

Performance Enhancement of Reduced Sensor UPQC-PV System Using PSO Tuned PI Controller

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Abstract

Modern electrical distribution systems suffer from severe power quality disturbances because of extensive utilization of nonlinear loads, renewable energy integrated converters, and power electronic devices. Voltage sag, voltage swell, harmonic distortion, reactive power burden, and current imbalance adversely affect the performance and reliability of sensitive electrical equipment. This paper presents a reduced voltage sensor based Unified Power Quality Conditioner integrated Solar Photovoltaic (UPQC-PV) system employing Enhanced Second Order Generalized Integrator based Modified Frequency Locked Loop (ESOGI-mFLL) synchronization and Particle Swarm Optimization (PSO) tuned PI controller for simultaneous mitigation of voltage and current related power quality disturbances. The proposed UPQC-PV system consists of a series active power filter and shunt active power filter connected back-to-back through a common DC-link capacitor. The ESOGI-mFLL synchronization algorithm accurately extracts positive sequence fundamental components under distorted operating conditions with reduced sensor requirement. In order to improve DC-link voltage regulation and dynamic performance, PSO based optimization of PI controller gains is incorporated. The complete system is modeled and implemented in MATLAB/Simulink under voltage sag, voltage swell, nonlinear load, distorted source voltage, and solar irradiation variation conditions. Simulation results demonstrate effective harmonic compensation, improved transient response, stable DC-link voltage regulation, reduced Total Harmonic Distortion within IEEE-519 limits, and enhanced overall power quality performance. The proposed PSO tuned reduced sensor UPQC-PV system provides a reliable and efficient solution for modern renewable energy integrated distribution networks.

Keywords— Unified Power Quality Conditioner, Solar Photovoltaic System, Particle Swarm Optimization, ESOGI-mFLL, harmonic compensation, voltage sag, voltage swell, power quality improvement.

I. INTRODUCTION

Modern electrical distribution systems are increasingly affected by power quality disturbances because of extensive utilization of nonlinear loads, renewable energy integrated converters, and power electronic equipment. Adjustable speed drives, switched mode power supplies, electric vehicle chargers, and distributed generation systems introduce severe harmonic distortion, reactive power burden, voltage fluctuations, and current imbalance into utility networks [1]–[3]. These disturbances reduce system efficiency, increase thermal stress, and adversely affect the reliable operation of sensitive electrical equipment.

Among various power quality problems, voltage sag, voltage swell, harmonic distortion, and poor power factor are considered the most critical disturbances in industrial and commercial distribution systems [4]. Voltage sag generally occurs because of short-circuit faults and sudden starting of large induction motors, whereas voltage swell is mainly caused by load rejection and capacitor bank switching. Harmonic distortion generated by nonlinear loads results in overheating of transformers, increased losses, malfunctioning of protection devices, and electromagnetic interference [5]. Therefore, mitigation of power quality disturbances has become an important research area in modern smart distribution networks. Initially, passive filtering techniques were employed for harmonic mitigation and reactive power compensation because of their simple structure and low implementation cost. However, passive filters suffer from resonance problems, bulky size, fixed compensation capability, and poor dynamic response under varying operating conditions [6]. To overcome these limitations, Active Power Filters (APFs) and custom power devices were introduced for dynamic compensation of power quality disturbances. Among various custom power devices, the Unified Power Quality Conditioner (UPQC) has emerged as one of the most effective solutions for simultaneous mitigation of voltage and current related disturbances [7]. The UPQC consists of a series active power filter and shunt active power filter connected back-to-back through a common DC-link capacitor. The series converter compensates voltage related disturbances such as voltage sag, voltage swell, voltage imbalance, and voltage harmonics by injecting compensating voltage into the distribution line [8]. Simultaneously, the shunt converter compensates current harmonics, reactive power burden, and load current imbalance by injecting compensating currents at the point of common coupling. Consequently, UPQC provides comprehensive power quality enhancement capability in modern electrical distribution systems.

