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Mitigation of Power Quality Issues in Three-Phase Four-Wire Distribution Systems Using a GWO-Tuned PV-UPQC

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Abstract: Power quality (PQ) issues in three-phase four-wire distribution systems, such as voltage sags, swells, harmonics, and neutral current imbalances, significantly affect system reliability and efficiency. This paper proposes a Grey Wolf Optimizer (GWO)-tuned Photovoltaic-Unified Power Quality Conditioner (PV-UPQC) to mitigate these PQ challenges effectively. The PV-UPQC integrates series and shunt active power filters with a solar PV system, enhancing power quality while harnessing renewable energy. The GWO algorithm optimizes the controller parameters to ensure superior dynamic response. Simulation results in MATLAB/Simulink validate the system's effectiveness in compensating voltage and current distortions, reducing neutral current, and maintaining grid stability under varying load and fault conditions. The proposed GWO-tuned PV-UPQC demonstrates improved performance over conventional methods, offering a robust solution for modern distribution networks.

Keywords: Power quality, PV-UPQC, Grey Wolf Optimizer (GWO), three-phase four-wire system, voltage compensation.

I. Introduction:

Power quality (PQ) issues in three-phase four-wire distribution systems, such as voltage sags, swells, harmonics, unbalanced loads, and excessive neutral currents, pose significant challenges to grid stability and equipment performance. These disturbances arise from the increasing penetration of nonlinear loads, renewable energy integration, and industrial automation, leading to inefficiencies, equipment failures, and financial losses [1]. Traditional mitigation techniques, including passive filters and static VAR compensators, often fall short in addressing dynamic PQ problems, necessitating advanced solutions like the Unified Power Quality Conditioner (UPQC).

The UPQC, a versatile custom power device, combines series and shunt active power filters (APFs) to simultaneously mitigate voltage and current distortions. Integrating photovoltaic (PV) systems with UPQC—forming a PV-UPQC—enhances its functionality by supplying renewable power while compensating for PQ disturbances [2]. However, the performance of PV-UPQC largely depends on the efficiency of its control strategy. Conventional proportional-integral (PI) controllers, though widely used, struggle with parameter tuning under dynamic conditions, leading to suboptimal compensation.

To overcome these limitations, met heuristic optimization techniques such as the Grey Wolf Optimizer (GWO) have gained attention for their ability to fine-tune controller parameters efficiently. GWO, inspired by the hierarchical hunting behavior of grey wolves, offers fast convergence, high accuracy, and robustness in solving complex optimization problems [3]. Applying GWO to PV-UPQC control ensures optimal performance under varying load and fault conditions, improving harmonic suppression, voltage regulation, and neutral current compensation.

This paper proposes a **GWO-optimized PV-UPQC** for mitigating PQ issues in three-phase four-wire distribution systems. The key contributions include:

1. **Design and modeling** of a PV-integrated UPQC for simultaneous power quality improvement and solar energy utilization.
2. **GWO-based tuning** of the PV-UPQC controller to enhance dynamic response and minimize total harmonic distortion (THD).

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3. **Performance validation** through MATLAB/Simulink simulations under different PQ disturbances, demonstrating superior compensation compared to conventional methods.

II. Unified Power Quality Conditioner

A Unified Power Quality Conditioner (UPQC) is an advanced device used in power systems to improve the quality of electricity by compensating for various power quality issues such as voltage sags, voltage swells, harmonics, and reactive power. It integrates the functions of both Series and Shunt compensators to provide a comprehensive solution to address multiple power quality problems. The Block diagram of UPQC as shown in Fig.1

Series compensator: Typically implemented as a Voltage Source Converter (VSC), which is connected in series with the load to mitigate voltage disturbances like sags, swells, and transients. It regulates the voltage supplied to the load, ensuring stable and clean power. The series compensator can inject or absorb voltage to correct any discrepancies in the supply.

***Shunt compensator**:* Usually a shunt VSC, connected parallel to the load. Its primary function is to manage reactive power and mitigate harmonic distortions by supplying or absorbing reactive power as needed. It can also filter out unwanted harmonics from the system, improving the power quality delivered to the load.

Dc-link capacitor: A capacitor is used to link the two converters (series and shunt). It helps in maintaining the power balance between the converters and provides necessary energy for operation.

Functionality: The Series Compensator filters voltage disturbances such as sags, swells, and transients, maintaining a constant voltage at the load. The Shunt Compensator handles reactive power compensation, reduces harmonic distortions, and balances the power factor to improve the system's overall efficiency.

Applications**:** Industrial Loads Protecting sensitive equipment in industries that rely on continuous, high-quality power for operations. Commercial Power Systems Ensuring power quality in commercial buildings and office complexes. Smart Grids Helping modern grids to handle fluctuations in demand and supply more effectively. Renewable Energy Integration Smoothens the power output from renewable energy sources like solar and wind by compensating for fluctuations.

