ISSN 2063-5346

ENHANCEMENT OF POWER SYSTEM STABILITY WITH UPQC IN RENEWABLE ENERGY INTEGRATION

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Article History: Received: 02.07.2023 Revised: 15.07.2023 Accepted: 23.07.2023

Abstract

Integrating renewable energy resources in power systems is crucial for economic, clean energy, and resilience goals. However, challenges arise due to the variability and uncertainty of renewables and the lack of inherent system inertia. Flexible Alternating Current Transmission Systems (FACTS) and the Unified Power Quality Conditioner (UPQC) are promising solutions for power quality issues. UPQC combines Active Power Filters (APF) and Shunt-APF series to address voltage fluctuations and consumer-related power problems. With two IGBT-based Voltage Source Converters (VSCs), UPQC ensures stable voltage profiles, efficient power generation, and reliable distribution. This review paper highlights UPQC's adaptability, making it a vital tool for modern power systems integrating renewable energy sources.

Keywords: *Power systems, Unified Power Quality Conditioner (UPQC), Active Power Filters (APF), Shunt-APF*.

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DOI:10.48047/ecb/2023.12.9.221

1. Introduction

There is no doubting the importance of electricity to the development of the global economy in the present and the centuries to come. Not only does the human population grow, but so do the social and economic activities that people engage in, which are increasingly moving from manual to automated processes that are mostly powered by electricity. As a result of its integration into so many human institutions, electricity becomes essential to the survival of modern society [1, 2]. Electricity can be produced from a variety of sources, and it is preferred that it be produced from a variety of sources to increase the total generation capacity and satisfy the growing demand. Instantaneous balancing becomes necessary because electrical energy cannot be stored, making it a crucial design factor for power systems [3].

In the years to come, there needs to be an increase in the penetration of non-dispatchable renewables in electrical power networks in order to attain a low-carbon economy [4]. Energy Storage (ES) is playing a bigger role in the power grid's capacity to balance power and energy. In contrast to the capacity for power generation (energy storage), installed ES capacity is currently very limited (though it is expanding rapidly).

By choosing the appropriate ES technology, Liu and Du [5] claim that there is a considerable technological influence for maintaining the demand and supply balance of renewable energy and lowering the costs of energy. Due to the varied levels of technological complexity, ES technologies have different risks associated with safety, capital, along with technology. They additionally suggested a multi-criteria decision support system based on group decision-making perspectives for the selection of ES technologies. They also mentioned that when numerous ES technology types are combined, the threats to the ES system are increased. Thus, choosing the optimal ES technology mix while taking multidimensional hazards into account is a never-ending task.

In order to achieve their objectives for economic growth, clean energy, and resilience, power system operators around the world are aiming to integrate higher percentages of variable renewable energy sources. Due to the inherent variability, uncertainty, and lack of intrinsic inertia against rapid changes or electrical transients to boost stability during disturbances, utilities and grid operators are experiencing substantial issues in their grid operation and management. As a result, system operators need a higher level of real-time observability to increase their situational awareness and decision-making in order to ensure reliable and secure operations. Phasor measurement units (PMUs) as well as prompt communications technologies are becoming more widely used, enabling system operators to monitor the dynamic operation of a system from a distance at faster time scales [6].

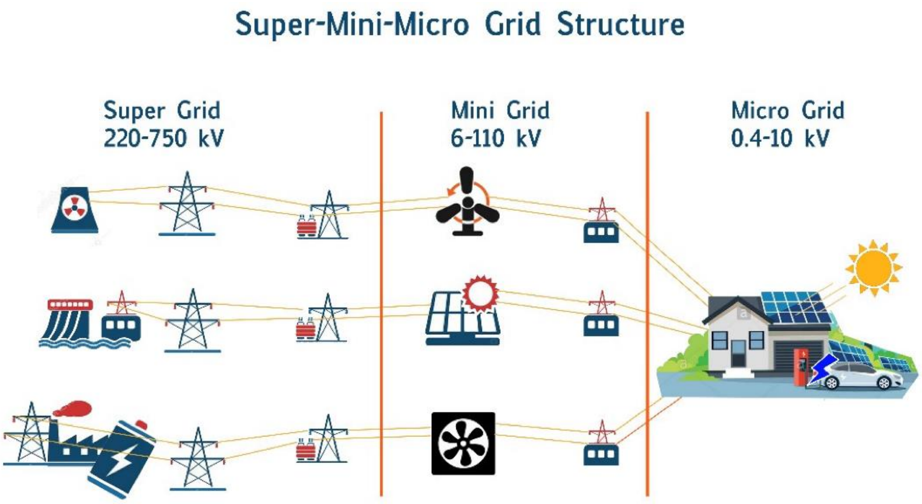

Fig. 1 Three-level structure of future electric power systems [7]

