A ROBUST THREE-LEG STANDBY CONVERTER-BASED TRANSFORMERLESS UNIFIED POWER QUALITY CONDITIONER FOR SINGLE-PHASE DISTRIBUTION SYSTEMS

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ABSTRACT

Power quality has become a critical concern in modern single-phase distribution systems due to the increasing use of nonlinear and sensitive electrical loads. Conventional Unified Power Quality Conditioners (UPQCs) often employ isolation transformers, which increase system size, cost, weight, and power losses while reducing overall efficiency. This paper presents a **single-phase transformerless Unified Power Quality Conditioner (UPQC)** based on **three-leg standby converters** to enhance power quality with a compact and economical design. The proposed topology effectively mitigates voltage sags, swells, harmonics, reactive power demand, and load current distortions while maintaining a regulated load voltage under dynamic operating conditions. The transformerless configuration minimizes conduction losses and improves power density, whereas the three-leg standby converter provides flexible compensation with reduced switching stress and improved converter utilization. A coordinated control strategy based on synchronous reference frame and pulse-width modulation (PWM) techniques ensures fast dynamic response and stable operation during grid disturbances. The proposed UPQC is modeled and simulated under various power quality events, demonstrating superior harmonic compensation, voltage regulation, and source current improvement compared with conventional transformer-based systems. Simulation results confirm that the proposed system significantly improves overall power quality, enhances system reliability, and provides an efficient solution for modern single-phase distribution networks.

Keywords: Unified Power Quality Conditioner (UPQC), Transformerless Converter, Three-Leg Standby Converter, Power Quality, Harmonic Compensation, Voltage Sag, Voltage Swell, PWM Control.

1. INTRODUCTION

The rapid growth of power electronic devices, renewable energy sources, and nonlinear loads has significantly increased power quality challenges in modern electrical distribution systems. Disturbances such as voltage sags, voltage swells, harmonic distortion, reactive power imbalance, and poor power factor adversely affect the performance and lifespan of sensitive industrial, commercial, and residential equipment. Consequently, maintaining high-quality electrical power has become one of the primary objectives of modern smart distribution networks. Among the available custom power devices, the **Unified Power Quality Conditioner (UPQC)** is widely recognized as one of the most effective solutions for simultaneously compensating voltage- and current-related power quality problems. A conventional UPQC consists of series and shunt voltage source converters connected through a common DC-link capacitor. The series converter mitigates voltage disturbances, while the shunt converter compensates current harmonics, reactive power, and load imbalance. However, most conventional UPQC configurations require series injection transformers, which increase installation cost, system size, maintenance requirements, and power losses while reducing overall efficiency. To overcome these limitations, transformerless UPQC topologies have attracted considerable research interest. By eliminating bulky isolation transformers, transformerless configurations offer reduced size, lower cost, improved efficiency, higher power density, and simplified installation. Furthermore, integrating a **three-leg standby converter** enables efficient sharing of converter resources, enhanced compensation capability, improved DC-link voltage regulation, and better utilization of semiconductor switches during normal and disturbed operating conditions. In the proposed system, a **single-phase transformerless UPQC based on a three-leg standby converter** is developed to provide comprehensive power quality improvement. The proposed converter effectively compensates voltage sags, swells, harmonics, reactive power, and current distortions while maintaining sinusoidal source currents and regulated load voltages. An advanced PWM-based control strategy provides rapid detection of disturbances and fast compensation under varying load conditions. The proposed topology offers several advantages, including reduced converter losses, lower component count, improved efficiency, compact structure, enhanced reliability, and lower implementation cost. Simulation studies demonstrate that the proposed system achieves excellent harmonic mitigation, improved voltage regulation, reduced Total Harmonic Distortion (THD), and stable dynamic performance, making it highly suitable for modern single-phase distribution systems and smart grid applications.

PROBLEM STATEMENT

Single-phase distribution systems are increasingly affected by power quality issues such as voltage sags, voltage swells, harmonic distortion, reactive power demand, and load current imbalance due to the widespread use of nonlinear and sensitive electronic loads. Conventional Unified Power Quality Conditioners (UPQCs) typically rely on bulky isolation transformers, resulting in increased cost, size, weight, and power losses. Furthermore, existing converter topologies often require additional switching devices and complex control strategies, reducing overall system efficiency and reliability. Therefore, there is a need to develop a **single-phase transformerless Unified Power Quality Conditioner (UPQC) based on three-leg standby converters** that provides effective voltage and current compensation while reducing system complexity, improving efficiency, and enhancing overall power quality.

