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Optimizing Renewable Energy Integration in Weak Grids with UPQC Controller

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Abstract

Integrating renewable energy into weak grids poses significant challenges, including voltage instability, power quality deterioration, and limited capacity to handle variable generation. This paper proposes a methodology to improve the Power Quality in the weak grid with renewable energy penetration using additional Unified Power Quality Conditioner (UPQC) Controller. Bird Swarm Optimization algorithm is implemented in the conventional scheme to minimize the oscillations in the voltage signals. The proposed control system evaluates the switching signals for the UPQC while accounting for variations in the grid's strength, wind speed, load currents, and dc link voltage dynamics. The efficiency of the suggested strategy for improving the PQ performance of weak grid-connected renewable energy sources in the presence of nonlinear loads was demonstrated by simulations conducted in MATLAB and experimental research.

Keywords

Unified Power Quality Conditioner (UPQC), Renewable Energy Sources, Weak Grid, Power Quality, MATLAB / Simulink.

Introduction

The global transition towards sustainable energy sources has accelerated the integration of renewable energy into power grids. Solar and wind energy, in particular, are pivotal in this transition due to their abundant and environmentally friendly nature. However, the intermittent and variable nature of these renewable energy sources presents significant challenges, particularly for weak grids. Weak grids, often found in remote or underdeveloped areas, have limited capacity, high impedance, and poor voltage regulation, making them susceptible to instability when subjected to fluctuating power inputs. Voltage instability is a predominant issue in weak grids, exacerbated by the unpredictable output of renewable energy sources (Gajendra Singh Chawda et al., 2023). Frequent voltage sags, swells, and harmonic distortions can disrupt the normal operation of electrical equipment, leading to inefficiencies and potential damage. These power quality problems hinder the optimal utilization of renewable energy and pose a significant barrier to achieving a stable and reliable power supply in weak grids.

The Unified Power Quality Conditioner (UPQC) emerges as a comprehensive solution to these challenges. A UPQC is a hybrid device that integrates the functionalities of both a Dynamic

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Voltage Restorer (DVR) and an Active Power Filter (APF). This dual capability allows the UPQC to simultaneously address voltage and current disturbances, providing a robust mechanism for enhancing power quality and grid stability. By mitigating voltage sags, swells, harmonics, and reactive power issues, UPQC controllers can significantly improve the reliability of weak grids (Bashar Aldbaiat et al., 2022). The operational principles of the UPQC involve injecting compensating voltage or current to counteract disturbances. The DVR component addresses voltage-related issues by inserting or absorbing voltage as required, while the APF component targets current-related problems by filtering out harmonics and managing reactive power. This integrated approach ensures a stable and clean power supply, which is essential for the efficient operation of sensitive electrical equipment and the broader integration of renewable energy.

Implementing UPQC controllers in weak grids requires careful consideration of various factors, including grid characteristics, the nature of renewable energy sources, and economic feasibility (Chuanyue Li et al., 2022). Advanced control strategies are crucial for the effective operation of UPQC devices, enabling real-time adaptation to changing grid conditions and renewable energy output. These strategies leverage sophisticated algorithms and sensor technologies to optimize the performance of UPQC controllers, ensuring they respond swiftly and accurately to disturbances.

Economic considerations are also vital in the deployment of UPQC technology (Muhammad F. Umar et al., 2022). While the initial investment in UPQC devices can be significant, the long-term benefits in terms of improved grid stability, reduced equipment damage, and enhanced energy efficiency can offset these costs. Moreover, regulatory frameworks and policy incentives can play a crucial role in promoting the adoption of UPQC technology, especially in regions with weak grid infrastructures (Mir Nahidul Ambia et al., 2022). Through detailed case studies and simulations, this paper demonstrates the practical impact of UPQC controllers on weak grids. These examples illustrate how UPQC technology can effectively mitigate the adverse effects of renewable energy variability, ensuring a stable and reliable power supply. The case studies also highlight the importance of tailored solutions, as the specific characteristics of each weak grid and renewable energy source can influence the effectiveness of UPQC devices.

The integration of renewable energy into weak grids, supported by UPQC technology, represents a significant step towards a resilient and sustainable energy system. By addressing the technical challenges associated with weak grids, UPQC controllers enable the broader adoption of renewable energy sources, contributing to global efforts to reduce carbon emissions and combat climate change. This paper underscores the critical role of UPQC technology in achieving these goals, offering insights into best practices and future research directions.