The AC supply systems can get contaminated for an array of reasons, including forced and natural ones such voltage distortions and notches, as well as natural ones such as flashover, lightning, equipment failure, as well as faults. As they draw non-sinusoidal current and behave as nonlinear loads, a number of client devices also contaminate the supply system. As a result, power quality is measured in terms of voltage, current, or frequency deviation in the supply system, which may cause failure or malfunction in the equipment of the client. Voltage harmonics, spikes, surge, glitches, sag/dip, unbalance, notches, swell, fluctuations, outages, flickers, along with other issues with power quality are frequently caused by the voltage at the point of common coupling (PCC), where various loads are connected. These issues are present in the supply system due to the presence of various nonlinear loads such as furnaces, adjustable speed drives (ASDs), as well as uninterruptible power supplies (UPSs), or because of various disturbances in the system.

Voltage sag - As shown in figure 2, it is characterized as a short-duration power variation phenomenon, and is one of the general types of power quality problems. The durations of voltage sags (dips) are split into three categories: immediate (12 to 30 cycles), momentary (30 to 3 sec), and temporary (3 seconds to 1 min). These times are meant to correspond to typical protection devices operating times as well as international technical organisations' recommended duration divides. Many production activities would've have shut down as a result of sags, which are generally acknowledged as one of the most prevalent and critical components of power quality issues afflicting commercial and industrial consumers - they are completely imperceptible by examining lights blinks [8,9].

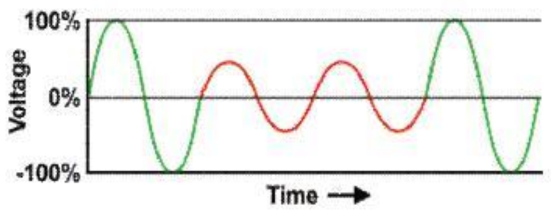

Fig. 2 Voltage Surge and Voltage Sag [9]

Weather and utility equipment issues are the most common causes of voltage sags, which usually result in system malfunctions on the transmission and distribution network. A fault on a paralleled feeders circuit, for examples, will cause a voltage drop on the substation bus, affecting all other feeds until the problem is resolved.

Voltage Swell - Voltage swell is a transient phenomena that occurs in power systems and is characterized by an abrupt and brief rise in voltage at power frequency. Switching operations, power grid flaws, or the disconnecting of heavy loads are only a few causes that it may happen for. Voltage increases above the nominal level for a brief period of time known as a voltage swell. This period can last anywhere between a cycle and a few seconds. The location of the fault, the system impedance, and the grounding circumstances can all affect the severity of voltage swell. Voltage surges, despite being generally brief in duration, can still cause serious disturbances to sensitive electrical equipment, which can result in breakdown or even damage.To ensure the stability of the power system and prevent electrical devices from suffering the adverse effects of voltage swells, proper monitoring and mitigation techniques are crucial.

Harmonic Distortion - The interference in an AC power signal caused by frequencies multiples of the sine wave is known as frequency deviation. The level of Harmonic distortion in the system can be measured using Total Harmonic Distortion. The energy ratios in the feed owing to all harmonics to the energy in the fundamental source is known as THD.

Harmonic distortions are typical voltages abnormalities in electrical network caused by frequency changes. A multi-drive system uses multiple inverters, each of which uses a different harmonic rejection capability and obtains output current from other inverters based on its own impedance. This is in contrast to a single grid-connected inverter. In multi-parallel grid connected equipment, studying the interaction between inverters is therefore the key challenge. A multiple parallel drive setup can be shown in Fig. 3. Each inverter in a parallel set of inverters can produce harmonic currents from three different sources, which can interfere with its output current. The reference signal source may initially cause the grid side current of the inverter to become distorted. High-level harmonics that are transmitted into the inverter via the Phase Locked Loop (PLL) may cause the reference signal source to have harmonics in addition to the fundamental component. Second, other inverters' reference signal sources might vary in a similar way, but this would have a different impact on the inverter's grid side current [10].