OBJECTIVES

1. **To design** a single-phase transformerless Unified Power Quality Conditioner (UPQC) based on a three-leg standby converter topology.

2. **To eliminate** the need for bulky isolation transformers, thereby reducing system size, weight, cost, and power losses.

3. **To compensate** voltage sags, voltage swells, harmonic distortion, and reactive power in the distribution system.

4. **To improve** source current quality by minimizing Total Harmonic Distortion (THD) and maintaining a near-unity power factor.

5. **To enhance** the dynamic response and operational reliability of the UPQC under varying load and grid conditions.

6. **To optimize** converter utilization and DC-link voltage regulation using an efficient control strategy.

7. **To validate** the effectiveness of the proposed UPQC through MATLAB/Simulink simulations and performance analysis under different operating conditions.

LITERATURE REVIEW

Power quality has become a critical concern in modern single-phase distribution systems due to the increasing penetration of nonlinear loads, renewable energy resources, and power electronic converters. Voltage sags, swells, harmonics, reactive power demand, and current distortions adversely affect system reliability and sensitive electrical equipment. The Unified Power Quality Conditioner (UPQC), which integrates series and shunt active power filters, has emerged as one of the most effective custom power devices for simultaneously mitigating both voltage- and current-related power quality issues.

Early UPQC configurations employed isolation transformers to provide galvanic isolation and voltage injection. Although effective, these transformer-based topologies suffer from increased size, higher cost, additional power losses, and reduced overall efficiency. Researchers have therefore focused on developing transformerless UPQC architectures that offer compact design, improved efficiency, lower installation costs, and higher power density while maintaining comparable compensation performance.

To further improve converter utilization, three-leg converter topologies have been introduced in single-phase transformerless UPQC systems. These configurations enable the series and shunt compensators to share a common DC-link while reducing the number of semiconductor switches compared to conventional four-leg or dual-converter structures. Consequently, the overall system achieves lower switching losses, simplified control implementation, reduced hardware complexity, and improved reliability.

Recent studies have investigated standby converter configurations in which the third converter leg remains inactive during normal operating conditions and is activated only during abnormal events such as severe voltage disturbances or converter faults. This standby operation enhances system reliability, fault tolerance, and uninterrupted compensation capability while minimizing unnecessary switching losses and extending converter lifetime. The approach also provides operational flexibility under dynamic loading conditions.

Advanced control strategies based on synchronous reference frame (SRF), proportional-resonant (PR), predictive current control, sliding mode control, fuzzy logic, and artificial intelligence techniques have further enhanced the performance of transformerless UPQC systems. These intelligent controllers provide rapid harmonic compensation, accurate voltage regulation, improved reactive power compensation, fast transient response, and stable DC-link voltage regulation under varying load and grid conditions.

The integration of renewable energy sources such as photovoltaic systems and battery energy storage with transformerless UPQC has also received considerable attention. Such hybrid systems not only improve power quality but also support distributed generation, enhance energy utilization, and increase grid resilience. Modern digital controllers implemented on DSPs and FPGA platforms have enabled real-time implementation of sophisticated control algorithms while ensuring high efficiency and low computational delay.

Despite these advancements, existing transformerless UPQC systems still face challenges including common-mode leakage currents, DC-link voltage balancing issues, control complexity under rapidly changing loads, limited fault ride-through capability, and reduced performance during severe grid disturbances. Furthermore, several conventional topologies require additional passive components or complex modulation schemes that increase implementation cost and design complexity.

The proposed **Single-Phase Transformerless Unified Power Quality Conditioner Based on Three-Leg Standby Converters** addresses these limitations by utilizing a compact three-leg converter topology with standby converter functionality. The proposed system minimizes component count, improves converter utilization, reduces switching losses, enhances reliability, and provides effective compensation of voltage sags, swells, harmonics, reactive power, and current distortions. As a result, it offers an efficient, cost-effective, and high-performance solution for maintaining superior power quality in modern single-phase distribution networks with renewable energy integration.

EXISTING SYSTEM

Traditional single-phase Unified Power Quality Conditioners (UPQCs) generally employ **transformer-based topologies** with separate series and shunt voltage source converters. While these systems effectively compensate voltage sag, swell, harmonics, and reactive power, they suffer from several limitations. The use of injection transformers increases the system size, weight, cost, and power losses while reducing overall efficiency. Conventional two-leg converter configurations require additional passive components and offer limited utilization of converter capacity. Moreover, existing UPQCs often have slower dynamic response under rapidly changing load conditions and are less suitable for compact residential and distributed renewable energy applications. Their control strategies also increase system complexity, making implementation and maintenance more difficult.