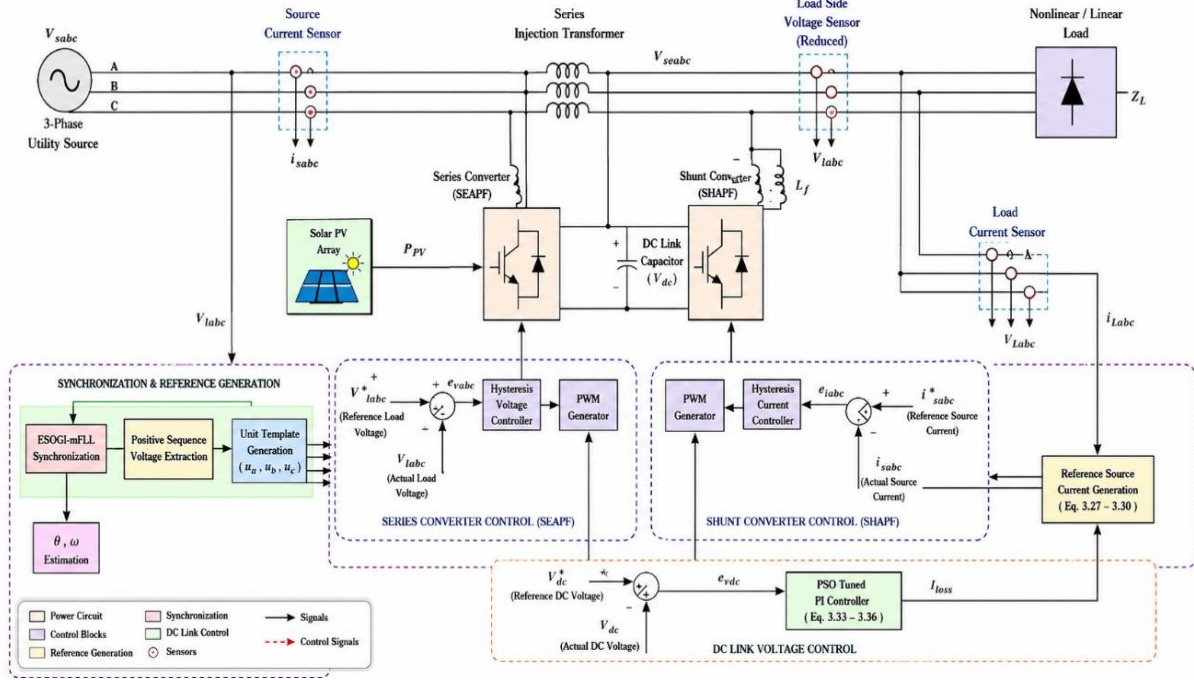


Fig.1: Overall Control Architecture of Proposed PSO Tuned UPQC-PV System

Recently, integration of renewable energy sources into utility grids has increased significantly because of environmental concerns and depletion of fossil fuel resources [9]. Among renewable energy technologies, solar photovoltaic (PV) systems have become highly attractive because of their clean operation, modular structure, low maintenance requirement, and global availability [10]. However, grid integration of solar PV systems introduces additional challenges including voltage fluctuation, harmonic injection, synchronization problems, and intermittent power generation. Integration of solar photovoltaic systems with UPQC provides simultaneous renewable energy utilization and power quality enhancement [11]. In UPQC-PV systems, the shunt converter transfers active power generated by the PV array into the utility grid while compensating harmonic and reactive current components. During voltage disturbances, the series converter injects compensating voltage to maintain regulated load voltage. Therefore, UPQC-PV systems improve harmonic suppression capability, voltage regulation, system efficiency, and renewable energy utilization simultaneously.

Various control algorithms have been proposed for UPQC applications including Synchronous Reference Frame (SRF) theory, Instantaneous Reactive Power Theory, Model Predictive Control (MPC), and artificial intelligence based controllers [12]. Although SRF based controllers provide simple implementation, they suffer from delayed response because of filtering operation. Synchronization techniques also play an important role in UPQC performance under distorted grid conditions. Conventional Second Order Generalized Integrator (SOGI) based synchronization methods provide effective harmonic filtering capability; however, they suffer from DC offset sensitivity and inaccurate estimation under

distorted operating conditions [13]. To overcome these limitations, Enhanced Second Order Generalized Integrator based Modified Frequency Locked Loop (ESOGI-mFLL) synchronization techniques have been introduced for accurate extraction of positive sequence fundamental components while effectively rejecting harmonics and DC offset components [14].