The optimization of renewable energy integration in weak grids through UPQC controllers is essential for achieving a sustainable and reliable power supply (Saeed Rezaee et al., 2021). The multifaceted capabilities of UPQC devices make them indispensable in addressing the complex challenges posed by weak grids and variable renewable energy sources. As the demand for clean energy continues to grow, the deployment of UPQC technology will play a pivotal role in ensuring that even the most vulnerable power grids can support the transition to a greener future.

Proposed Methodology

A general schematic of the control scheme of a typical double-stage grid-connected solar system is displayed in Fig. With the aid of a cuk sepic converter, the system can track the highest possible PV power and raise the PV voltage within the allowed range of the PV inverter. A DC capacitor is used to connect the three-phase voltage inverter's boost output terminals.

Keeping an eye on the quantity of active and reactive electricity fed into the grid is the main duty of the dc-ac converter. To connect the converter to the ac grid and manage the high-order harmonics caused by the inverter switching behaviour, an LC filter is employed (Javad Khazaei et al., 2018).

Grid FOM and NOM are the two main modes of operation for the suggested grid-connected PV system. It is therefore recommended to use a quick grid fault detecting block. When the grid voltage drop hits a specific threshold, the transition from NOM to FOM is enabled. The recommended control can be utilized as reference profiles in the NOM and around the grid side converter by setting the reference powers (active power (P*) and reactive power (Q*) (Chuanyue Li et al., 2022). The reactive power reference should be zero and the active power reference should roughly match the maximum PV power in order to guarantee that the grid voltage and current are in phase (high power factor). The active power can be regulated by adjusting the dc-link voltage.

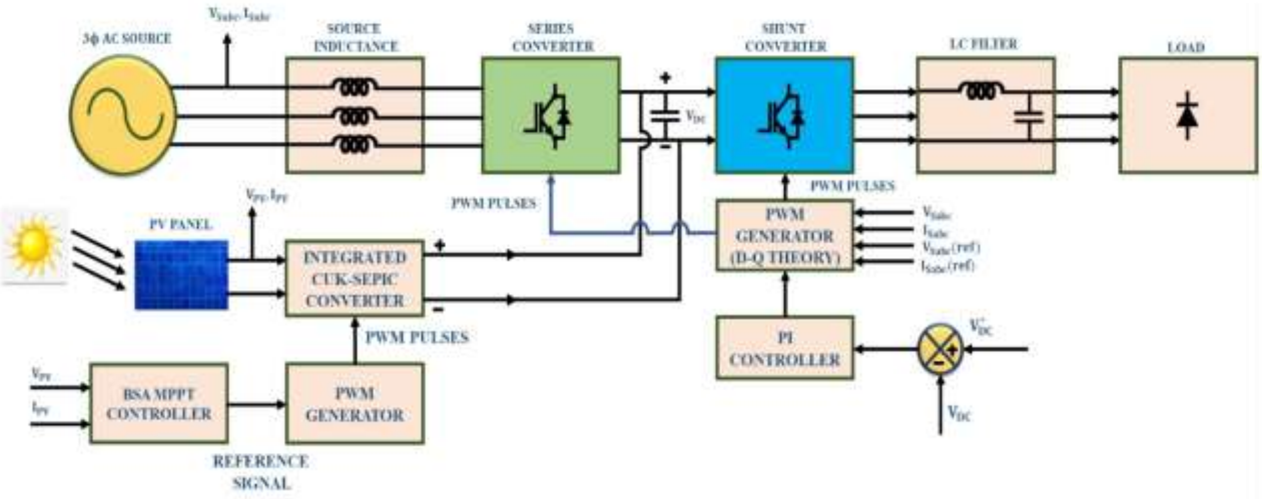

Figure 1. Proposed Methodology of Grid Integrated PV System

The MPPT algorithm has been used around the first stage to extract the most PV power due to its ease of use and lower implementation costs. Upon sensing an SGVD at the PCC, the inverter immediately boosted its output current to maintain the power balance between the grid and PVG. The inverter rating current nevertheless places a restriction on the current. By switching from NOM to FOM control, the system's overall stability can be raised without a disconnect (R. Rajasree et al., 2023). An inverter that can adjust its reactive power injection in response to voltage sag levels is needed. The power supplied by the PVG must match the output power of the inverter in order to preserve a constant dc-link voltage and safeguard the bus capacitor.