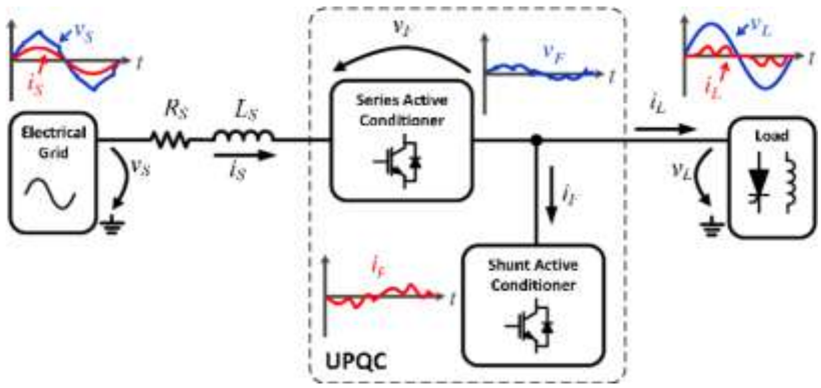

Fig. 1 Block diagram of unified power quality conditioner

The schematic diagram of four wire double stage UPQC-PV system connected to a three-phase four wire distribution grid network is shown in Fig. 2. Two voltage source inverters (VSIs) connected back-to-back through DC-bus are the main components of the UPQC system. The solar photovoltaic

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array is connected to this common DC-bus through a DC-DC boost converter. The series compensator is connected through interfacing inductors and transformer towards the grid network. Whereas the shunt compensator is connected towards the load end through interfacing inductors. Moreover, the ripple filters are installed at the load end to lessen the effect of ripple due to switching frequency

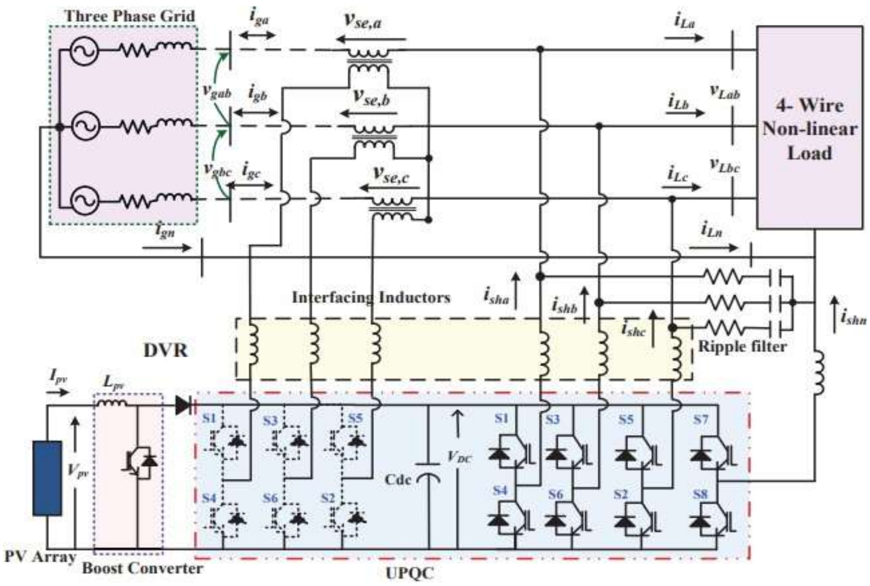

Fig. 2 Three-phase four wire UPQC with double stages PV array

III. Grey Wolf Optimizer (GWO)

GWO is a M**eta-heuristic optimization algorithm** inspired by the leadership hierarchy and hunting behavior of grey wolves. It's widely used for: Solving complex engineering optimization problems, Tuning controller parameters (e.g., PI, fuzzy logic) and Enhancing power quality compensation in UPQC

The general workflow of a Unified Power Quality Conditioner (UPQC) integrated with the Grey Wolf Optimization (GWO) algorithm involves a systematic approach to enhance power quality in electrical systems. Initially, the UPQC system is connected to the power network to mitigate issues such as voltage sags/swells, harmonics, and reactive power imbalance using its series and shunt active power filters. The performance of the UPQC depends on control parameters like voltage references and current compensation, which must be accurately tuned. This is where GWO comes into play. The GWO algorithm, inspired by the social hierarchy and hunting behavior of grey wolves, is used to optimize these control parameters dynamically. It starts by initializing a population of possible solutions and evaluates their fitness based on a predefined objective function typically minimizing total harmonic distortion (THD) or improving voltage regulation. Through iterative updates based on the positions of the best-performing solutions (α, β, and δ wolves), GWO fine-tunes the UPQC control strategy. This optimized control ensures the UPQC responds effectively to disturbances, maintaining power quality and system stability in real time.

i. Social Hierarchy:

Alpha (α): The dominant wolf, responsible for decision-making and leading the pack.

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Beta (β): Subordinate wolves that help the alpha and are considered the best candidates to replace the alpha.

Delta (δ): Wolves that submit to the alpha and beta, but dominate the omega wolves. They can be scouts, sentinels, elders, hunters, or caretakers.

Omega (ω): The lowest-ranking wolves, often scapegoats, and the last to eat.

ii. Hunting Process:

Encircling the Prey: The wolves surround the prey, gradually decreasing the distance between them and the target.

Hunting: The alpha, beta, and delta wolves lead the hunt, while the omega wolves follow.

iii. Attacking the Prey: The wolves attack the prey when it stops moving, usually after being harassed and encircled.