Another practical challenge associated with UPQC systems is the requirement of multiple voltage and current sensors for control implementation. Increased sensor count results in higher implementation cost, increased hardware complexity, and reduced system reliability. Therefore, reduced sensor based UPQC control techniques have gained considerable research interest in recent years [15]-[17]. In this paper, a reduced voltage sensor based UPQC-PV system employing ESOGI-mFLL synchronization and Particle Swarm Optimization (PSO) tuned PI controller is proposed for simultaneous mitigation of voltage and current related power quality disturbances. The ESOGI-mFLL synchronization technique improves harmonic extraction accuracy and synchronization capability under distorted operating conditions while reducing voltage sensor requirement. Furthermore, PSO based optimization is employed for tuning PI controller gains to improve DC-link voltage regulation, transient response, overshoot reduction, and overall system stability during sudden load variations and grid disturbances.

Power quality enhancement has become an important research area because of increasing penetration of nonlinear loads and renewable energy integrated converters.

Initially, passive filters were widely utilized for harmonic mitigation. However, passive filters suffer from resonance problems and fixed compensation characteristics.

Active Power Filters (APFs) were introduced to provide dynamic compensation capability. The main types include:

- Shunt Active Power Filter
- Series Active Power Filter

Various control techniques have been proposed for UPQC systems including:

- Synchronous Reference Frame (SRF) theory
- Instantaneous reactive power theory
- Model Predictive Control (MPC)
- Artificial intelligence based controllers

Although SRF controllers are simple to implement, they suffer from slow transient response and filtering delay.

Generalized Integrator based synchronization techniques have gained popularity because of their excellent harmonic filtering capability and fast dynamic response. Conventional Second Order Generalized Integrator (SOGI) methods suffer from DC offset sensitivity, frequency estimation error, Poor harmonic rejection under distorted conditions.

Enhanced Second Order Generalized Integrator based Modified Frequency Locked Loop (ESOGI-mFLL) techniques overcome these limitations and provide accurate synchronization under dynamic operating conditions.

Particle Swarm Optimization (PSO) has been widely investigated for controller tuning because of Fast convergence, Better global optimization capability, Reduced computational burden.

The following research gaps are identified:

- Conventional UPQC systems require large number of voltage sensors.
- Existing synchronization methods suffer from DC offset sensitivity.
- Fixed PI gains do not provide optimal performance under varying operating conditions.
- Existing methods involve increased implementation complexity.
- Limited research is available on PSO optimized reduced sensor based ESOGI-mFLL controlled UPQC-PV systems.

The proposed UPQC-PV system is modelled and implemented in MATLAB/Simulink under various operating conditions including voltage sag, voltage swell, nonlinear load operation, distorted source voltage, and solar irradiation variation. Simulation results demonstrate that the proposed PSO tuned ESOGI-mFLL based UPQC-PV system effectively maintains sinusoidal source currents, regulated load voltages, reduced Total Harmonic Distortion (THD), improved DC-link voltage stability, and enhanced dynamic response within IEEE-519 harmonic standards.

The major contributions of the proposed work are summarized as follows:

- Development of reduced voltage sensor based UPQC-PV system.
- Implementation of ESOGI-mFLL synchronization technique for accurate positive sequence extraction.
- PSO based optimization of PI controller gains for improved DC-link voltage regulation.
- Effective compensation of voltage sag and voltage swell disturbances.
- Significant reduction in source current harmonic distortion.
- Improved dynamic response and transient stability.

- MATLAB/Simulink validation under nonlinear and renewable energy integrated operating conditions.

The remainder of the paper is organized as follows. Section II presents the literature review and research gap analysis. Section III describes the proposed UPQC-PV system and mathematical modelling. Section IV explains the control strategy implementation using ESOGI-mFLL synchronization and PSO tuned PI controller. Section V discusses MATLAB/Simulink results and performance analysis under various operating conditions. Finally, Section VI concludes the paper with important findings and future scope of the proposed work.

II. PROPOSED SYSTEM AND MATHEMATICAL MODELLING

A. Proposed UPQC-PV Configuration

The proposed Unified Power Quality Conditioner integrated with a Photovoltaic (UPQC-PV) system comprises a three-phase utility source, a series active power filter (SAPF), a shunt active power filter (ShAPF), a solar photovoltaic (PV) array, a DC-link capacitor, interfacing inductors, injection transformers, and a nonlinear load. The solar PV array supplies renewable energy to the common DC-link, thereby enhancing the overall system efficiency and reducing dependence on the utility grid. The series active power filter is connected through injection transformers to compensate for voltage-related power quality disturbances such as voltage sags, swells, and harmonics, ensuring a regulated and sinusoidal load voltage. Simultaneously, the shunt active power filter mitigates load current harmonics, compensates reactive power, and maintains source current quality by enforcing near-unity power factor operation. The DC-link capacitor provides a stable DC voltage for both converters, while the interfacing inductors facilitate controlled power exchange between the converters and the utility grid. The coordinated operation of the series and shunt converters enables effective compensation of both voltage and current disturbances, thereby significantly improving the overall power quality of the distribution system.