The UPQC System has voltage source inverters are used for both series and shunt rectification. It is common knowledge that a single dc interface capacitor regulates both voltage source inverters. Voltage source inverter is connected to the ac framework in parallel, while the other is connected to the ac framework in an arrangement. An inverter connected in parallel with its control circuit makes up the shunt compensation circuit. In contrast, the series compensation circuit consists of an inverter connected in series with the proper control circuit. To ensure optimal performance, the UPQC requires the DC capacitor voltage to be at least 150% of the highest line-line supply voltage. For constant capacitor voltage management, a PI controller or a fuzzy controller can be employed. The shunt compensator and arrangement compensator control circuits are separated in this way within the UPQC control framework. Presumptively, we provide the UPQC two roles to perform the taking.

Feed forward control: A feed forward control pathway is a part of a control system that sends a controlling signal from a system source - typically a command signal from an outside operator—to a load located anywhere in the external environment of the system. A control system with only feed forward behaviour responds to its control signal in a predetermined way without taking into consideration how the load responds, in contrast to a control system that adjusts the output to account for how it affects the load and how the load itself may shift unexpectedly.

Feedback control: A feedback mechanism, process, or signal can be used to internally control a system. This type of loop is known as a feedback loop. In systems with input and output, positive feedback is the process of feeding back some of the output in a way that increases the input, while negative feedback is the process of feeding back some of the output in a way that partially opposes the input. An external signal source provides the input for a control system, and an external load receives the output.

Bird Swarm Optimization Technique

Particle Swarm Optimization (PSO) is a computational algorithm inspired by the social behaviour of bird flocking or fish schooling, used to solve optimization problems. In PSO, a population of candidate solutions, called particles, moves through the solution space, each representing a potential solution to the problem. Each particle adjusts its position based on its own previous best position and the best position found by its neighbours, allowing the swarm to explore and exploit the search space effectively. The algorithm iteratively updates the particles' positions and velocities, balancing exploration of new areas with exploitation of known good regions (Gajendra Singh Chawda et al., 2023). This dynamic process helps PSO converge towards optimal or near-optimal solutions, making it a powerful tool for various optimization tasks in fields such as engineering, computer science, and economics.

Each particle in the swarm has its velocity updated based on both its own best-known position and the best-known positions of its neighbours, which helps navigate the search space efficiently. The inertia weight parameter is crucial for balancing exploration and exploitation, with a high inertia weight promoting broad searches and a low one focusing on refining solutions. PSO also incorporates cognitive and social components in its velocity update formula, guiding particles towards both personal and global best positions (Mir Nahidul Ambia et al., 2022). The algorithm's convergence speed can be influenced by parameter settings like the number of particles and coefficients for cognitive and social learning. Variants of PSO, such as Binary PSO for discrete problems and Multi-objective PSO for handling multiple objectives, extend its applicability to diverse optimization tasks. Careful initialization and parameter tuning are essential for optimizing performance, as PSO is used across various fields, including engineering, machine learning, and financial modelling, demonstrating its adaptability and effectiveness in solving complex problems.

