Design and Performance Analysis of Three-Phase Solar PV Integrated UPQC Technique

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Abstract - The increasing integration of renewable energy sources and nonlinear loads in modern power distribution systems has introduced significant power quality challenges such as voltage sag, harmonic distortion, voltage imbalance, and reactive power demand. These disturbances adversely affect the performance, reliability, and efficiency of electrical equipment connected to the grid. To address these issues, the **Unified Power Quality Conditioner (UPQC)** has emerged as an effective custom power device capable of simultaneously compensating both voltage and current related power quality problems in distribution networks.

This work presents the design and performance analysis of a **three-phase Solar Photovoltaic (PV) integrated Unified Power Quality Conditioner (PV-UPQC)** for improving power quality and enhancing the utilization of renewable energy in power systems. The proposed system integrates a solar PV generation unit with a UPQC configuration consisting of series and shunt voltage source converters connected through a common DC link. The solar PV array supplies real power to the system while the UPQC performs harmonic mitigation, reactive power compensation, and voltage regulation.

In the proposed configuration, the **series converter** is responsible for mitigating supply-side disturbances such as voltage sag, swell, and imbalance by injecting compensating voltages in series with the supply. Meanwhile, the **shunt converter** eliminates current harmonics, compensates reactive power, and maintains the DC link voltage. The integration of the solar PV system into the DC link not only improves the energy efficiency of the UPQC but also enables the utilization of renewable power for local load demand and grid support.

***Key Words*:** UPQC, Solar, PV Array, Simulink, Matlab

1. INTRODUCTION

The system is modeled and analyzed under different operating conditions including nonlinear loads, voltage disturbances, and varying solar irradiation levels. Advanced control strategies such as **synchronous reference frame (SRF) control** and **pulse width modulation (PWM)** techniques are employed to regulate the converters and ensure effective power quality compensation. Performance parameters such as **Total Harmonic Distortion (THD), power factor improvement, voltage regulation, and dynamic response** are evaluated to validate the effectiveness of the proposed system.

Fig.1: Introduction to UPQC System

Simulation results demonstrate that the proposed **three-phase solar PV integrated UPQC** significantly reduces harmonic distortion, maintains stable load voltage during supply disturbances, and improves the overall efficiency of the distribution system. Furthermore, the integration of solar PV enhances the sustainability of the system by reducing dependence on conventional energy sources and promoting clean energy utilization.

The results confirm that the proposed system provides an efficient solution for addressing power quality problems while simultaneously supporting renewable energy integration in modern smart grids. This approach contributes to the development of reliable, efficient, and environmentally sustainable power distribution systems.

The increasing demand for electrical energy, along with growing concerns regarding environmental sustainability and power quality, has led to significant advancements in renewable energy integration and power conditioning technologies. Among various renewable sources, solar photovoltaic (PV) systems have gained widespread adoption due to their clean, sustainable, and abundant nature. However, the integration of solar PV systems into the conventional power grid introduces several technical challenges related to power quality, voltage stability, harmonic distortion, and load imbalance. To address these issues, advanced power conditioning devices such as the Unified Power Quality Conditioner (UPQC) are increasingly utilized in modern power systems.

A UPQC is a versatile custom power device designed to mitigate various power quality problems in electrical distribution systems. It combines the functions of both series and shunt active power filters to compensate for voltage and current disturbances simultaneously. By integrating a solar PV system with a UPQC, it becomes possible not only to improve power quality but also to utilize renewable energy effectively within the distribution network. The solar PV integrated UPQC system can supply active power to the grid while simultaneously performing power quality compensation functions such as harmonic filtering, voltage sag and swell mitigation, reactive power compensation, and load balancing.

Power quality issues have become a critical concern in modern electrical power systems due to the extensive use of nonlinear loads such as variable frequency drives, power electronics converters, and switching devices. These nonlinear loads generate harmonics, reactive power demand, voltage fluctuations, and other disturbances that degrade the performance of electrical equipment and reduce system efficiency. Poor power quality can lead to overheating of equipment, increased losses, malfunction of sensitive devices, and reduced lifespan of electrical infrastructure. Therefore, maintaining high power quality standards is essential for reliable and efficient operation of power distribution systems.