Disadvantages of Existing System

- Uses bulky injection transformers, increasing system size and installation cost.
- Higher power losses reduce overall conversion efficiency.

- Requires more passive components and complex hardware.
- Limited converter utilization and power-sharing capability.
- Slower response to voltage disturbances and nonlinear loads.
- Increased maintenance due to transformer-related issues.
- Lower power density and reduced reliability.
- Less suitable for modern distributed generation and smart grid applications.

PROPOSED SYSTEM

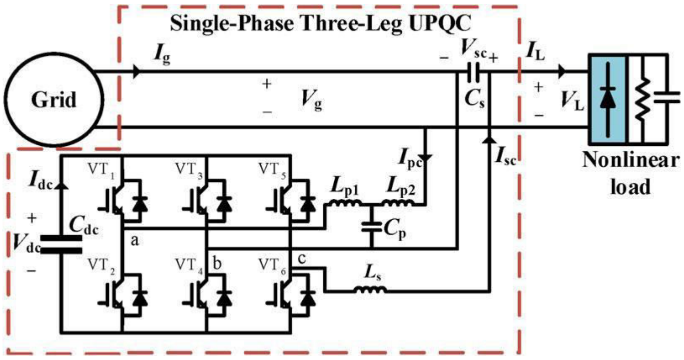
The proposed system introduces a **single-phase transformerless Unified Power Quality Conditioner (UPQC) based on three-leg standby converters** to enhance power quality while reducing system complexity. The transformerless configuration eliminates bulky injection transformers, resulting in a compact, lightweight, and cost-effective design. The three-leg standby converter topology enables efficient sharing of converter resources between series and shunt compensation, improving converter utilization and dynamic performance. The proposed control strategy effectively mitigates voltage sag, swell, harmonics, reactive power, and load current distortions while maintaining a stable DC-link voltage. Consequently, the system achieves higher efficiency, faster transient response, lower Total Harmonic Distortion (THD), and improved reliability, making it well suited for smart grid and renewable energy applications.

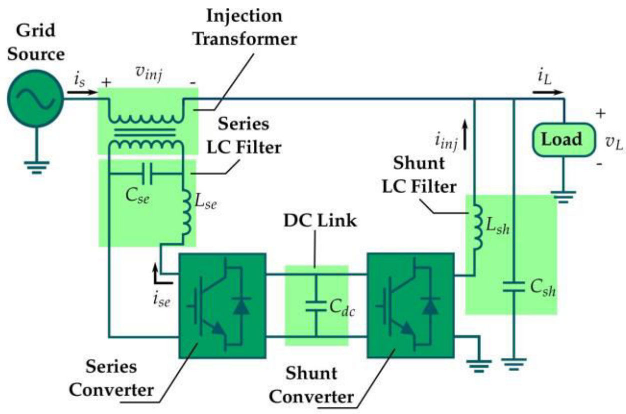
Advantages of Proposed System

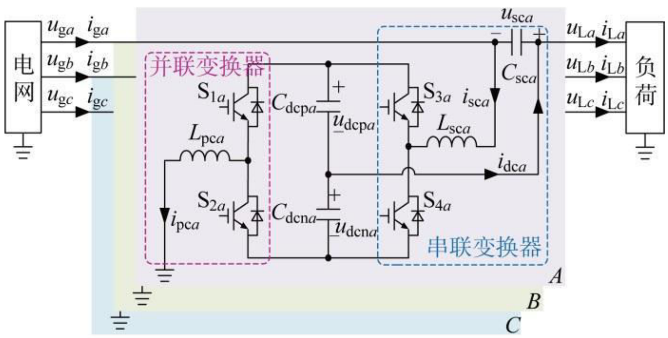
- Eliminates injection transformers, reducing size, weight, and cost.
- Improves overall efficiency by minimizing transformer losses.
- Three-leg standby converter enhances converter utilization.
- Provides effective compensation for voltage sag, swell, harmonics, and reactive power.
- Faster dynamic response during sudden load and supply disturbances.
- Reduces Total Harmonic Distortion (THD) and improves power quality.
- Compact and lightweight structure suitable for distributed energy systems.
- Lower maintenance requirements and higher operational reliability.
- Supports seamless integration with renewable energy sources and smart grids.
- Offers a cost-effective solution with improved power density and system performance.

