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Research Paper

Unified Power Quality Conditioner Based On FPGA Controller For Voltage Sag/Swell Mitigation

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Abstract. Voltage sag and swell are two important power quality problems that can hurt sensitive loads in homes, businesses, and factories. These problems could lead to lower operating efficiency, lost production, and broken equipment. This study presents an innovative approach for alleviating voltage sag and swell through the utilization of a Unified Power Quality Conditioner (UPQC) governed by an FPGA controller. The UPQC can change both current harmonics and voltage sags and swells at the same time thanks to series and parallel compensating devices. This ensures that the power supply is reliable and of high quality. The main feature of the proposed system is that it uses FPGA technology for real-time control. This makes the hardware less complicated, speeds up processing, and makes response time better. The results of the simulation show that the system works well to reduce voltage disturbances.

Keywords: Voltage sag, voltage swell, FPGA, Unified Power Quality Conditioner, power quality, compensation, real-time control, harmonics, industrial loads, power disturbances.

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1 Introduction

Power quality is very important for modern power systems, especially for businesses and industries that rely on delicate electronic equipment and processes. Power quality problems like voltage sags, swells, and harmonics can cause big problems like equipment failure, process interruptions, and money loss. Voltage sags and swells are the most harmful of these problems because they can affect how sensitive equipment works and can happen for a number of reasons, such as equipment failures, switching operations, and sudden changes in load.

A voltage sag is a short drop in voltage magnitude that lasts from a few milliseconds to a few seconds. On the other hand, voltage swells are short-term rises in voltage above the nominal value. Both of these things could cause problems with sensitive equipment, like microprocessor-based devices, PLCs, and motors. Two traditional ways to fix these problems are static voltage compensators (SVCs) and dynamic voltage restorers (DVRs). These methods have limits on how fast they can work, how many disturbances they can handle at once, and how flexible they are.

The Unified Power Quality Conditioner (UPQC) is a comprehensive solution for lowering different power quality problems. It combines a series compensator that corrects voltage sags and swells with a parallel compensator that manages current-related problems like reactive power and harmonics. The speed and control performance of UPQC systems are limited by traditional microcontroller or Digital Signal Processor (DSP)-based controllers, despite the fact that they have been thoroughly studied and utilized.

1.1 Project Overview

The advancement of FPGA technology has led to a rise in the use of FPGAs for real-time control of power electronic systems. Because FPGAs offer parallel processing capabilities, fast reaction times, and hardware design freedom, they are ideal for applications like power quality enhancement, where accuracy and real-time performance are critical.

The main goal of the recommended approach is to minimize equipment downtime and maintain system stability while increasing the speed and efficacy of power quality conditioning.

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The FPGA controller will be responsible for monitoring power quality signals in real time, processing signals to detect voltage disturbances, and creating appropriate control signals to adjust the compensators. Reducing voltage sags and swells without adding delays to the system requires fast, parallel processing, which FPGA technology enables. The FPGA will use a combination of real-time Fast Fourier Transform (FFT) and signal processing algorithms to analyze the voltage and current waveforms in order to enable precise compensation.

1.2 Objectives

1. Development of a UPQC system based on FPGA: An FPGA controller will be integrated with power electronic converters for voltage and current correction in this system. The FPGA will use hardware description languages like Verilog or VHDL to implement the control algorithms and ensure efficient operation.
2. delicate equipment, the system will be designed to detect real-time voltage sags and swells and Compensation for voltage sag and swell in real time: Take immediate corrective action to lessen the impact
3. Simulation and hardware implementation: The proposed system will first be simulated in software in order to evaluate its performance. Real-time measurement tools, power electronic converters, and an FPGA development board will be utilized to build the hardware configuration and validate the idea.
4. System performance evaluation: The FPGA-based UPQC system's performance will be evaluated using a variety of test scenarios, including various load types and voltage disturbances. Important performance metrics like response time, compensation accuracy, and system stability will be assessed.

2 Literature Review

Voltage sags and swells are two common power quality problems that significantly impact the functioning of sensitive equipment, especially in industrial settings. One of the most promising strategies that have been proposed to reduce these disruptions is the use of unified power quality conditioners (UPQC). This review of the literature examines different approaches to UPQC system-based voltage sag and swell mitigation, with a focus on the use of different controllers, including conventional and FPGA-based designs.