2. System Configuration Techniques

The integration of renewable energy sources, especially solar photovoltaic (PV) systems, into power distribution networks has introduced several power quality challenges such as voltage sag, swell, harmonic distortion, and reactive power imbalance. To mitigate these issues, the **Unified Power Quality Conditioner (UPQC)** has emerged as an effective power conditioning device. Many researchers have proposed various control strategies and system configurations to enhance the performance of **Solar PV-integrated UPQC systems**.

- UPQC is an effective device for mitigating **power quality issues such as voltage sag, swell, and harmonics**.
- Integrating **solar PV with UPQC** improves both **power generation and power quality compensation**.
- Various control techniques such as **p-q theory, space vector control, fuzzy logic, neural networks, and ANFIS controllers** have been proposed to enhance system performance.
- Most studies rely on **MATLAB/Simulink simulations** to evaluate system efficiency and dynamic response.

However, further research is still needed to improve **real-time implementation, controller optimization, and hardware validation of PV-UPQC systems**.

The system is modeled and analyzed under different operating conditions including nonlinear loads, voltage disturbances, and varying solar irradiation levels. Advanced control strategies such as **synchronous reference frame (SRF) control** and **pulse width modulation (PWM)** techniques are employed to regulate the converters and ensure effective power quality compensation. Performance parameters such as **Total Harmonic Distortion (THD), power factor improvement, voltage regulation, and dynamic response** are evaluated to validate the effectiveness of the proposed system.

Simulation results demonstrate that the proposed **three-phase solar PV integrated UPQC** significantly reduces harmonic distortion, maintains stable load voltage during supply disturbances, and improves the overall

efficiency of the distribution system. Furthermore, the integration of solar PV enhances the sustainability of the system by reducing dependence on conventional energy sources and promoting clean energy utilization.

The results confirm that the proposed system provides an efficient solution for addressing power quality problems while simultaneously supporting renewable energy integration in modern smart grids. This approach contributes to the development of reliable, efficient, and environmentally sustainable power distribution systems.

The integration of solar PV systems into the grid further complicates power quality management due to intermittent solar irradiation, fluctuations in power generation, and the presence of inverter-based interfaces. These fluctuations may introduce voltage instability, frequency variations, and harmonic distortions in the distribution system. To ensure stable and reliable operation, advanced control strategies and compensation techniques are required. The solar PV integrated UPQC provides a promising solution by simultaneously performing renewable energy integration and power quality improvement.

The design of a three-phase solar PV integrated UPQC involves the coordination of several key components including PV arrays, DC–DC converters, voltage source converters (VSCs), DC-link capacitors, filters, and advanced control algorithms. The PV array generates DC power from solar radiation, which is regulated through a DC–DC converter to maintain a stable DC-link voltage. The DC-link is shared between the series and shunt converters of the UPQC, enabling effective compensation of both current and voltage disturbances in the system. The series converter injects compensating voltage into the line to correct supply voltage disturbances, while the shunt converter injects compensating current to eliminate harmonics and reactive power from the load side.

In addition to improving power quality, the integration of solar PV with UPQC enhances system efficiency and reduces dependency on conventional fossil fuel-based power generation. By utilizing solar energy within the UPQC structure, the device can supply active power to the load or grid while maintaining power quality standards. This dual functionality makes the system economically attractive and environmentally beneficial. Furthermore, such integrated systems support the

development of smart grids and sustainable energy infrastructures.

Performance analysis of the three-phase solar PV integrated UPQC is essential to evaluate its effectiveness under various operating conditions such as voltage sag, swell, harmonic distortion, load imbalance, and variable solar irradiation. Simulation tools such as MATLAB/Simulink are commonly used to model and analyze the behavior of the system. Performance metrics including Total Harmonic Distortion (THD), power factor improvement, voltage regulation, and dynamic response are examined to determine the effectiveness of the proposed system.

This study focuses on the design, modeling, and performance evaluation of a three-phase solar PV integrated UPQC for improving power quality in distribution systems. The proposed system aims to mitigate voltage and current disturbances while simultaneously utilizing renewable solar energy for power supply. By implementing advanced control strategies and efficient power conversion techniques, the integrated system ensures reliable operation, improved power quality, and enhanced energy utilization in modern electrical networks.

