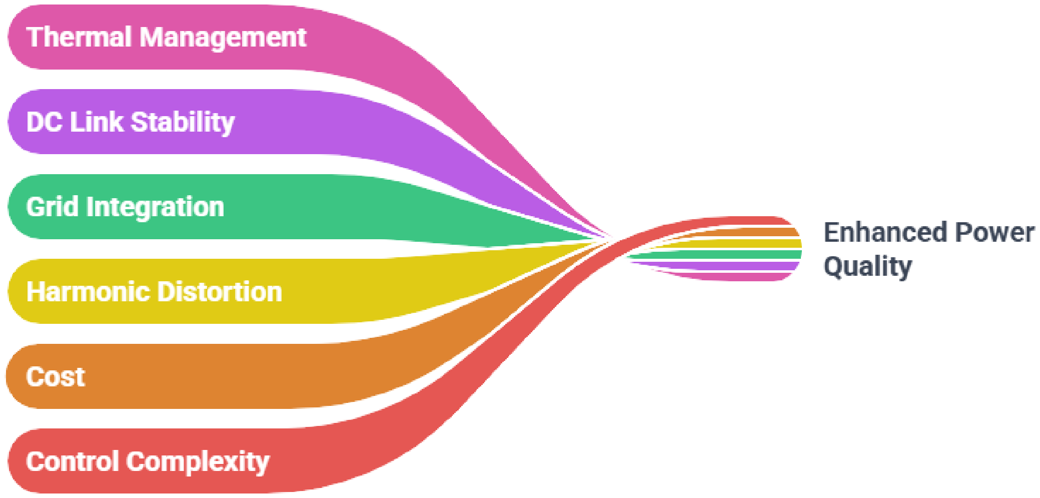

Fig. 3 Challenges in the Integration of Unified Power Quality Conditioner

This figure visually represents the key factors contributing to Enhanced Power Quality in power systems. Each colour stream—Thermal Management, DC Link Stability, Grid Integration, Harmonic Distortion, Cost, and Control Complexity—symbolizes a distinct technical or economic aspect that influences overall power quality. As these factors converge towards the center, they collectively emphasize that addressing each area is crucial for achieving a high standard of power quality. The smooth, unified flow into the outcome highlights the interconnected nature of these elements in modern electrical and power electronics systems.

V. Conclusion

The deployment of UPQC in power distribution systems interfaced with renewable energy sources offers a holistic approach to power quality enhancement by addressing both voltage and current-related disturbances. As this review elucidates, UPQC technologies—through their integrated series and shunt compensation—demonstrate substantial efficacy in mitigating harmonics, stabilizing voltage, and enhancing system reliability under the dynamic conditions introduced by RES. However, practical realization remains constrained by high system costs, complex control algorithms, thermal management demands, and compatibility challenges with existing grid infrastructure. Furthermore, the lack of universal implementation standards hampers widespread adoption. Advancing the design of UPQC systems requires not only innovative control strategies and optimized hardware configurations but also harmonized regulatory frameworks to guide deployment. Future research should focus on modular, intelligent UPQC topologies that are both economically viable and adaptable to evolving smart grid paradigms, particularly within high-penetration RES scenarios.

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