B. Source Voltage Modelling

The three-phase source voltages are represented as:

$$V_{sa} = V_m \sin \omega t \quad (1)$$

$$V_{sb} = V_m \sin \left(\omega t - \frac{2\pi}{3} \right)$$

$$V_{sc} = V_m \sin \left(\omega t + \frac{2\pi}{3} \right)$$

Where V_{sa}, V_{sb}, V_{sc} are the instantaneous three phase voltages with maximum value V_m and with angular frequency ' ω '.

The source currents are expressed as:

$$I_{sa} = I_m \sin(\omega t - \phi) \quad (2)$$

$$I_{sb} = I_m \sin\left(\omega t - \frac{2\pi}{3} - \phi\right)$$

$$I_{sc} = I_m \sin\left(\omega t + \frac{2\pi}{3} - \phi\right)$$

Where I_{sa}, I_{sb}, I_{sc} are the instantaneous three phase Currents with maximum value I_m

C. Series Active Power Filter Modelling

Applying Kirchhoff's Voltage Law:

$$V_{sa} = R_s I_{sa} + L_s \left(\frac{dI_{sa}}{dt} \right) + V_{inja} + V_{la}$$

Where R_s and L_s are the source resistance and reactance, V_{inja} and V_{la} is injected voltage and load voltage respectively.

The injected compensating voltages are represented as:

$$V_{inja} = V_{la}^* - V_{sa}$$

$$V_{injb} = V_{lb}^* - V_{sb}$$

$$V_{injc} = V_{lc}^* - V_{sc}$$

D. Shunt Active Power Filter Modelling

Applying Kirchhoff's Current Law:

$$I_{la} = I_{sa} + I_{ca}$$

$$I_{lb} = I_{sb} + I_{cb}$$

$$I_{lc} = I_{sc} + I_{cc}$$

The shunt converter voltage equation is represented as:

$$V_{sha} = R_f I_{ca} + L_f \left(\frac{dI_{ca}}{dt} \right)$$

The Clarke transformation is represented as:

$$[V_\alpha V_\beta]^T = \left(\frac{2}{3}\right) \left[1 - \frac{1}{2} - \frac{1}{2}; 0 \frac{\sqrt{3}}{2} - \frac{\sqrt{3}}{2} \right] [V_a V_b V_c]^T$$

The dq transformation is expressed as:

$$[V_d V_q]^T = [\cos\theta \sin\theta; -\sin\theta \cos\theta] [V_\alpha V_\beta]^T$$

The instantaneous active and reactive powers are represented as:

$$P = V_\alpha I_\alpha + V_\beta I_\beta$$

$$Q = V_\beta I_\alpha - V_\alpha I_\beta$$

The in-phase transfer function of ESOGI is represented as:

$$D(s) = \frac{k\omega s}{s^2 + k\omega s + \omega^2}$$

The quadrature transfer function is:

$$Q(s) = \frac{k\omega^2}{s^2 + k\omega s + \omega^2}$$

The positive sequence voltage components are expressed as:

$$V_\alpha^+ = \frac{V_{\alpha d} + V_{\beta q}}{2}$$

$$V_\beta^+ = \frac{V_{\beta d} - V_{\alpha q}}{2}$$

The voltage magnitude estimation is:

$$V_t = \sqrt{V_\alpha^{\{+2\}} + V_\beta^{\{+2\}}}$$

The dc-link voltage equation is represented as:

$$C_{dc} \left(\frac{dV_{dc}}{dt} \right) = I_{sh} - I_{se}$$

The stored energy equation is:

$$E_{dc} = \left(\frac{1}{2} \right) C_{dc} V_{dc}^2$$

The PI controller output is expressed as:

$$u(t) = K_{pe}(t) + K_i \int e(t) dt$$

The error signal is:

$$e(t) = V_{dc}^* - V_{dc}$$

E. PSO Optimization Equations

The velocity update equation is represented as:

$$V_i(k+1) = wV_i(k) + c_1 r_1 (pbest_i - x_i) + c_2 r_2 (gbest - x_i)$$

The position update equation is:

$$x_i(k+1) = x_i(k) + V_i(k+1)$$

F. Solar PV Mathematical Model

The photovoltaic output current equation is:

$$I_{pv} = I_{ph} - I_o [\exp(q(V_{pv} + I_{pv}R_s)/nkT) - 1]$$

The photovoltaic output power is:

$$P_{pv} = V_{pv}I_{pv}$$

III. CONTROL STRATEGY IMPLEMENTATION

The proposed control strategy employs an Enhanced Second-Order Generalized Integrator based Modified Frequency-Locked Loop (ESOGI-mFLL) synchronization technique to accurately extract the positive-sequence voltage components, fundamental frequency components, and unit templates required for converter control. The ESOGI-mFLL algorithm exhibits superior synchronization performance under distorted and unbalanced grid conditions by effectively suppressing harmonic components and eliminating DC offset. Furthermore, it provides accurate grid frequency estimation with a fast dynamic response, enabling reliable tracking of grid voltage variations. The improved harmonic rejection capability and robust synchronization characteristics of the ESOGI-mFLL ensure precise reference signal generation, thereby enhancing the dynamic performance, stability, and power quality compensation capability of the proposed UPQC-PV system.

A. Control of Series Active Power Filter

The series active power filter (SAPF) is responsible for mitigating voltage-related power quality disturbances by injecting an appropriate compensating voltage into the distribution system through series injection transformers. It effectively compensates voltage sags, voltage swells, voltage harmonics, and voltage imbalances, thereby ensuring that the load

receives a balanced, sinusoidal, and regulated supply voltage. During a voltage sag condition, the series converter injects a compensating voltage in phase with the source voltage to restore the load voltage to its nominal value. Conversely, during a voltage swell condition, the converter injects a compensating voltage that is 180° out of phase with the source voltage, thereby reducing the excess voltage and maintaining the desired load voltage magnitude. This compensation strategy enables uninterrupted operation of sensitive loads and significantly enhances the overall voltage quality of the distribution network.

B. Hysteresis Voltage Controller

The hysteresis voltage controller compares:

- Reference load voltage
- Actual load voltage

and generates switching pulses whenever voltage error exceeds predefined hysteresis band.

Advantages include:

- Fast compensation response
- Simpler implementation
- High accuracy

C. Control of Shunt Active Power Filter

The shunt converter compensates:

- Current harmonics
- Reactive power
- Load imbalance
- Nonlinear load effects

The generated reference source currents are compared with actual source currents using hysteresis current controller.

D. PSO Tuned PI Controller

Particle Swarm Optimization (PSO) is employed to optimally tune the proportional–integral (PI) controller gains in order to enhance the control performance of the proposed UPQC-PV system. The optimization process is formulated with an objective function that minimizes key performance indices, including settling time, peak overshoot, steady-state error, and DC-link voltage oscillations. By iteratively searching for the optimal controller

parameters, the PSO algorithm achieves an effective balance between transient and steady-state performance. The optimized PI controller provides faster dynamic response, improved DC-link voltage regulation, and enhanced system stability under varying load and grid conditions. Consequently, the proposed PSO-based tuning approach ensures robust operation of the UPQC-PV system while significantly improving its power quality compensation capability and overall control performance.

E. PWM Strategy

Hysteresis PWM strategy is employed for pulse generation of both series and shunt converters.

The PWM controller ensures:

- Fast switching response
- Stable converter operation
- Accurate harmonic compensation

IV. RESULTS AND DISCUSSION

The proposed UPQC-PV system is implemented in MATLAB/Simulink under various operating conditions.

Table 1: Simulation Parameters

Parameter	Value
Source Voltage	415 V
Frequency	50 Hz
DC-Link Voltage	700 V
Switching Frequency	10 kHz
Filter Inductance	3 mH
DC-Link Capacitor	2200 μ F

A. Performance Under Voltage Sag Condition

A 40% voltage sag is introduced between 0.2 s and 0.4 s.