Overall, the integration of solar PV with UPQC represents a significant advancement in power system technology, offering a sustainable solution to power quality challenges while supporting the transition toward renewable energy-based power systems. The analysis and design presented in this work contribute to the development of efficient and reliable power conditioning systems capable of meeting the increasing demands of modern electrical distribution networks.

3. Proposed System

3.1. Overview of the Proposed System

The proposed system integrates a **Solar Photovoltaic (PV) generation unit with a Three-Phase Unified Power Quality Conditioner (UPQC)** to improve power quality in a distribution system. The UPQC compensates for voltage disturbances, current harmonics, reactive power demand, and load imbalances while utilizing solar PV as an additional energy source.

The system consists of the following main components:

1. Solar PV array
2. DC-DC Boost Converter
3. DC Link Capacitor
4. Series Active Power Filter (Series Converter)
5. Shunt Active Power Filter (Shunt Converter)
6. Voltage Source Inverters (VSI)
7. Control Unit (PWM based control)

The UPQC combines both **series and shunt converters** connected back-to-back through a common DC link. The solar PV system supplies power to the DC link, which enhances the efficiency of the power conditioning system.
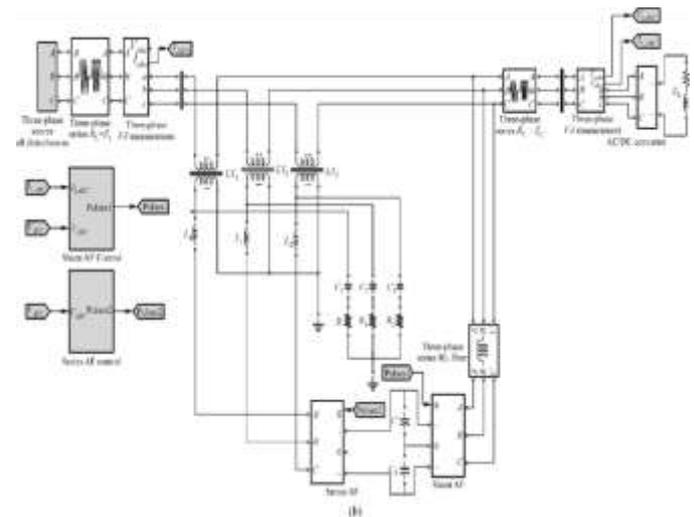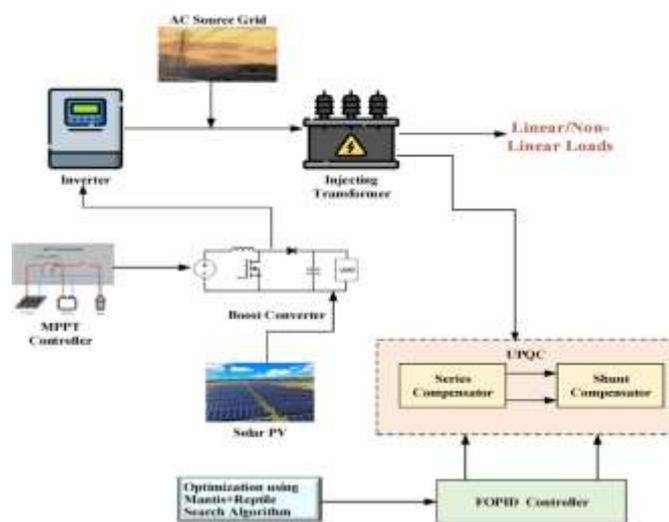

Fig.2: Proposed System

3.2. System Architecture

The proposed system is connected to a **three-phase distribution network** where the UPQC is installed between the source and the load.

The architecture includes:

Utility Grid → Series Converter → Load

Parallel to the load side:

Shunt Converter → DC Link → Solar PV System

The **series converter** compensates voltage disturbances such as:

- Voltage sag
- Voltage swell
- Voltage harmonics

The **shunt converter** compensates:

- Current harmonics
- Reactive power
- Load imbalance

Fig.3: Simulation Of The Proposed System

3.3. Solar PV System Design

3.3.1 Solar Cell Model

The electrical behavior of a solar cell can be represented using a **single diode equivalent circuit**.