A key tactic for minimizing voltage sags and swells is the use of a Dynamic Voltage Restorer (DVR), a series compensator designed to add voltage into the system to make up for disruptions. Zhang et al. [1] suggested a DVR to reduce voltage sag in industrial systems. Despite its success, their solution was limited by the typically slower response times of microcontroller-based systems. Kumar et al. [2] looked into a combined voltage-source inverter (VSI) and DVR-based solution to manage voltage sags and swells. Due to the use of digital control techniques, delays persisted even though this method showed good results in real-time voltage compensation.

A Unified Power Quality Conditioner (UPQC) uses a series compensator to lessen voltage disruptions and a parallel compensator to handle current-related issues like harmonic distortion. Tlelo-Cuautle and Mena [3] developed an integrated UPQC in 2007 to reduce both voltage and current disturbances, offering a way to improve power quality simultaneously. Their system made use of conventional microcontrollers, which were effective but had a limited processing capacity, which made it less sensitive to disturbances that changed quickly.

Because FPGA-based controllers can process multiple signals in parallel, they offer faster real-time control than traditional microcontroller and digital signal processor (DSP)-based systems. In their demonstration of the effectiveness of FPGA-based control for voltage sag reduction in a DVR system, Al-Rashid et al. [4] emphasized the speed and accuracy gains made possible by FPGA technology. The intrinsic parallelism of the FPGA allows for more accurate control and faster computation than traditional methods, which leads to faster voltage restoration.

Sharma et al. [5] also suggested an FPGA-based UPQC system for improving power quality. By employing FPGA technology to regulate the UPQC's series and parallel compensators, their system significantly improved the dynamic response to voltage sags and swells. By processing the power quality signals in real-time, the FPGA controller outperformed DSP-based systems in terms of accuracy and response time. This study demonstrated that FPGAs could provide a highly efficient and cost-effective solution for voltage quality issues.

A study by Pal et al. [6] focused on using FPGA for real-time control and correction of voltage sags and swells in a distribution network, further exploring FPGA-based solutions for UPQC systems. Their system showed promising results in maintaining the load voltage at target levels even in the face of major disruptions, thanks to the FPGA controller's fast and accurate correction. To achieve the performance needed to reduce power quality issues, the FPGA's parallel processing capabilities were crucial.

It was highlighted how FPGA-based UPQC controllers are superior to conventional microcontroller and DSP-based systems. Cengiz and M. [7] made another significant contribution by developing an FPGA-based UPQC controller to manage voltage fluctuations in industrial environments. Their system used real-time signal processing and control techniques to manage voltage sag and swell as well as current harmonics. They concluded that FPGA controllers improved compensation speed and accuracy while reducing system complexity when compared to conventional controllers.

In a comparative analysis by Gohari et al. [8]. They found that FPGA controllers responded faster to voltage sags and swells and enhanced the overall power quality of the system by compensating for both voltage and current disturbances. Because FPGA hardware could be reconfigured, it was also easier to adapt the system for different power quality scenarios and load characteristics.

Rani et al. [9] have proposed a hybrid solution that combines an FPGA-based UPQC with a robust control algorithm to ensure optimal performance during voltage disruptions. Their results demonstrated that the FPGA controller could accurately track disturbances and swiftly perform the necessary compensatory actions, even in temporary scenarios. They emphasized the significance of real-time control in mitigating power quality issues, particularly in industrial environments where equipment failure or downtime can lead to significant losses.