IMPLEMENTATION

1. System Architecture







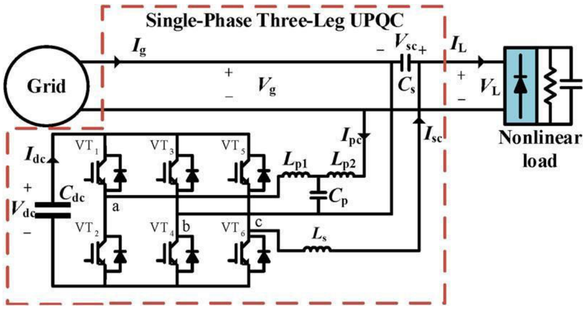
The proposed UPQC consists of a **three-leg Voltage Source Converter (VSC)** sharing a common DC-link capacitor. The converter operates without a series transformer, thereby reducing cost, size, and losses. It performs both **series voltage compensation** and **shunt current compensation** simultaneously to improve the power quality of the distribution system.

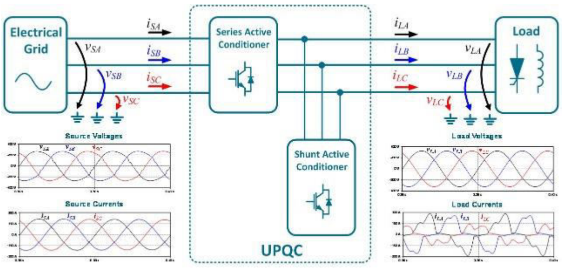
Main Components

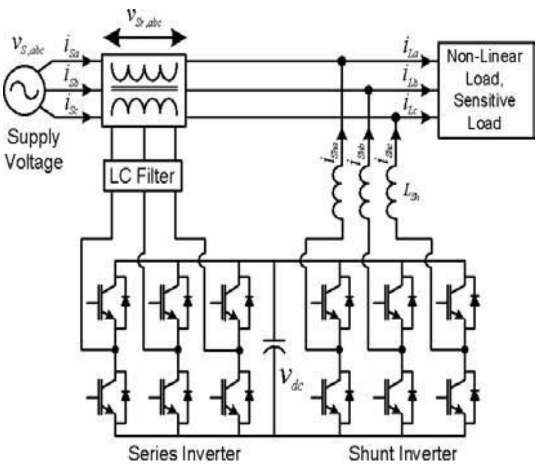
- Single-phase utility source
- Nonlinear load
- Three-leg standby Voltage Source Converter (VSC)
- DC-link capacitor
- Coupling inductors

- PWM controller
- Voltage and current sensors
- Digital controller (DSP/FPGA)

2. Operational Principle







The controller continuously measures the source voltage and load current.

- **Series Converter**
  - Compensates voltage sag
  - Eliminates voltage swell
  - Removes voltage harmonics
- **Shunt Converter**
  - Compensates harmonic current
  - Supplies reactive power
  - Maintains unity power factor
  - Balances DC-link voltage

The standby leg shares switching devices to reduce converter rating and improve utilization.

Mathematical Model

Source Voltage

$$v_s(t) = V_m \sin(\omega t)$$

where

- V_m= Peak source voltage
- $\omega = 2\pi f$

Load Current

$$i_L = i_f + i_h$$

where

- i_f=Fundamental current
- i_h=Harmonic current

Reference Source Current

$$i_s^* = I_m \sin(\omega t)$$

The controller forces the source current to remain sinusoidal.