Fig. 3 Voltage Variation due to Harmonic Distortion [10]

2. UPQC (Unified Power Quality Controller)

UPQC is used to correct for various voltage disturbances in the electrical supply, appropriate voltage variations, and prevent harmonic current from entering the power source. The tortoise method of voltage balancing is a quick sorting technique, and the hare sorting technique is examined. For applications requiring medium and high voltage, the modular multilevel matrix converter (M3C) topology-based single-phase UPQC is proposed [11]. Four identical multilevel converter arms with corresponding filtering inductors make up the type of M3C under consideration. By balancing the instantaneous active power of each arm with the DC circulating current, voltage balance is achieved by preventing the capacitor voltages from varying across and within the arms. The arm inductance and submodule capacitance designs are studied. A thirteen-level MMC-based UPQC is considered for power quality mitigations. The reference signal is extracted with the utilization of the park transformation control approach [12]. Separate discussions are made of the control strategies for shunt and series inverters. A series inverter reduces all types of supply-side disturbances, and a shunt inverter eliminates harmonic current and compensates for reactive power generated by nonlinear loads. The discrete-time linear control multicell UPQC has been discussed in [13]. The topology's design comprises of a multilevel three-phase UPQC with single-phase power cells. Reactive power compensation and fundamental frequency disturbances have been examined. The root locus approach is utilized for the selection of the controller parameters for single variable linear controllers.

A passive shunt filter that is already in place must now absorb the current harmonics produced by a non-linear load in UPQC, the active serial power filter, where the supply voltage blinks or is out of balance with the voltage across the load. However, the active series filter's input/output of actual power is accompanied by a low frequency fluctuation that occurs when the supply voltage is suppressed, which reduces the flicker. A series dynamic channel and a working shunt channel are combined to produce the series dynamic shunt channel, as the name suggests. The solution to various QP issues recently has been found to be FACTS. New developments in netting agreements were made possible by the concepts found in spreadsheets. At the corporate level, a UPQC is the expansion of the UPFC concept. A typical DC capacitor is provided by the integration of the APF and Shunt-APF series, dynamic power channels coupled in series on the DC side. Voltage drops/swells, flicker, voltage asymmetry, and harmonics are upstream disturbances that are attenuated by the UPQC of the series component. Add limitations to keep the load constraints balanced and free of distortion at the specified level. Low power factor, harmonic load currents, load imbalance, etc., caused by the consumer must be mitigated by the shunt section, along with source voltage concerns. The series and APF shunt controllers play a significant role in the overall operation of UPQC.

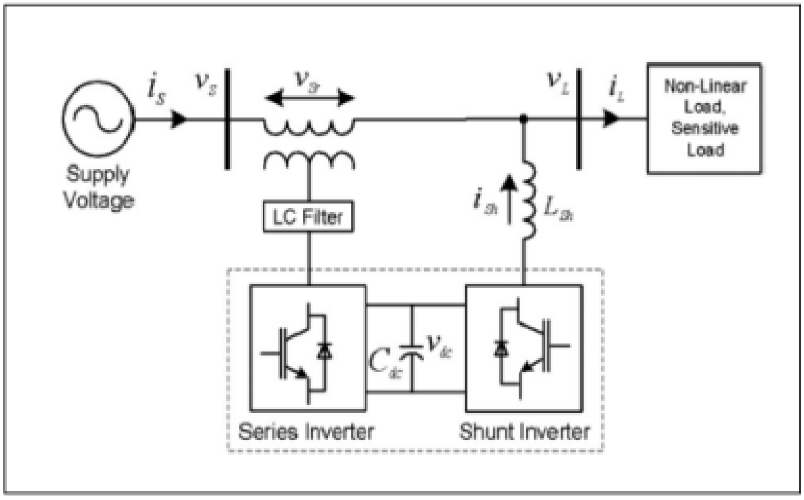

Fig. 4 Block Diagram of UPQC [13]

Two IGBT-based VSC, one series, as well as one shunt are the components of the UPQC, which are cascaded by a common DC bus. Low-pass and high-pass passive filters, DC capacitors, series and shunt transformers, and power converters (both shunt and series), are the basic components of a UPQC. These are this system's main building blocks [13].