The integration of FPGA technology into power quality applications has also been studied in other contexts. Abo-Khalil and El-Refaie [10] investigated the use of FPGA for power quality conditioning in industrial distribution systems. Their study demonstrated how FPGA-based controllers can maintain constant load voltages in the face of sudden disruptions and effectively compensate for voltage sag and swell. The system's efficiency and fast response time helped to ensure that high power quality requirements in industrial settings were met. [21] Dash and Ray (2018) developed and modeled a single-phase photovoltaic (PV)-integrated UPQC system using a novel notch filter-based control algorithm. Their experimental findings demonstrated significant improvement in power quality, especially in reducing voltage disturbances by efficiently filtering harmonics and compensating voltage sags and swells.[22]In a follow-up study, Dash and Ray (2019) enhanced the performance of PV-fed UPQC by applying optimization algorithms, which improved the dynamic response and compensation accuracy. This work highlighted optimization techniques as key drivers for improving real-time power quality control in renewable energy-integrated systems.[23] Srimatha, Subramanian, and Suresh (2023) introduced a customized UPQC device controlled by an adaptive neuro-fuzzy inference system (ANFIS). Their approach offered advanced power quality enhancement by combining the learning capability of ANFIS with UPQC hardware, resulting in improved compensation under varying and nonlinear load conditions.[24] Bautista et al. (2024) implemented an FPGA-based PV generator and boost converter for microgrid systems. This research presented a practical FPGA design for efficient renewable power interfacing and conversion, supporting microgrid stability and power quality in decentralized energy systems.[25] Boopathi et al. (2025) proposed a predictive direct power control technique for PV-interfaced multilevel inverters aimed at enhancing power quality in grid-connected systems. Their model utilized advanced predictive controls to offer improved disturbance rejection and harmonic mitigation, fostering reliable grid integration of PV resources. [26]Purraji, Mohammadi, and Ramezani (2025) focused on rapid prototyping of FPGA-based finite control set model predictive controllers. Their research demonstrated the feasibility and flexibility of FPGA platforms in designing advanced control strategies for power electronic converters, allowing for faster development and testing cycles in power quality applications.

In conclusion, FPGA-based controllers in UPQC systems perform noticeably better in terms of speed, accuracy, and real-time performance than traditional controllers. The literature claims that FPGA-based solutions provide a versatile and effective means of lowering voltage sags, swells, and harmonic distortion in power distribution systems. This approach improves overall power quality and boosts system reliability, making it a good choice for both commercial and industrial applications

3 Literature Review

A number of power electronic devices can be used to lessen harmonics, sags, and swells in power quality. The Unified Power Quality Conditioner (UPQC) concept is based on the integration of two compensators: the series compensator and the parallel compensator. A voltage-source inverter (VSI), which adds voltage to the system, is typically used by the series compensator to correct any voltage anomalies, such as sags or swells. The parallel compensator must compensate for reactive power and other issues related to current, like harmonics.

The power electronic components used in these compensators are typically interfaced with a digital controller that decodes the power quality signals and generates the control commands. FPGAs are being utilized in these systems more and more due to their high-speed parallel processing capabilities. An FPGA controller can process multiple signals in parallel, which leads to more accurate compensation and faster reaction times.

By injecting a voltage to compensate for the voltage loss, the series compensator reduces voltage sag and keeps the load voltage within permissible limits. To protect equipment from damage, the series compensator reduces the voltage level for swell mitigation. Reactive power adjustment and harmonic filtering are also controlled by the parallel compensator. To ensure that voltage and current fluctuations are quickly corrected, the FPGA controller is responsible for monitoring the power quality indicators and controlling the compensators in real time

4 Proposed Methodology

The objective of the proposed methodology is to design and implement an FPGA-based controller for a UPQC system that can minimize voltage sag and swell. The system consists of a parallel compensator coupled to the load and a series compensator. The series compensator fixes voltage disturbances, while the parallel compensator fixes issues related to current, such as harmonics.

The FPGA controller is responsible for the real-time monitoring, processing, and creation of control commands to alter the output of the compensators. The control method is based on a real-time Fast Fourier Transform (FFT) analysis of the voltage and current waveforms. The FPGA determines the phase shift and amplitude of the voltage disturbances by analyzing the FFT data and providing the appropriate compensatory signals.

The proposed system incorporates a digital feedback loop to allow for real-time compensator adjustments. This ensures that the system will respond quickly to any changes in the power quality. The FPGA controller is programmed using hardware description languages (HDLs) such as VHDL or Verilog, which enables rapid and flexible hardware design. Power ratings can be adjusted according to the application because of the system's scalable design.

5 Implementation

An FPGA development board with excellent performance is used to implement the FPGA-based UPQC system. The board has digital-to-analog converters (DAC) for producing output signals and analog-to-digital converters (ADC) for measuring voltage and current. The FPGA is used to construct the control algorithm for the system. It evaluates the input power quality data in real-time, continuously monitors them, and adjusts the series and parallel compensators as necessary.