IV. Simulation Results and Analysis

Case 1: UPQC with GWO algorithm of three phase four wire double stage SPV for load unbalancing condition

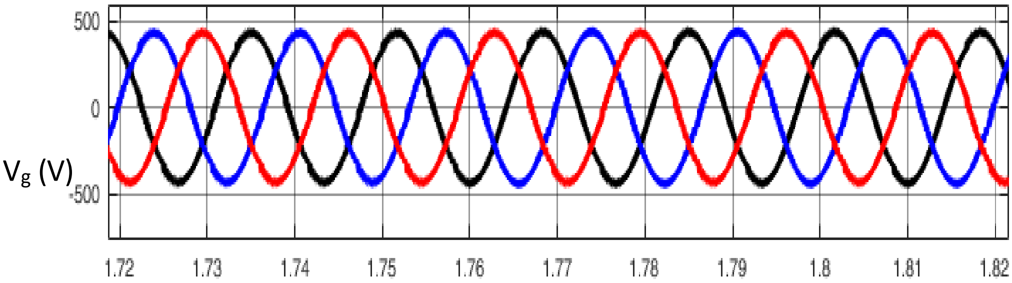

Fig (a)

This Pot describes the information about grid voltage in volts

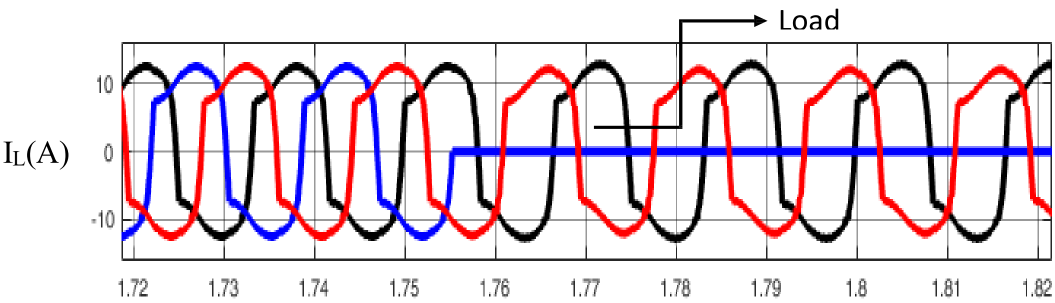

Fig (b)

This plot describes the sudden removal of one of the load and suddenly becoming of one of the phase current inti zero

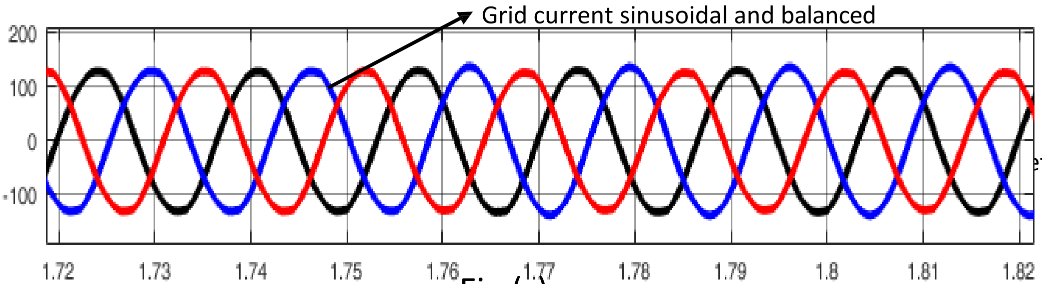

Fig (c)

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I_g(A)

This plot shows the balanced sin-soidal grid current after the sudden change, by using GWO algorithm

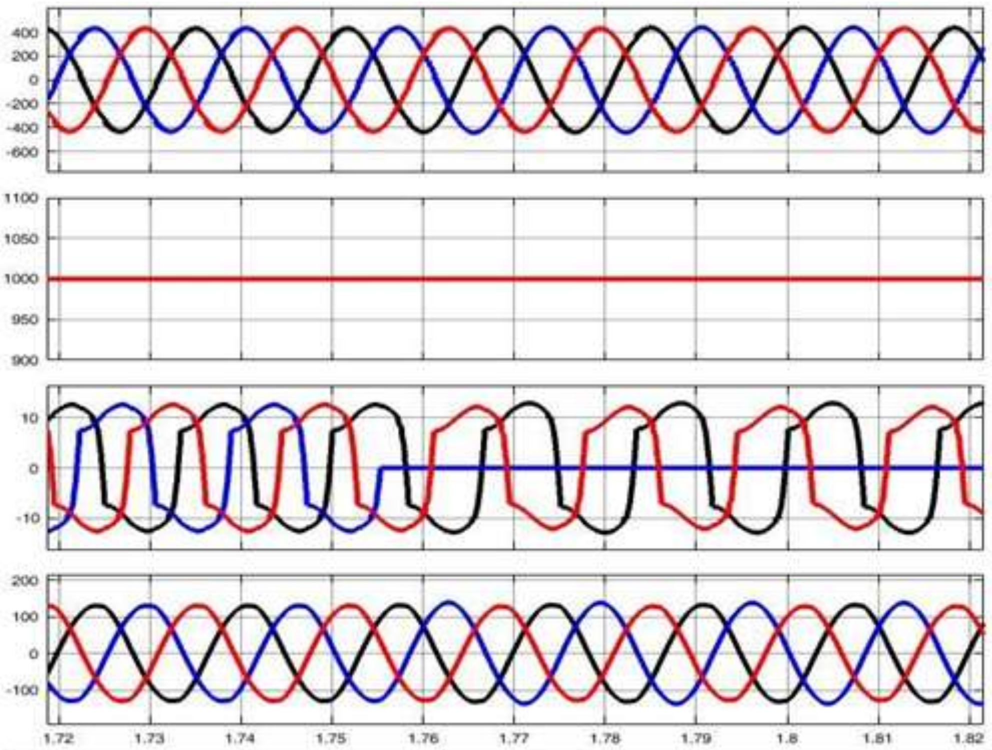

Fig 3 performance of a three phase four wire double stage SPV for load unbalancing condition