The study by **Abdel Mohsen et al. (2023) [14]** provides a power quality (PQ) method to lessen voltage increases, harmonic mitigation of grid current, and light intensity flickers in broad networks of LED lighting at Cairo airport, Egypt. The vast majority of power quality (PQ) problems in a network can be resolved by a transformer-less unified power quality conditioner (TL-

UPQC) and associated controllers. The TL-UPQC is made up of an active power filter (APF), which lowers harmonic currents and injects reactive currents, and a dynamic voltage restorer (DVR), which functions as a series compensator to swiftly maintain the load voltage in the case of a voltage drop, surge, or flickering in the network. To determine the gain values for the PI controller, an extended bald eagle search (EBES) optimizer is used. The performance of the PI controller and quick dynamic response is evaluated using a comparison of the three optimizers moth flame (MFO), cuckoo search (CSA), and salp swarm algorithm (SSA). The results demonstrated that the APF almost attained unity PF and that the harmonics produced by LED lights as THD for current at the grid were removed, becoming 3.29%.Additionally, the outcomes demonstrated that TL-UPQC was able to eliminate voltage fluctuations at grid issues, enabling UPQC to successfully supply a flicker-free LED lighting network, as was proved when used for the LED lighting network at Cairo Airport. The performance of the recommended TL-UPQC has been examined with the implementation of a MATLAB simulation.

According to **Garikapati, R. et al., (2023) [15]**, In order to enhance power quality, fuzzy-based MMC-UPQC is suggested in this work for solar-integrated power systems. Using an analysis of how the MMC suppresses harmonics and controls voltage, this paper establishes the switching strategy of the MMC. The outcomes of this study serve as a basis for the design of a compound control strategy that combines a series and shunts hybrid active power filter with a synchronous method using SGDFT (Sliding-Mode Generalized Discrete Fourier Transform) filtered PLL (Phase Locked Loop). Since it is capable of handling nonlinearities and system uncertainties, a fuzzy controller is used as the DC voltage regulator. In order to translate input signals to output signals, the system utilizes a set of fuzzy rules, making it appropriate for usage in situations where system dynamics are complex. The performance of the MMC-UPQC in a supply system is validated in the paper's conclusion using MATLAB/Simulink simulations. It is shown how effectively the MMC-UPQC controls reduces load harmonic current, regulate grid energy, and makes up for lost control immediately.

Using equipment like unified power quality conditioners (UPQCs) in distribution networks looks crucial for better electricity quality, according to **Zhigao Huang et al. (2022) [16]**. Furthermore, the widely used method of reconfiguring distribution networks is perfect for enhancing network characteristics including loss reduction and voltage rise for distribution networks. A suitable model is provided in this study for evaluating the periodic updating of distribution networks for UPQC. The optimal branch for the UPQC's placement and the best amount of reactive power to inject into the grid in order to use series and shunt filters are computed in addition to the ideal distribution network layout. Two standard-bus networks, 69 and 84, have been subjected to the simulations. The simulation findings show that the presence of UPQC compensators significantly reduces power loss and significantly increases voltage.

An artificial intelligence-based hybrid control method for the unified power quality conditioner combined with solar PV and battery storage systems is presented by **Srilakshmi, K., et al. in 2022 [17]**. A dc link connects a series and shunt voltage source converter that make up the UPQC. Fuzzy Logic and an artificial neural network are both adapted by the hybrid controller. The Neuro-Fuzzy Hybrid Controller (NFHC) regulates the voltage of the DC-Link. The reduction of harmonics in current waveforms, enhancement of power factor, quick response to dc-link voltage balancing, elimination of sag/swell in source voltage, superior response to large disturbances, and adequate compensation for unbalanced networks are the main goals of the proposed work. Three separate test scenarios with varied combinations of loads, solar irradiation, and performance analysis of the proposed controller were used to compare its performance to those of existing techniques.