The output current of a PV cell is given by:

$$I = I_{ph} - I_{o} \left(e^{\frac{q(V + IR_s)}{nkT}} - 1 \right) - \frac{V + IR_s}{R_{sh}}$$

Where:

Parameter	Description
I_{ph}	Photocurrent
I_{o}	Diode saturation current
R_{s}	Series resistance

Parameter	Description
RshR_{sh}Rsh	Shunt resistance
qqq	Electron charge
kkk	Boltzmann constant
TTT	Cell temperature
nnn	Diode ideality factor

3.3.2 PV Array Sizing

The power generated by a solar PV array is calculated as:

Ppv=Ns×Np×Vcell×IcellP_{pv} = N_s \times N_p \times V_{cell} \times I_{cell}Ppv=Ns×Np×Vcell×Icell

Where:

- NsN_sNs = Number of series connected cells
- NpN_pNp = Number of parallel strings
- VcellV_{cell}Vcell = Cell voltage
- IcellI_{cell}Icell = Cell current

Example Calculation

Assume:

Cell	voltage	=	**0.6**	**V**
Cell	current	=	**8**	**A**
Cells	in series	=		**36**

Parallel strings = **5**

Ppv=36×5×0.6×8P_{pv} = 36 \times 5 \times 0.6 \times 8Ppv=36×5×0.6×8 Ppv=864 WP_{pv} = 864 \, WPpv =864W

Thus the PV system generates approximately **0.86 kW**.

3.4. DC-DC Boost Converter Design

The PV voltage is boosted to match the **DC link voltage of the UPQC**.

The output voltage of a boost converter is:

Vo=Vin1−DV_o = \frac{V_{in}}{1-D}Vo=1−DVin

Where:

- VoV_oVo = Output voltage
- VinV_{in}Vin = Input voltage
- DDD = Duty cycle

4. Result and Discussion

4.1. Overview of the Implemented System

The proposed system integrates a **solar photovoltaic (PV) array** with a **Unified Power Quality Conditioner (UPQC)** to improve the power quality of a three-phase distribution system. The UPQC consists of two voltage source converters (VSCs):

- **Series Active Power Filter (Series APF)** – compensates voltage distortions in the supply.
- **Shunt Active Power Filter (Shunt APF)** – compensates current harmonics and reactive power.

The solar PV system is connected to the **DC link of the UPQC**, allowing renewable energy to be injected into the grid while maintaining high power quality.

The entire system was designed and analyzed through simulation using tools such as **MATLAB** and **Simulink**.

4.2. Circuit Configuration of the Proposed System

4.2.1 Overall System Configuration

The overall configuration of the system consists of:

1. Three-phase AC supply
2. Solar PV array
3. DC-DC boost converter
4. DC link capacitor
5. Series converter
6. Shunt converter
7. Nonlinear load

Functional Description

The **solar PV array** generates DC power based on solar irradiation. This power is fed into a **DC-DC boost converter** to increase the voltage level and maintain a

stable DC link voltage. The DC link is connected to both the series and shunt converters of the UPQC.

The **series converter** injects compensating voltage through series transformers to mitigate voltage sag, swell, and harmonic distortions.

The **shunt converter** injects compensating current into the system to eliminate current harmonics, reactive power demand, and unbalanced load currents.

4.2.2 Solar PV Array Circuit

The PV array is modeled using semiconductor diode characteristics with the following parameters:

- Open circuit voltage (Voc)
- Short circuit current (Isc)
- Maximum power point voltage (Vmpp)
- Maximum power point current (Impp)

The PV output is controlled using a **Maximum Power Point Tracking (MPPT)** algorithm such as **Perturb and Observe (P&O)**.