The system exhibits stable and balanced three-phase output voltages and inverter currents (Fig a,b), despite clear distortion in the load current waveforms (third row, left side), indicating the presence of load unbalancing and possible nonlinearity. The GWO-optimized controller effectively maintains constant DC-link voltage (~1000 V) and solar irradiance, ensuring uninterrupted power delivery from the photovoltaic array. Moreover, the inverter output currents (bottom left) remain sinusoidal and balanced, confirming that the GWO algorithm successfully regulates the inverter to mitigate the effects of unbalanced loads**.** The neutral current waveform (middle right) shows low-level oscillations near zero, demonstrating effective compensation and current balancing across phases. Additionally, the total power delivered remains steady (middle right), and the power factor (bottom right) is consistently around 0.105, suggesting that the system operates efficiently within a controlled range. Overall, the GWO-enhanced control strategy proves robust in maintaining power

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quality, voltage balance, and effective neutral current suppression under unbalanced load conditions.

Case: 2 UPQC with GWO algorithm of three phase four wire double stage SPV for load unbalanced voltage sag

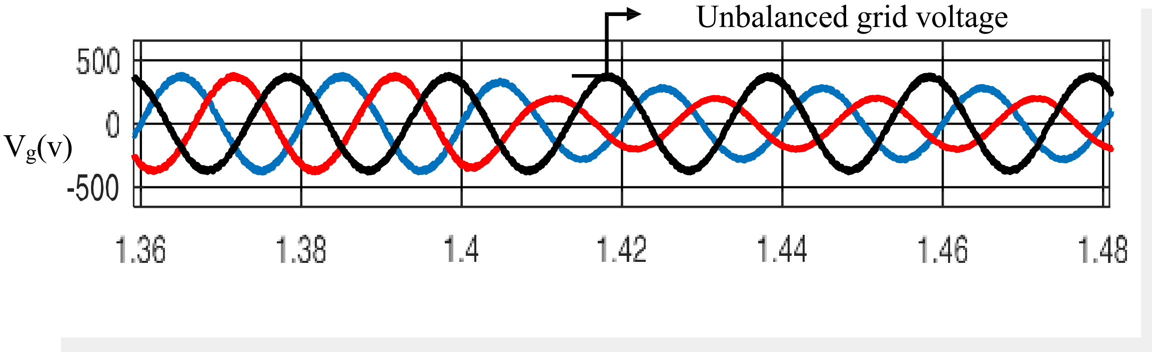

Fig (d)

This plot shows the grid voltage under unbalanced voltage sag condition

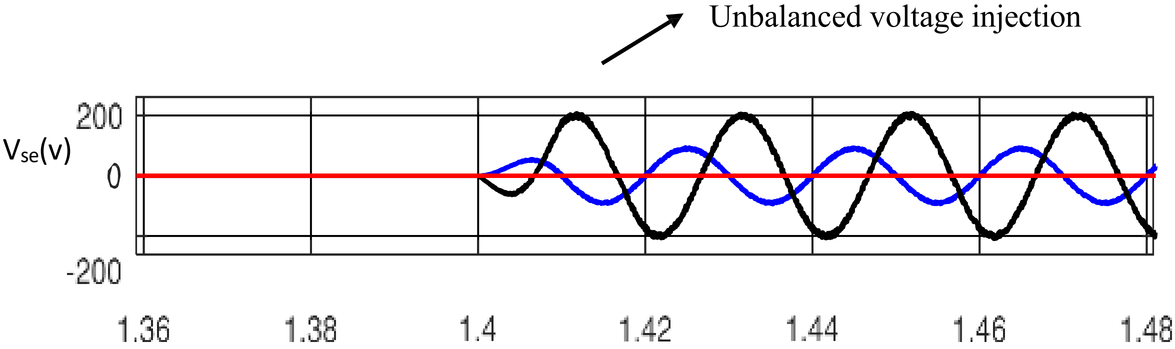

Fig (e)

This plot shows the series voltage that is to be injected into the grid to compensate the variation in the voltage.

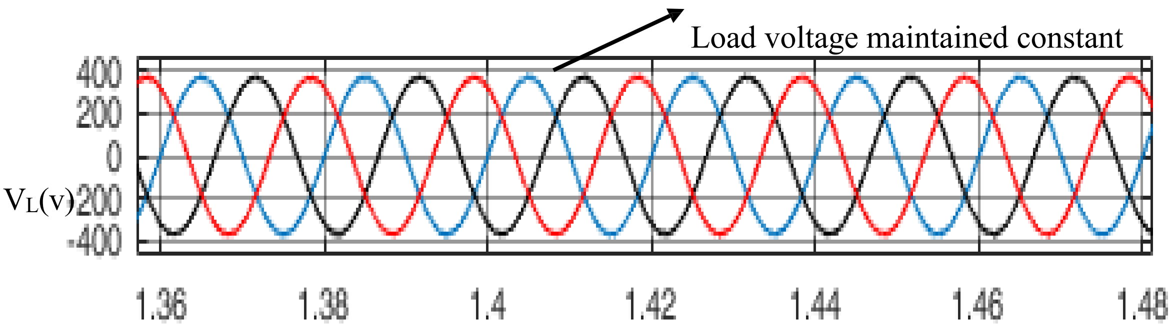

Fig (f)