3. Literature Study

Study	Authors	Objective	Methodology	Key Findings
[18]	Choayb, et al. (2023)	Power quality in utility systems and industry.	- Study the impact of power quality issues on consumers and suppliers. - Investigate power quality problems like voltage sag, swell, harmonics, and interruptions. - Focus on UPQC and its effectiveness in mitigating both voltage and current-based distortions. - Model series APF, shunt APF, and UPQC using MATLAB/Simulink.	UPQC enhances power quality by compensating for harmonics and load current, making source current and load voltage sinusoidal at the desired level.
[19]	Mahar, H., et al. (2022)	Enhancing power quality using UPQC in a grid-connected microgrid.	- An ANN controller for UPQC based on voltage source converters is suggested to reduce system complexity. - Assess UPQC performance with nonlinear unbalanced loads and harmonic supply voltage. - Maintain the voltage on the dc-link capacitor taking the usage of an ANN control system with Levenberg-Marquardt backpropagation, and deliver efficient reference signals. - Utilise MATLAB/Simulink for the simulation of PV-battery-UPQC implementing SRF-based control and ANN-control techniques.	The proposed ANN-based controller outperforms SRF-based control, reducing the total harmonic distortion (THD) in load voltage and supply current.

[20]	Sunil Kumar et al. (2022)	Focus on UPQC for improving power quality in the presence of nonlinear loads.	- Examine the influence of power electronic gadget development on electric power supply quality. - Address concerns about harmonics caused by nonlinear loads. - Investigate the efficiency of UPQC in alleviating voltage and current-based aberrations. - Simulate shunt APF, series APF, along with UPQC using MATLAB/Simulink.	By modifying both harmonics and load current, UPQC efficiently raises power quality through generating sinusoidal source current and load voltage at the intended level.
[21]	G. Kavitha a, et al. (2021)	Implementing UPQC to improve power flow in Large Scale Distribution Networks (LSDN).	- To enhance Optimal Power Flow (OPF), introduce the Prognostic Energy Optimization Technique (PEOT) with a UPQC-based self-organizing network. - Utilize Internet of Things (IoT) to share bus power flow data for fault identification. - Use MATLAB 2017b to assess the performance of 14-bus system.	PEOT with UPQC-based compensator improves OPF, enhances power flow, and reduces power loss in the grid power system.

- Shunt and Series Converter

This is a voltage converter determined on a similar AC line and utilized as a force source to smother current mutilation, make up for the responsive current of the heap and further develop the force factor. It additionally plays out the voltage guideline of the transitional circuit, which prompts a huge decrease in the force of the DC capacitor. By adjusting the state of the strong state switches, the yield current of the shunt converter may be modified through a distinct hysteresis band so the yield current follows the reference sign and remains inside a predetermined hysteresis band. This voltage converter functions as a voltage source to reduce voltage bending and is connected in series with the AC power line. It is used to power the detour branch and suppress supply voltage flickering or voltage unbalanced characteristics throughout the stack to current sounds generated by the non-direct load. Typically, sinusoidal pulse width modulation is used to modify the serial converter's output voltage. The converter's gate pulses are generated by comparing a base voltage reference of the signal with the high frequency of triangular shape.

The exceptional Unified Power Quality Conditioner (UPQC) revolutionizes the way power quality is managed and offers a plethora of benefits to power systems. Its unique combination of series and shunt active power filters enables it to address voltage and current-based distortions concurrently and independently, making it extremely adaptable and successful in resolving power quality issues. One of the main advantages of UPQC is its capacity to reduce several power quality issues such voltage sag, swell, harmonics, and interruptions, which can cause expensive damages and disruptions for both customers and suppliers.

4. Challenges Faced By Unified Power Quality Conditioner (UPQC)

Powerful technology called the Unified Power Quality Conditioner (UPQC) serves to overcome problems with power quality in contemporary power systems. For its successful implementation and wide-scale adoption, it must also overcome various obstacles:

- Control and Coordination: Successful control and coordination of the UPQC components is essential for obtaining the intended performance. It is technically difficult to create sophisticated control algorithms that guarantee flawless communication between the series and shunt components.
- Cost: The cost of adopting UPQC, particularly for large-scale applications, can be rather significant. For utilities and other companies with tight budgets in particular, this cost element might be problematic.
- Sizing and Scalability: Finding the ideal UPQC configuration and size for a given application can be difficult. It is crucial to adapt the solution to the specific needs of each system because the sizing and scalability of UPQC depend on the particular power quality concerns to be addressed and the load characteristics.
- Complexity: UPQC demands the fusion of a number of parts, including Voltage Source Converters (VSCs), DC capacitors, Active Power Filters (APF), Shunt-APF series, and Active Power Filters. These components' management and coordination might be difficult to manage, necessitating advanced control techniques.
- Reactive Power Compensation: While UPQC excels at compensating for harmonics and load currents, it may have limitations in providing sufficient reactive power compensation, especially under certain operating conditions. This limitation can impact voltage regulation and power factor correction.
- Grid Integration and Standards: Integrating UPQC into existing power systems requires compliance with grid codes and standards. Ensuring seamless integration and meeting regulatory requirements can be a challenge, especially in diverse utility environments.
- Maintenance and Reliability: Like any complex electrical system, UPQC requires regular maintenance to ensure optimal performance. Ensuring high reliability and availability of UPQC systems over the long term can be a concern for grid operators and utilities
- Compatibility and Interoperability: UPQC should be compatible with different power system configurations and components. Ensuring interoperability with existing grid infrastructure and equipment is essential for smooth integration.
- Environmental Impact: As with any power electronics-based technology, UPQC's environmental impact needs consideration. Sustainable manufacturing processes, end-of-life recycling, and reducing energy losses are crucial for minimizing the technology's carbon footprint.

Addressing these challenges requires collaborative efforts from researchers, manufacturers, utilities, and policymakers. As the demand for efficient power systems grows, addressing these challenges will pave the way for UPQC's wider adoption and its positive impact on power quality and grid stability.

5. Advances in Unified Power Quality Conditioner (UPQC):

By compensating for harmonics and load current, UPQC ensures that the source current and load voltage maintain sinusoidal waveforms at the required voltage level. This improvement in power quality leads to increased system stability, reduced equipment failures, and enhanced overall operational efficiency. The advantages of UPQC extend further, making it an indispensable asset in modern power systems.

A reliable power supply must maintain a stable voltage profile, and UPQC excels at achieving this. It successfully regulates voltage levels, reducing deviations and fluctuations, hence preventing voltage-related problems and enhancing the resilience of the power grid. Additionally, UPQC is essential for enabling effective power generation and distribution in utility systems and industrial setups. Power delivery becomes more dependable and constant by reducing power quality issues, which benefits not only end users but also boosts the nation's economy as a whole. Customized solutions based on particular system needs are possible because to the flexibility of UPQC in control techniques. It can adjust to a variety of loads, making it suited for a variety of applications in various sectors. From this point on, UPQC's compatibility with renewable energy sources and microgrids makes it an excellent option for the integration of clean energy technologies. By mitigating power quality issues in these systems, UPQC facilitates smoother and more effective integration of renewable energy, promoting sustainable power generation. Furthermore, UPQC offers an array of advantages that collectively contribute to a significant improvement in power quality and system performance. Its ability to address voltage and current-based distortions, maintain voltage stability, and adapt to various loads and energy sources establishes it as a cutting-edge and indispensable tool for ensuring a reliable and high-quality electrical power supply in modern power systems.

6. Conclusion

Due to their inherent fluctuation and uncertainty, variable renewable energy resources pose substantial issues for power system operators in terms of grid stability. Flexible Alternating Current Transmission Systems (FACTS) have emerged as a feasible solution to these power quality challenges, according to this review paper. The Unified Power Quality Conditioner (UPQC) stands out as a comprehensive approach for the enhancement of power system stability with management of disturbances. UPQC combines Active Power Filters (APF) and Shunt-APF series on the DC side, effectively mitigating upstream disturbances and addressing consumer-related power quality issues. Its core components, including IGBT-based Voltage Source Converters (VSCs), ensure a stable voltage profile and balanced, distortion-free load constraints. The significance of UPQC extends to various aspects of power systems, playing a vital role in facilitating efficient power generation and distribution while ensuring a reliable power supply. Its adaptability to diverse loads and flexibility in control strategies make it suitable for various industries. As power systems continue to evolve, UPQC emerges as an indispensable tool, driving sustainable economic growth and contributing to a cleaner, greener future for global power systems.

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