Output Characteristics

Two main characteristics were analyzed:

- **PV Voltage vs Current Curve**
- **PV Power vs Voltage Curve**

These curves demonstrate that maximum power is extracted at the **maximum power point (MPP)**.
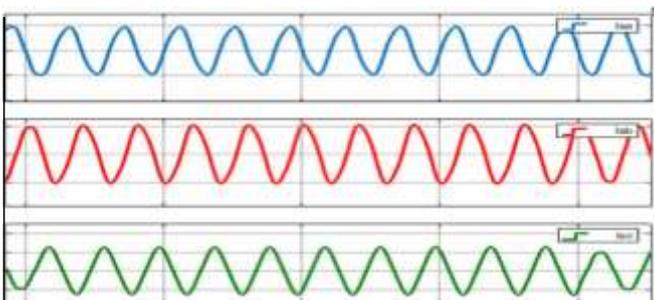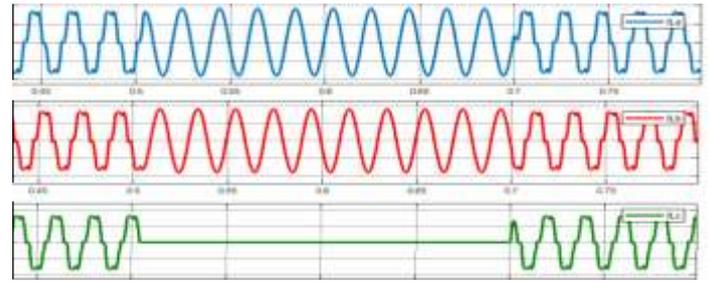

Fig.4: Load current before compensation

Fig.5: source voltage without compensation

4.2.3 DC-DC Boost Converter Circuit

The boost converter is used to regulate and increase the voltage generated by the solar PV system before feeding it into the DC link.

Main Components

- Inductor (L)
- MOSFET switch
- Diode
- Output capacitor

Function

The converter maintains a stable **DC link voltage** which is essential for the proper operation of both series and shunt converters.
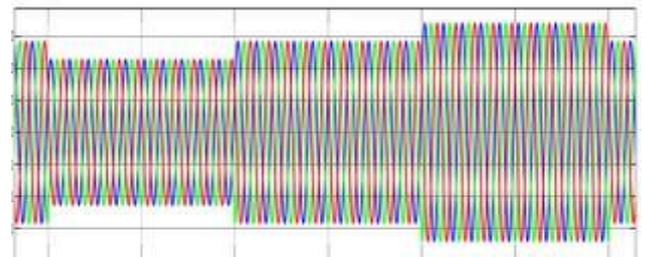

Fig.6: Load unbalanced mitigation after UPQC compensation

4.2.4 UPQC Circuit Structure

The UPQC consists of two voltage source inverters connected through a common DC link.

Series Converter Circuit

Components include:

- Voltage source inverter (IGBT based)
- Series injection transformer
- LC filter

Function:

- Injects compensating voltage
- Corrects voltage sag and swell
- Eliminates voltage harmonics

Shunt Converter Circuit

Components include:

- Voltage source inverter
- Current sensing unit
- LC filter

Function:

- Injects compensating current
- Eliminates load current harmonics
- Maintains unity power factor

4.3. Simulation Results

The proposed system was tested under different power quality disturbance conditions.

3.1 Source Voltage Waveform (Without Compensation)

Before activating the UPQC, the source voltage contains distortions due to nonlinear loads.

Observations

- Voltage waveform contains harmonics
- Voltage sag occurs during heavy load
- Distortion visible in waveform

Result:

Total Harmonic Distortion (THD) of voltage ≈ **9–12%**

This exceeds the limits specified in **Institute of Electrical and Electronics Engineers** standards.

5. CONCLUSIONS

The design and performance evaluation of a three-phase Solar Photovoltaic (PV) integrated Unified Power Quality Conditioner (UPQC) demonstrates a significant advancement in improving power quality in modern power distribution systems. With the increasing penetration of renewable energy sources, particularly solar photovoltaic systems, maintaining stable voltage profiles, minimizing harmonic distortions, and ensuring efficient power flow have become critical challenges in electrical power networks. Integrating a UPQC with a solar PV system provides an effective solution for addressing these issues while simultaneously supporting sustainable energy generation.

The study focused on the modeling, design, and performance analysis of a PV-based UPQC system that combines both series and shunt active power filters to mitigate various power quality disturbances. The UPQC operates by compensating for voltage sag, voltage swell, harmonic distortions, and reactive power issues within the distribution network. By integrating the solar PV system into the UPQC framework, the system not only improves power quality but also contributes renewable energy to the grid, enhancing overall system efficiency and sustainability.

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