This plot shows the load voltage maintained constant after voltage imbalance in grid get injection of series voltage into the grid

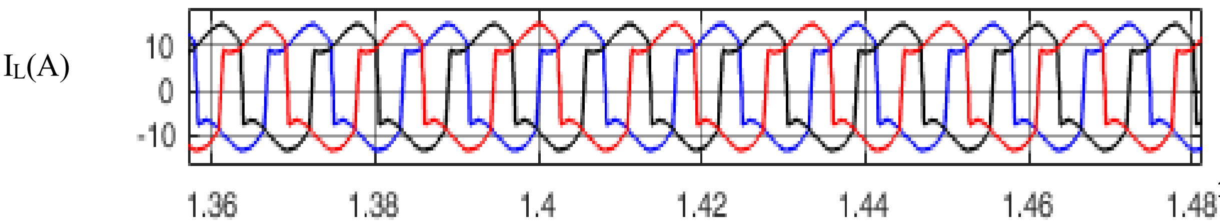

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Fig (g)

The plot in the fig (g) shows the load current and the range of the load current is 0 to +or- 10 amperes

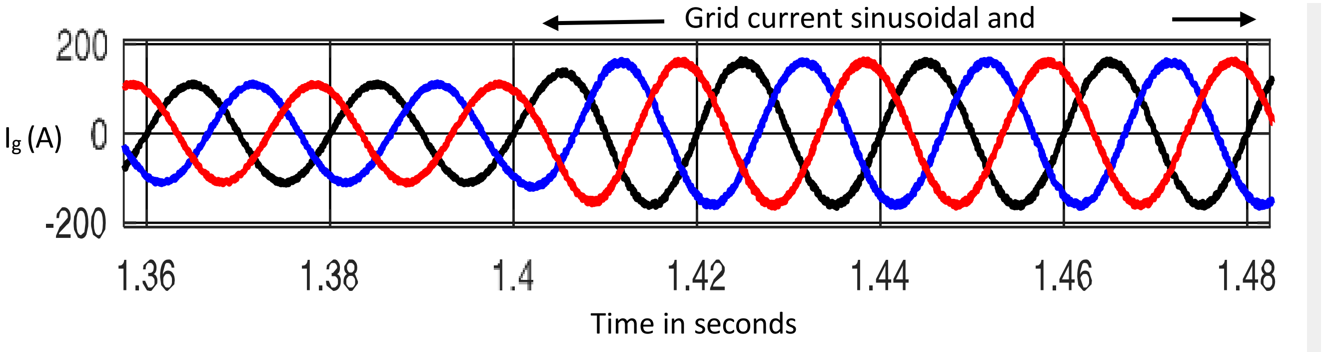

Fig (h)

This plot shows the Grid current maintained sinusoidal and balanced.

Fig 4 (d, e, f, g, h) Performance of the Three- Phase Four UPQC with Double Stage SPV array system for unbalanced voltage sag.

The provided plot illustrates the dynamic performance of a Three-Phase Four-Wire Unified Power Quality Conditioner (UPQC) integrated with a Double Stage Solar Photovoltaic (SPV) system under conditions of unbalanced voltage sag. The source voltage waveforms initially show clear unbalance and sag in one or more phases, but the load voltage waveforms are effectively restored to balanced sinusoidal signals, demonstrating the UPQC's compensating capability. The SPV system maintains a constant output voltage around 1000V, which is regulated by the boost converter to approximately 700V to stabilize the DC-link voltage at about 60V, indicating efficient power conversion and control. The load currents are initially distorted due to the unbalanced source, but after compensation, they become balanced and sinusoidal. The inverter currents closely track their reference values, confirming the accuracy of the current control using hysteresis and PWM techniques. The reactive power and neutral current are minimized, reflecting the system's ability to maintain power quality and reduce imbalance. Additionally, the active power supplied by the SPV remains steady throughout, supporting the load effectively. Overall, the system successfully mitigates unbalanced voltage sag while maintaining continuous and clean power delivery, showcasing the coordinated operation of the UPQC and the double-stage SPV array.

Case: C UPQC with GWO algorithm of three phase four wire double stage SPV for load unbalanced voltage Swell.