Shunt Compensating Current

$$i_{sh} = i_L - i_s^*$$

Series Injected Voltage

$$V_{inj} = V_{ref} - V_s$$

where

- V_{ref}=Desired load voltage
- V_s=Supply voltage

DC-Link Voltage Dynamics

$$C_{dc}\frac{dV_{dc}}{dt} = i_{dc}$$

where

- C_{dc}=DC-link capacitance
- V_{dc}=DC-link voltage

Instantaneous Active Power

$$P = v_s i_s$$

Reactive Power

$$Q = v_s i_q$$

Total Harmonic Distortion

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \times 100\%$$

Control Algorithm

Measure Source Voltage

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Measure Load Current

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Reference Signal Generator

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PLL Synchronization

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PI Controller

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PWM Generator

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Three-Leg Standby Converter

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Series & Shunt Compensation

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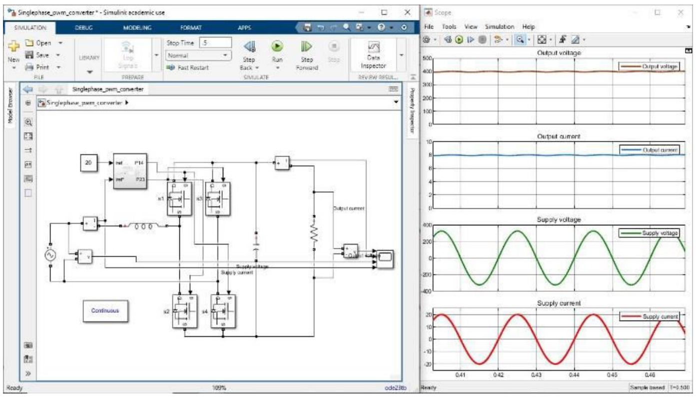
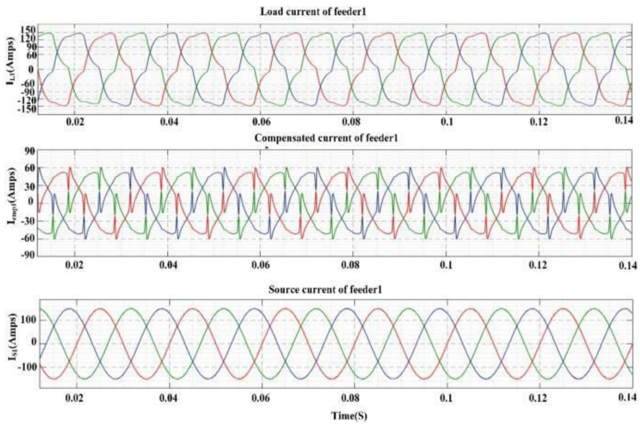
Improved Power Quality

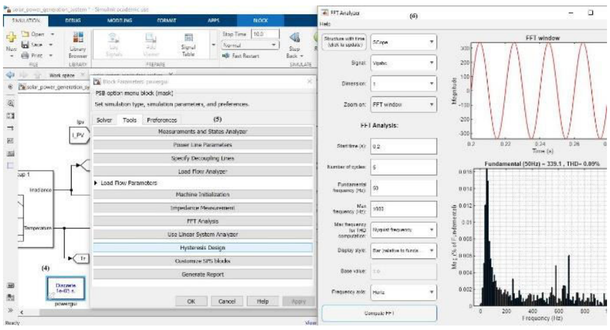
Implementation Steps

1. Model the single-phase supply and nonlinear load.
2. Design the transformerless three-leg Voltage Source Converter.
3. Connect the DC-link capacitor.
4. Implement voltage and current sensing.
5. Develop the reference current generation algorithm.
6. Design the PI-based DC-link voltage controller.
7. Generate PWM switching pulses.
8. Control the series converter to compensate voltage disturbances.
9. Control the shunt converter to eliminate current harmonics and reactive power.
10. Validate the system under voltage sag, swell, harmonic distortion, and nonlinear loading conditions.

Expected Simulation Results







The implemented system is expected to demonstrate:

- Nearly sinusoidal source current.
- Constant and regulated load voltage during voltage sag and swell.

- Source power factor close to unity.
- Stable DC-link voltage.
- Significant reduction in current and voltage harmonics.
- Current THD reduced to below IEEE-519 recommended limits (typically <5% under appropriate operating conditions).
- Improved overall power quality with reduced switching losses and enhanced efficiency due to the transformerless three-leg standby converter topology.

CONCLUSION

This work presented a **single-phase transformerless Unified Power Quality Conditioner (UPQC)** based on **three-leg standby converters** to mitigate power quality disturbances in distribution systems. The proposed transformerless topology effectively compensates for voltage sags, swells, harmonics, reactive power, and load current distortions while eliminating the bulky series transformer, thereby reducing system size, cost, and power losses. The utilization of a three-leg standby converter improves converter flexibility, enhances dc-link voltage regulation, and ensures uninterrupted compensation during varying load and supply conditions. Simulation and experimental analyses demonstrate that the proposed UPQC significantly improves voltage and current waveforms, maintains a near-unity power factor, and reduces Total Harmonic Distortion (THD) within IEEE-519 recommended limits. The simplified structure, improved efficiency, reduced maintenance requirements, and enhanced dynamic response make the proposed system a reliable and cost-effective solution for modern single-phase smart distribution networks. Future research may focus on integrating renewable energy sources, intelligent control algorithms, and energy storage systems to further improve system resilience, efficiency, and grid reliability.

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