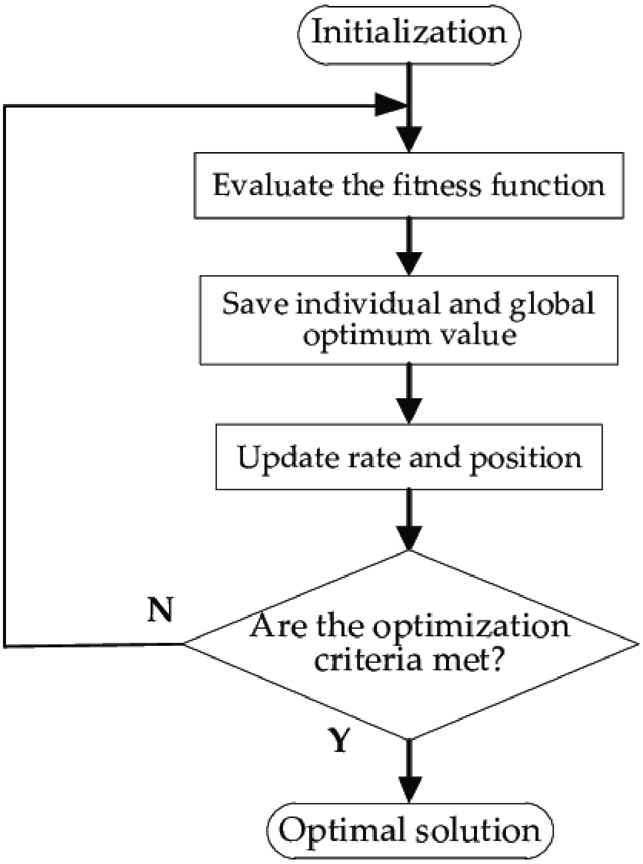

Figure 2. Flowchart of Particle Swarm Optimization Technique

Results and Discussion

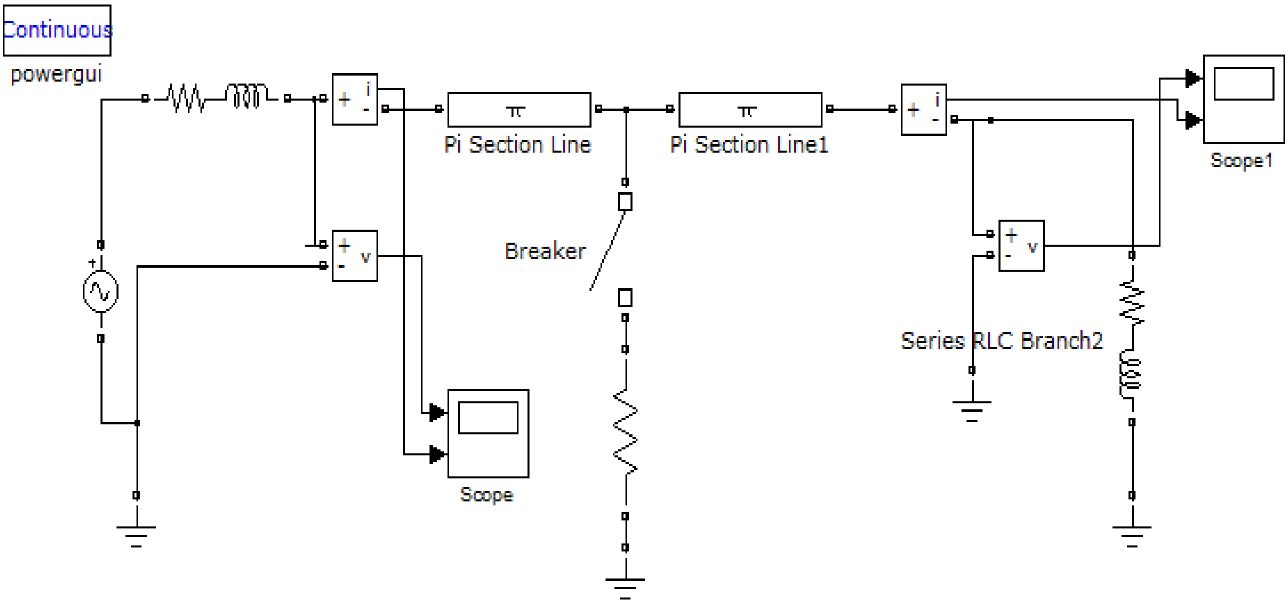

Figure 3. Simulation without Controller

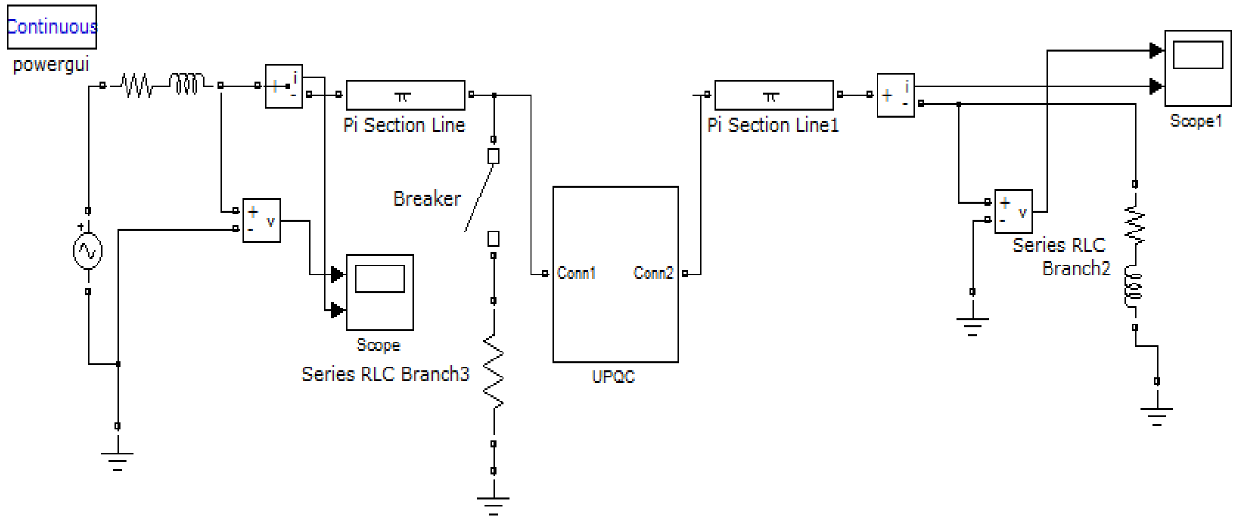

Figure 4. Simulation with UPQC Controller

Figure 3 and 4 represents the simulation diagram for the grid connected renewable system with and without controller (Unified Power Quality Conditioner).