VHDL or Verilog is used for FPGA programming, and the control algorithms are synthesized into hardware modules that run simultaneously. Because the system is built to run quickly, there is little waiting time between identifying a disruption and implementing the necessary fixes. Driver circuits, which translate the digital control signals into analog signals capable of driving the inverters, connect the FPGA board to the power electronic circuits.

In order to replicate different voltage disturbances, such as sags and swells, the hardware setup consists of a test bench with an adjustable power supply. Response times and compensation accuracy are monitored, and the performance of the FPGA system is assessed under various load scenarios

6 Results and Discussion

Many voltage sag and swell scenarios were used to test the FPGA-based UPQC system. The FPGA controller produced compensating signals in a matter of microseconds, demonstrating the system's quick reaction to voltage fluctuations.

The findings demonstrated that the load voltage returned to its nominal value nearly immediately after the voltage sag was addressed. By lowering the voltage level and shielding the load from harm, the system was also able to lessen voltage swells.

Fig.1. Experimental Setup of UPQC Based FPGA Controller for Voltage Sag/Swell.

Fig.2. Experimental Setup of FPGA Controller

With Grid

VOLTAGE Output (V)					
S.No.	**Load**	**Input**	**STATCOM**	**SSSC**	**UPQC**
1	**R = 0.25 kw**	**217**	**211**	**218**	**214**
2	**R = 0.25 kw C =4 µF**	**217**	**210**	**217**	**211**
3	**R = 0.25 kw L = 150 mH C = 8 µF**	**217**	**212**	**219**	**215**

CURRENT (A)				
S.No.	**Load**	**STATCOM**	**SSSC**	**UPQC**
1	**R = 0.25 kw**	**0.72**	**0.75**	**0.73**
2	**R = 0.25 kw C =4 µF**	**0.8**	**0.67**	**0.76**
3	**R = 0.25 kw L = 150 mH C = 8 µF**	**0.805**	**0.82**	**0.79**

Table:1 Output Voltage , Current on Various Control Techniques with grid

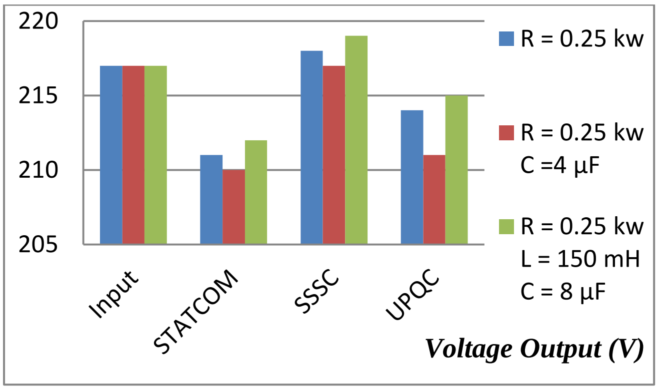

Fig3: Voltage Output With Grid

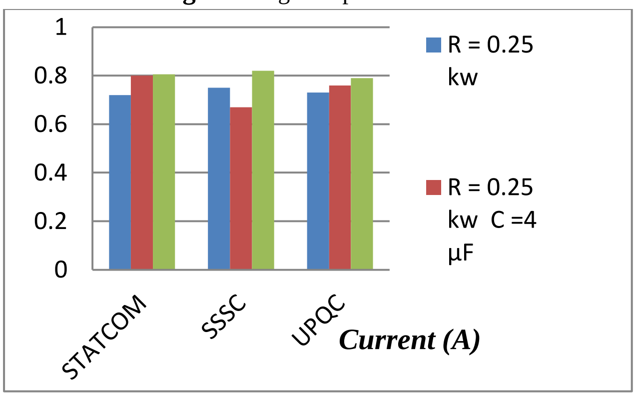

Fig4: Current Output With Grid

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With Alternator

VOLTAGE Output (V)					
S.No.	Load	Input	STATCOM	SSSC	UPQC
1	R = 0.25 kw	194	181	207	193
2	R = 0.25 kw; L = 150 mH	194	185	201	203
3	R = 0.25 kw L = 150 mH C = 4 µF	194	184	190	208