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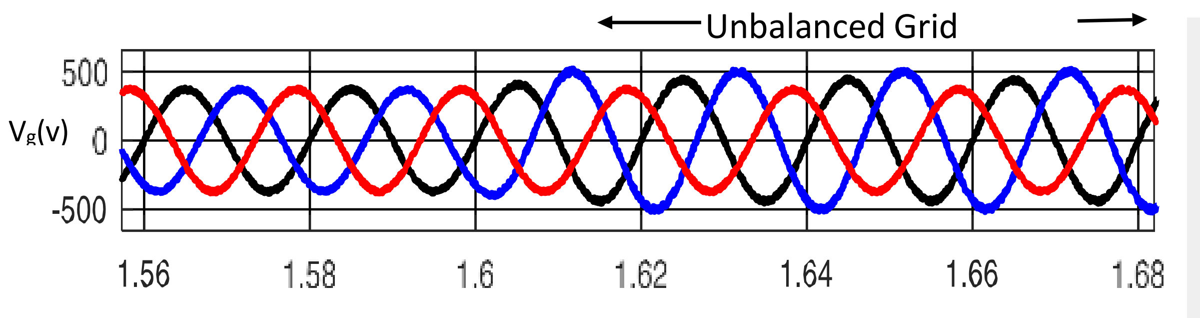
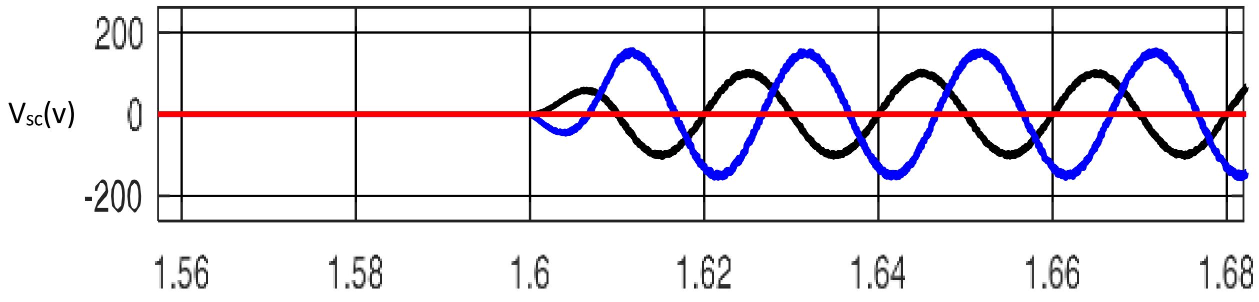


Fig(i)

This plot shows the sudden imbalance of grid voltage because of some nonlinear load, and the time period is taken in seconds.



Fig(j)

This plot shows the series voltage that is to be injected into the grid to compensate the variation in the voltage.

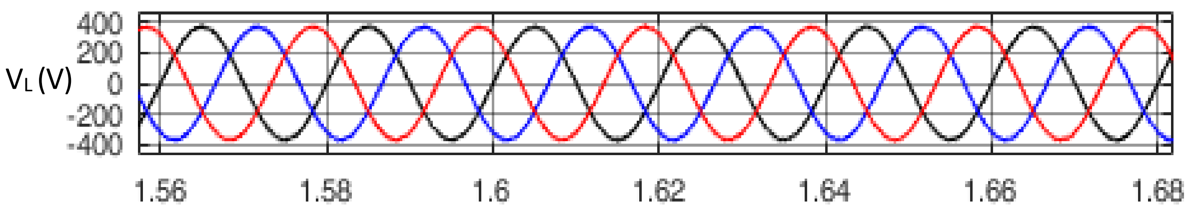


Fig (k)

This plot shows the load voltage maintained constant after voltage imbalance in grid get injection of series voltage into the grid.

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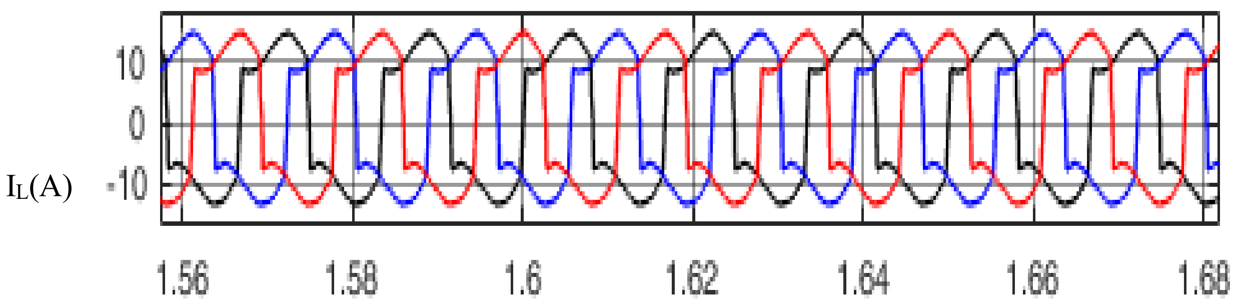

Fig (l)

The plot in the fig (l) shows the load current and the range of the load current is 0 to +or- 10 amperes

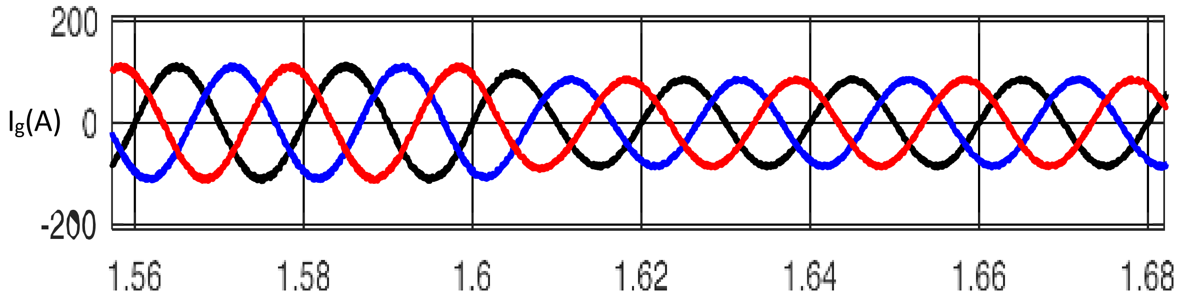

Fig (m)

This plot shows the load voltage maintained constant after voltage imbalance in grid get injection of series voltage into the grid

Fig 5 (i, j, k, l, m) Performance of the Three- Phase Four UPQC with Double Stage SPV array system for unbalanced voltage swell.