Figure 5 represents the output voltage and current waveform variations for without controller in which there will be a high THD.

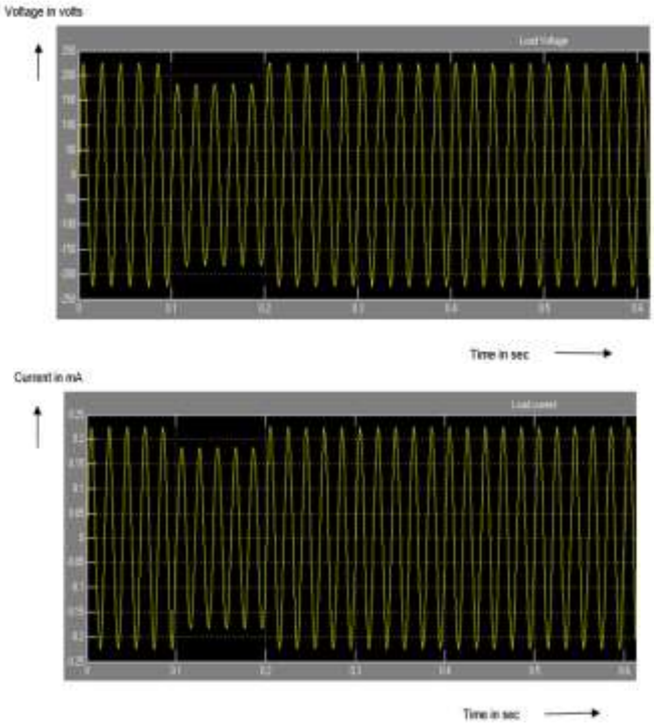

Figure 5. Output Voltage and Current waveforms without Controller

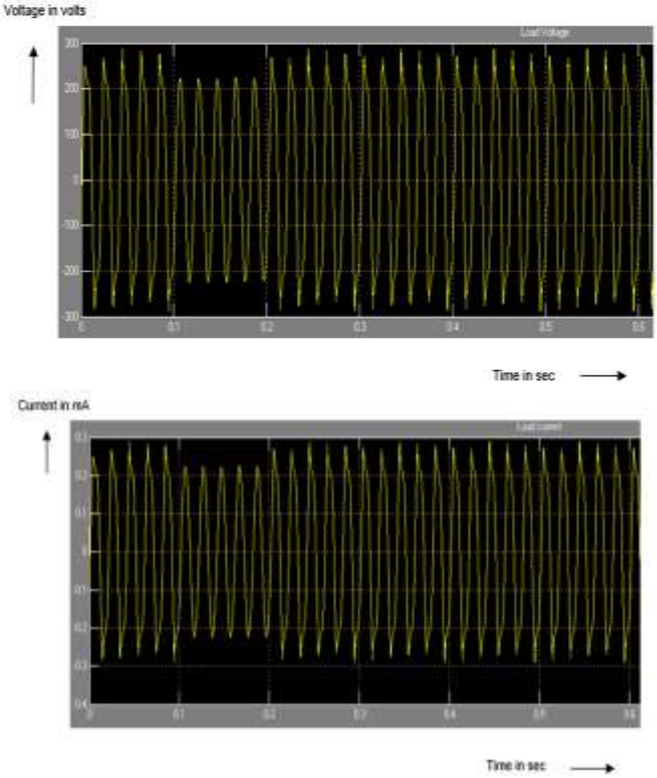

Figure 6. Output Voltage and Current waveforms with Controller

Figure 6 represents the output voltage and current waveform variations for with controller (UPQC) in which there will be a low THD and reduce approximately to 50%.