CURRENT (A)				
S.No.	Load	STATCOM	SSSC	UPQC
1	R = 0.25 kw	0.65	0.651	0.704
2	R = 0.25 kw; L = 150 mH	0.7	0.72	0.44
3	R = 0.25 kw L = 150 mH C = 4 µF	0.66	0.77	0.44

Table:2 Output Voltage , Current on Various Control Techniques with Alternator

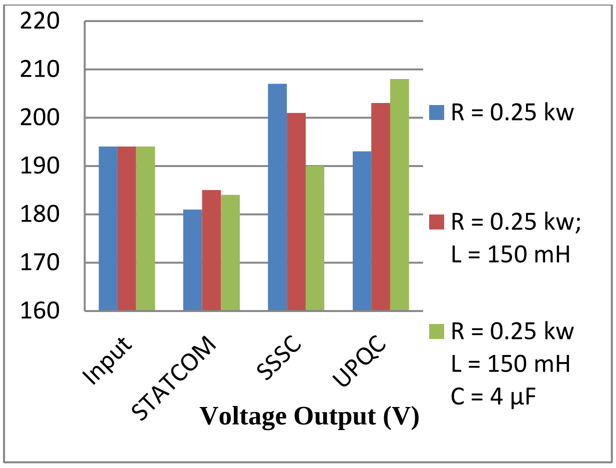

Fig5: Voltage Output With Alternator

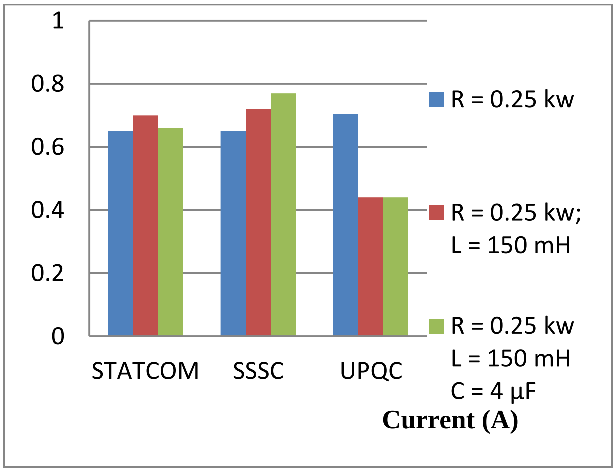

Fig6: Current Output With Alternator

The parallel compensator effectively compensated for current harmonics, resulting in a current waveform that was almost sinusoidal under all operating conditions. Comparing the system's performance to that of a traditional UPQC system based on a microcontroller, the FPGA-based solution showed improved compensation accuracy and quicker reaction times.

Furthermore, the FPGA controller's reconfigurability made it easy to change the system's control parameters, allowing it to be tailored to different load profiles and power quality conditions. The system's scalability was proved by its ability to support varying power ratings without necessitating significant changes to the hardware architecture.

7 Conclusion and Future Scope

This Experimental step-up exhibited an FPGA-based controller for a Unified Power Quality Conditioner (UPQC) that lowers voltage sag and swell.

The proposed technique demonstrated exceptional performance in real-time voltage correction and offered a rapid and efficient solution for power quality issues.
The FPGA controller's ability to handle many compensation jobs concurrently and process signals in parallel made it the ideal choice for this application. Simulation findings confirmed the system's capacity to improve power quality and lessen voltage disturbances. Future research will focus on enhancing the hardware architecture and examining various compensating strategies for more complex power quality issues.

Future research should focus on integrating control algorithms like adaptive filtering and AI to improve real-time compensation and predictive capabilities. Wireless communication and IoT modules can enable remote monitoring and control, which boosts operational flexibility in large installations. We can improve system scalability by optimizing the FPGA controller for extensive power networks and coordinated multi-unit operation. Using efficient power electronics and cost-effective hardware designs will enhance performance and make commercialization more realistic. Better fault detection and diagnostics through FPGA signal processing will also increase system resilience and reliability.
For citations of references, we prefer the use of square brackets and consecutive numbers. Citations using labels or the author/year convention are also acceptable. The following bibliography provides a sample reference list with entries for journal articles [1], an LNCS chapter [2], a book [3], proceedings without editors [4], as well as a URL [5].

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