This illustration evaluates the performance of a Three-Phase Four-Wire Unified Power Quality Conditioner (UPQC) integrated with a Double Stage Solar Photovoltaic (SPV) array when subjected to an unbalanced voltage swell. The system's response, captured across multiple subplots, confirms its efficacy in enhancing power quality. The source-side voltages and currents, depicted in the top-left subplots, maintain balanced sinusoidal waveforms despite the grid disturbance, indicating excellent voltage conditioning and harmonic isolation. The stability of the DC-Link voltage underscores the reliability of the double-stage SPV configuration in sustaining a consistent DC bus voltage.

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Analysis of the load-side waveforms reveals that the load voltages are well-regulated and the load currents remain sinusoidal and balanced, signifying that the critical load is effectively protected from the voltage swell. The corresponding compensating voltages and currents (plotted in red) display the necessary transient and non-sinusoidal characteristics required to actively mitigate the fault condition.

Finally, the stable profiles of the neutral current compensation and SPV integration metrics (bottom-right) further attest to the system's comprehensive capability to manage power quality issues. In summary, the plot validates the system's robustness in maintaining voltage stability, ensuring current quality, and seamlessly integrating solar power under unbalanced network faults.

Case d: UPQC with GWO algorithm of three phase four wire double stage SPV for Insolation change.

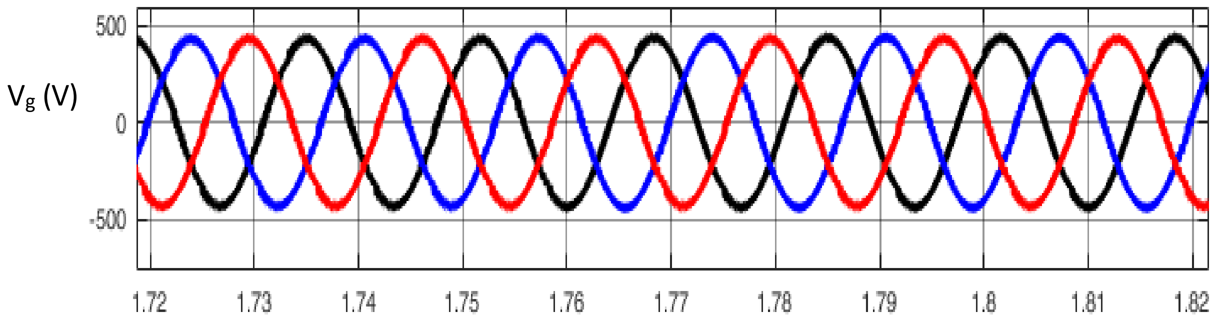

Fig (n)

This Pot describes the information about grid voltage in volts.

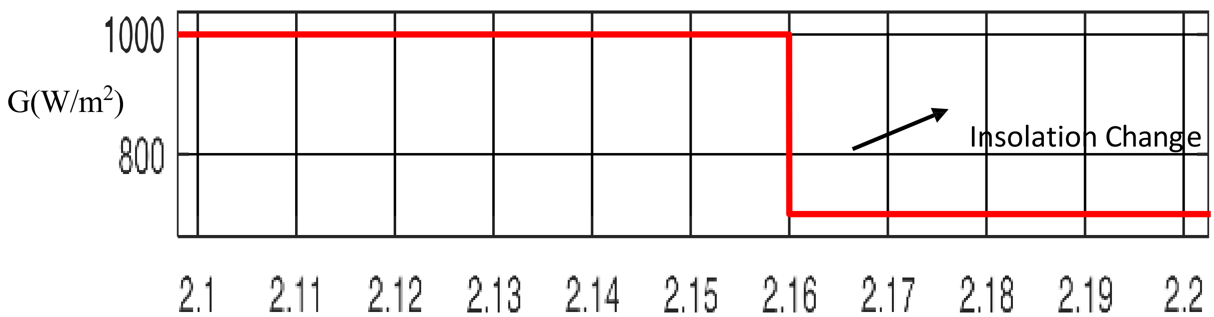

Fig (O)

This plot shows the sudden change of insolation that means the amount of photon energy reaching the spv array

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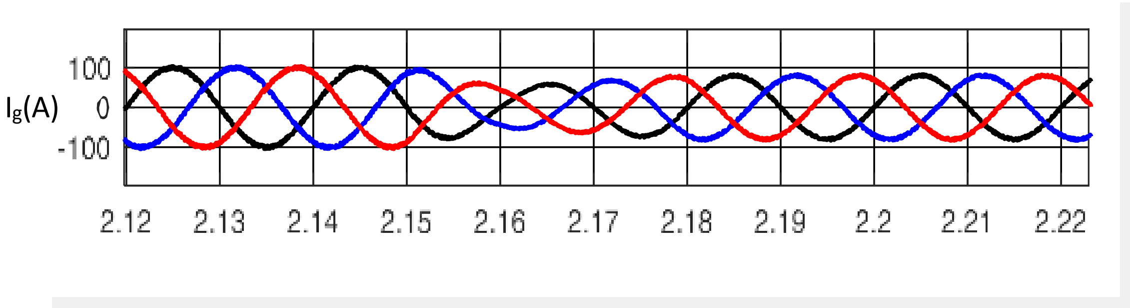


Fig (p)

The Plot shown above give the information about the unbalancing of the gird current based on the insolation change.