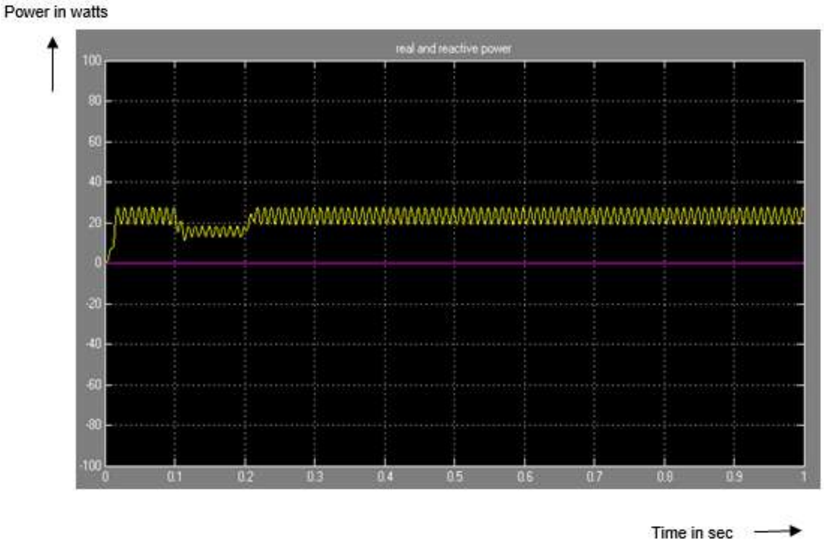

Figure 7. Real and Reactive Power waveforms without Controller

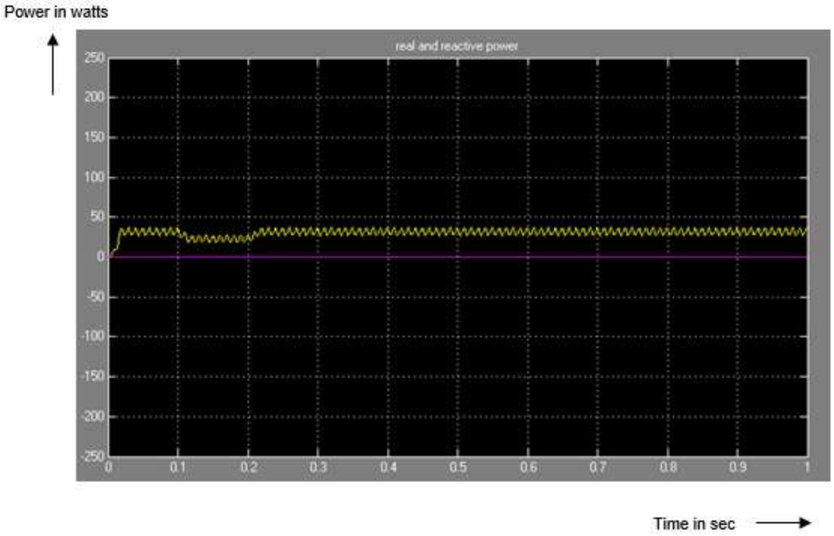

Figure 8. Real and Reactive Power waveforms with Controller

Figure 7 and 8 represents the real and reactive power waveforms for with and without controller.

Table 1. Measurements of total harmonic distortion (THD) for Grid connected System.

Parameter	Without UPQC Controller	With UPQC Controller
THD value	8.88%	4.98%
Reactive Power	11.7	41

Conclusion

In this study, an optimal controller design scheme is utilized to mitigate the reactive power compensation in renewable energy resources connected in weak grid. Through a novel modelling approach, the grid equipped with UPQC as a nonlinear system that accommodates grid tie inverter in weak grid. The UPQC performs a damping controller through injected series voltage because of power quality issues. A bird swarm optimization algorithm approach is adopted to design a nonlinear optimal controller through successive approximation of cost function using BSA algorithm. When it is applied to weak grid a reduced structure UPQC is shown effective in improving the dynamic stability of the grid. The use of a Unified Power Quality Conditioner (UPQC) controller offers an effective solution to these challenges by enhancing grid stability, improving power quality, and ensuring the seamless integration of renewable energy. This approach not only supports the transition to a more sustainable energy future but also contributes to the resilience and efficiency of power networks in regions with weak grid infrastructure.

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