During sag condition:

- Source voltage decreases significantly

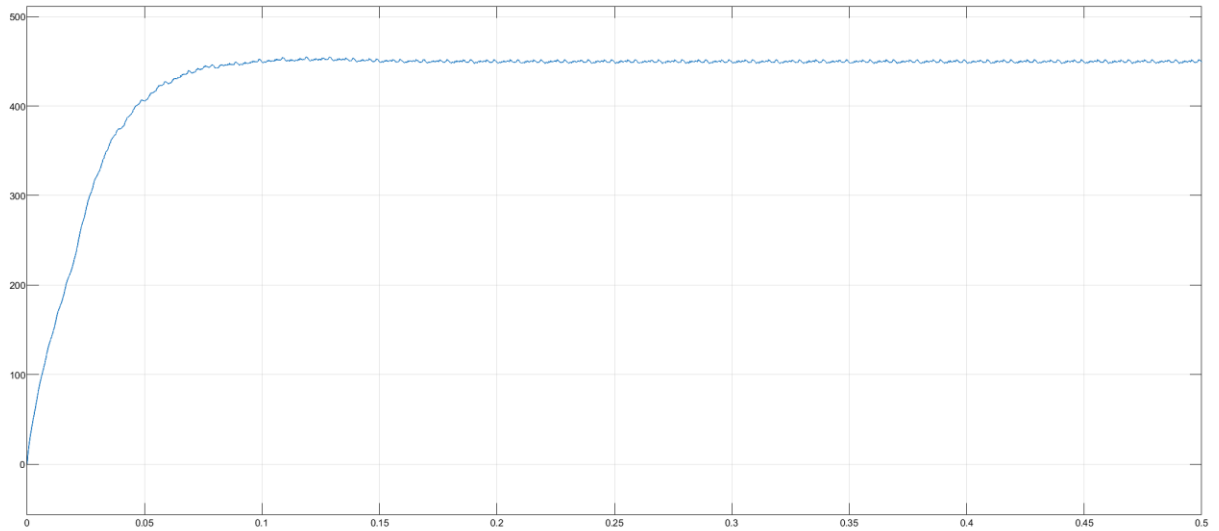


Fig 2: DC link Voltage Waveform

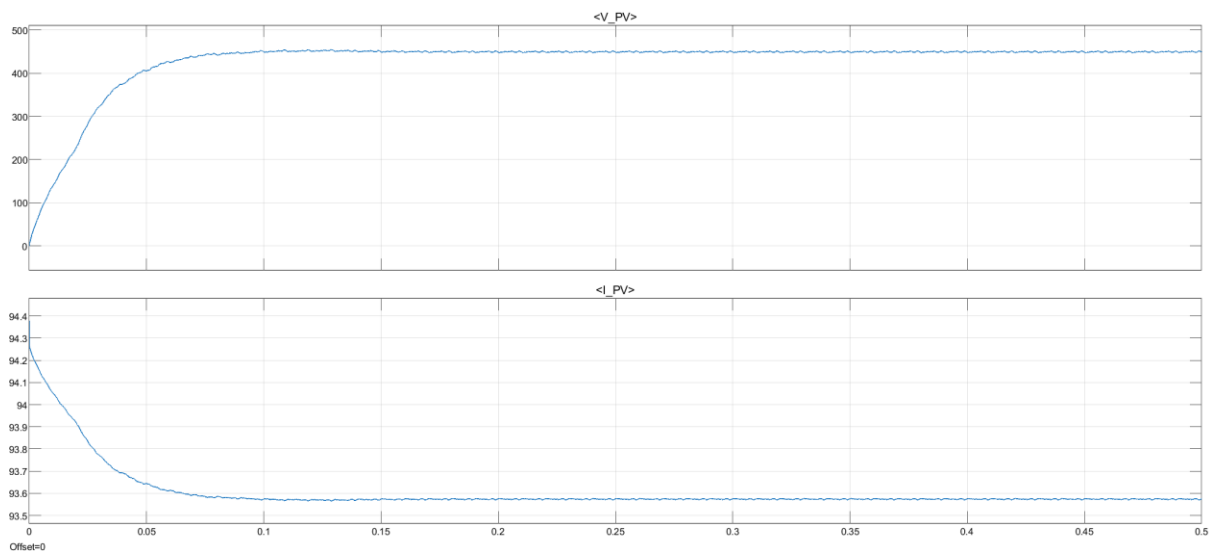


Fig 3: PV Voltage and current waveforms .

- Series converter injects compensating voltage
- Load voltage remains regulated

The proposed controller effectively compensates voltage sag and maintains sinusoidal load voltage.