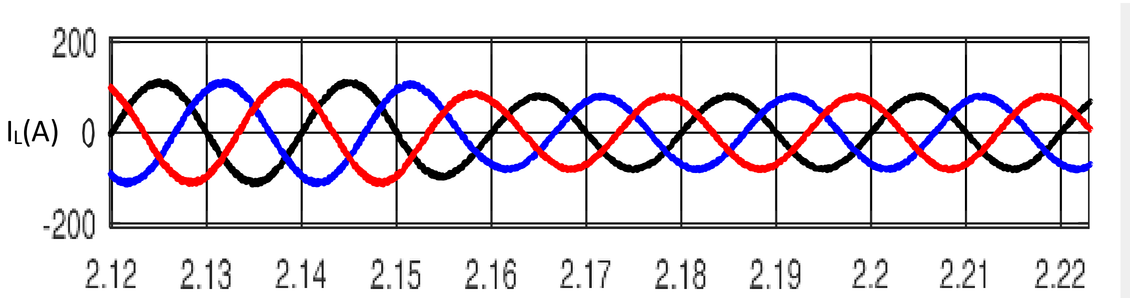
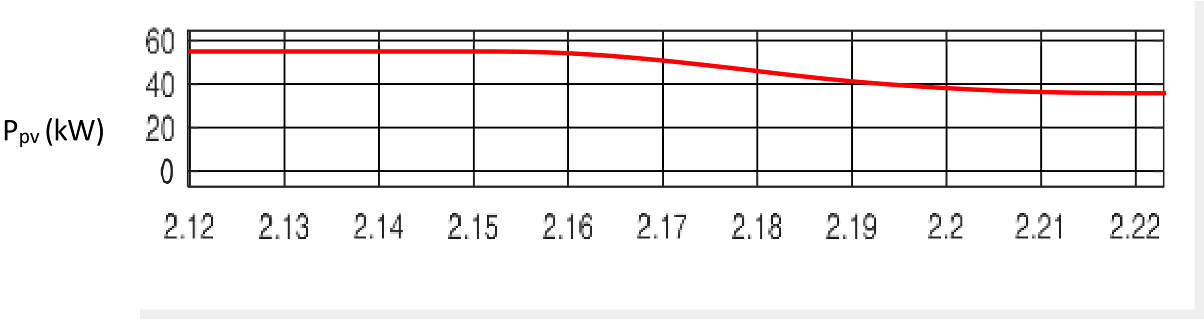


Fig (q)

This plot shows the unbalanced load current getting balanced



This plot shows the decay in the generated power by solar PV array because of the change in the insolation

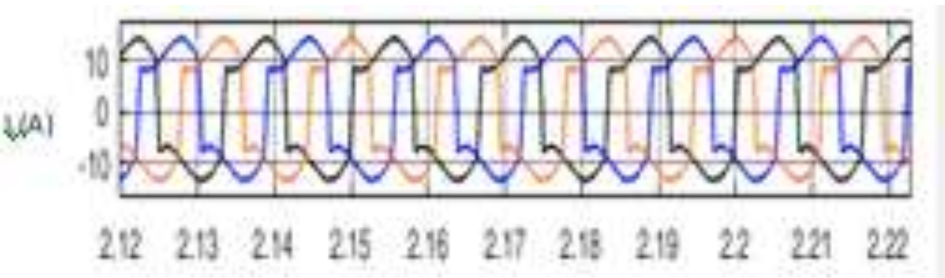


Fig (s)

The plot in the fig (s) shows the load current and the range of the load current is 0 to +or-

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10 amperes

Fig 6 (n, o, p, q, r, s) UPQC with GWO algorithm of three phase four wire double stage SPV for Insolation change**.**

Under a simulated step-change in solar irradiance, this plot evaluates a Unified Power Quality Conditioner (UPQC) coupled with a Double Stage Solar PV array. The irradiance drop and subsequent recovery directly impact the PV output. The UPQC's response is shown to effectively decouple the load from these source variations: the load voltage (top subplot) is held balanced and sinusoidal, demonstrating precise voltage regulation. Concurrently, the source current (third subplot) is compensated to be sinusoidal and free of harmonics. The DC link voltage remains tightly regulated with minor deviations, while other metrics confirm stable neutral current compensation and power factor correction. Overall, the system demonstrates robustness in maintaining voltage stability and current quality amidst irradiance fluctuations.

V. CONCLUSION

This paper proposes a novel integration of a double-stage solar PV array with a Unified Power Quality Conditioner (UPQC), optimized by the Grey Wolf Optimization (GWO) algorithm for three-phase four-wire systems. The system synergizes renewable energy injection with comprehensive power quality mitigation, addressing voltage sags, swells, harmonic distortions, unbalanced loads, and neutral current. The GWO-based control strategy ensures real-time parameter tuning, leading to superior dynamic response, reduced THD, and enhanced stability under diverse operational scenarios. The study concludes with a proposal for future hardware-in-the-loop testing and comparative analysis with other meta- heuristic algorithms.

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