B. Performance Under Nonlinear Load Condition

A nonlinear diode bridge rectifier load is employed to evaluate the harmonic mitigation capability of the proposed UPQC-PV system under practical operating conditions. The nonlinear load introduces significant current harmonics, increases the reactive power

demand, and may result in current imbalance, thereby degrading the overall power quality of the distribution system. To mitigate these adverse effects, the shunt active power filter (ShAPF) injects compensating currents that effectively suppress the harmonic components and provide the required reactive power compensation. As a result, the source currents become balanced and nearly sinusoidal, with substantially reduced total harmonic distortion (THD). In addition, the reactive power burden on the utility source is minimized, leading to improved power factor and enhanced overall system efficiency. These results demonstrate the effectiveness of the proposed control strategy in maintaining high power quality under nonlinear loading conditions.

Table 2: FFT analysis demonstrates significant harmonic reduction after compensation.

Quantity	Before Compensation	After Compensation
Source Current THD	26.63%	1.91%
Load Voltage THD	19.95%	1.46%

The obtained THD values satisfy IEEE-519 harmonic standards.

C. DC-Link Voltage Performance

The PSO-tuned proportional–integral (PI) controller effectively regulates the DC-link voltage of the proposed UPQC-PV system under a wide range of operating conditions, including voltage sag, voltage swell, nonlinear load operation, and variations in solar irradiance. By optimally tuning the controller gains, the Particle Swarm Optimization (PSO) algorithm enhances the dynamic performance of the DC-link voltage control loop, ensuring rapid recovery from transient disturbances while maintaining a stable operating point. The optimized controller significantly reduces transient overshoot, shortens the settling time, and suppresses DC-link voltage oscillations, thereby improving the overall stability and robustness of the system. Consequently, the proposed PSO-based control strategy ensures reliable power quality compensation and uninterrupted operation of the UPQC-PV system under both steady-state and dynamic conditions.

Table 3: PI Controller Performance

Parameter	Value
Proportional Gain	8.742
Integral Gain	215.37
Settling Time	0.042 s
Overshoot	1.84%

The PSO optimized controller provides superior transient response compared to conventional PI controllers.

D. Solar Irradiation Variation Analysis

To evaluate the robustness of the proposed UPQC-PV system under varying renewable energy conditions, the solar irradiance is reduced from 1000 W/m² to 600 W/m². The proposed PSO-tuned control strategy dynamically regulates the feed-forward current, source current reference, and DC-link voltage to accommodate the variation in photovoltaic power generation. By continuously adapting the converter control signals, the system maintains effective power flow management and stable DC-link voltage despite the reduction in available solar power. Furthermore, the proposed controller preserves the harmonic compensation capability of the UPQC, ensuring that the source current total harmonic distortion (THD) remains below the permissible limits specified by IEEE Standard 519. Consequently, stable system operation, effective power quality compensation, and reliable converter performance are maintained even under reduced solar irradiation conditions, demonstrating the robustness and adaptability of the proposed control approach.

V. VI. CONCLUSION

This paper presented a reduced-voltage-sensor-based Unified Power Quality Conditioner integrated with a photovoltaic (UPQC-PV) system employing an Enhanced Second-Order Generalized Integrator-based Modified Frequency-Locked Loop (ESOGI-mFLL) synchronization technique and a Particle Swarm Optimization (PSO)-tuned proportional–integral (PI) controller for simultaneous voltage and current power quality compensation. The proposed control strategy effectively compensated voltage sags, voltage swells, current harmonics, and reactive power under nonlinear load conditions while reducing the number of voltage sensors required for system implementation. The ESOGI-mFLL synchronization algorithm accurately extracted the positive-sequence fundamental voltage components under distorted and unbalanced grid conditions, providing robust synchronization, superior harmonic rejection, and reliable frequency estimation. Furthermore, the PSO-based optimization of the PI controller significantly enhanced the dynamic performance of the DC-link voltage regulation by reducing overshoot, minimizing settling time, suppressing voltage oscillations, and improving overall system stability. The proposed controller also ensured stable operation during variations in solar irradiance, enabling seamless integration of renewable energy into the distribution network. Simulation results demonstrated that the source current total harmonic distortion (THD) was reduced from 26.63% to 1.91%, which satisfies the harmonic limits specified by IEEE Standard 519. Therefore, the proposed UPQC-PV system provides an efficient, robust, and reliable solution for advanced power quality enhancement in renewable-energy-integrated smart distribution systems, offering improved dynamic performance, reduced sensing requirements, and enhanced operational reliability.

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