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Harmonics Analysis and Mitigation in Distributed Generation Using PQ Theory

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Abstract: *Harmonic distortion is a major power quality issue in distributed generation (DG) systems, especially in mini grids with nonlinear loads and inverter-based renewable sources. Traditional mitigation methods, such as synchronous reference frame (SRF) control, are effective but often limited by slower dynamic response and sensitivity to unbalanced conditions. This paper presents an approach using Instantaneous Reactive Power (PQ) Theory for fast and accurate harmonic detection and compensation. In this method, three-phase currents are transformed into - coordinates using Clarke transformation, and instantaneous active (p) and reactive (q) powers are calculated to extract harmonic components in real time. Reference compensating currents are then generated and injected through a PWM- controlled Voltage Source Inverter (VSI) configured as a Shunt Active Power Filter (SAPF). The PQ Theory enables effective harmonic elimination under both balanced and unbalanced nonlinear loads, making it suitable for modern DG applications. MATLAB/Simulink simulations demonstrate a significant reduction in Total Harmonic Distortion (THD) and an improvement in power quality compared to conventional techniques. This highlights PQ Theory as a practical and efficient control strategy for harmonic mitigation in advanced DG systems.*

Keywords: Mitigation, Power Quality Improvement, Instantaneous Reactive Power (PQ) Theory, Active Power Filter (APF), Nonlinear Loads, Inverter-Based DG Systems, α–β Transformation, Total Harmonic Distortion (THD).

I. INTRODUCTION

The rapid increase in global energy demand, combined with growing environmental concerns and the depletion of fossil fuel resources, has accelerated the transition from conventional centralized power generation to renewable energy–based Dis- tributed Generation (DG) systems. Among the various renewable sources, solar photovoltaic (PV) and wind energy systems have gained significant attention due to their abundance, sustainability, and technological maturity. These sources are increasingly integrated at the distribution level in the form of grid-connected and standalone DG units, microgrids, and mini-grids. The integration of solar and wind energy systems enhances energy security, reduces greenhouse gas emissions, and improves overall system efficiency by generating power close to load centres.

Despite their advantages, solar and wind–based DG systems introduce several technical challenges related to power quality, system stability, and control. One of the most critical power quality issues associated with DG integration is harmonic distortion. Solar PV and wind energy conversion systems inherently rely on power electronic converters such as inverters and rectifiers to interface with the grid. These converters, along with nonlinear consumer loads such as variable speed drives, switched-mode power supplies, and electric vehicle chargers, draw non sinusoidal currents from the supply. As a result, harmonic currents are injected into the power system, leading to distortion of current and voltage waveforms.

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Harmonic distortion becomes particularly severe in DG- based mini-grids and microgrids, where system impedance is relatively high, and the short-circuit capacity is low. In such systems, harmonic currents can cause excessive voltage distortion at the point of common coupling, resulting in increased losses, overheating of transformers and rotating machines, malfunction of sensitive electronic equipment, electromagnetic interference, and improper operation of protective devices. Furthermore, harmonics negatively affect the performance and reliability of inverter-based solar and wind generation units by increasing switching losses and thermal stress. To ensure safe and reliable operation, power quality standards such as IEEE 519 specify permissible limits for Total Harmonic Distortion

II. PROBLEM STATEMENT & MOTIVATION

Distributed Generation (DG) systems integrated with renewable energy sources introduce significant harmonic distortion due to inverter-based interfaces and nonlinear loads, leading to poor power quality, increased losses, and reduced equipment lifespan. Conventional harmonic mitigation techniques often exhibit slow dynamic response and limited performance under unbalanced conditions. This motivates the adoption of Instantaneous Reactive Power (PQ) Theory, which enables fast, accurate harmonic detection and effective compensation, ensuring improved power quality, reduced Total Harmonic Distortion, and reliable operation of DG-based power systems.

III. EXPERIMENTAL SETUP

The experimental setup is implemented using MATLAB/Simulink 2023a to evaluate harmonic analysis and mitigation in a distributed generation (DG) system. The modeled system consists of a three-phase inverter-based DG unit connected to the grid and supplying a nonlinear load, which introduces harmonic distortion in the source current. Instantaneous Reactive Power (PQ) Theory is employed for harmonic detection, where three-phase voltages and currents are transformed into α–β reference frames. Based on this transformation, instantaneous active and reactive power components are calculated to generate reference compensating currents. These reference currents are applied to a voltage source inverter through a suitable control strategy. The performance of the system is analyzed under two operating conditions: with harmonics and without harmonics compensation. Total Harmonic Distortion (THD) is measured using FFT analysis in MATLAB to quantify power quality improvement. The simulation results, including voltage and current waveforms and THD spectra, demonstrate the effectiveness of PQ theory–based harmonic mitigation.

A. BLOCK DIAGRAM

The proposed PQ theory–based control scheme accurately detects harmonic components using instantaneous power calculations and injects compensating currents through a VSI controlled by hysteresis current control. As a result, source currents become nearly sinusoidal, reactive power is minimized, and THD is significantly reduced, ensuring enhanced power quality in distributed generation systems.

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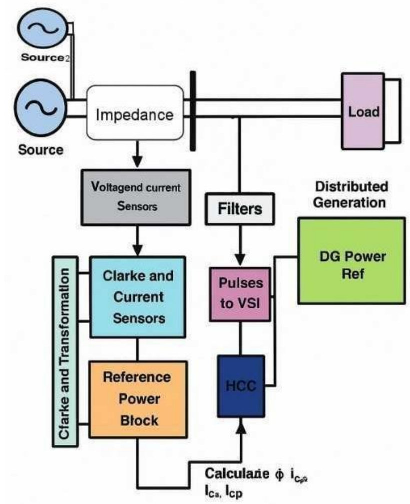

Fig a:

1. SOURCE / SOURCE :

The sources represent the three-phase utility grid and distributed generation (DG) units supplying power to the system. These sources may include inverter-based renewable energy systems such as solar PV or wind energy. Due to power electronic interfaces and nonlinear loads, the source currents are often distorted, leading to harmonic pollution in the grid.

2. LINE IMPEDANCE:

The impedance block models the practical transmission line parameters, including resistance and inductance between the source and the point of common coupling (PCC). This block plays a crucial role in determining voltage drops, current distortion propagation, and overall system stability under harmonic conditions.

3. LOAD:

The load represents nonlinear consumer loads, such as rectifiers, adjustable speed drives, or power electronic converters. These loads draw non-sinusoidal currents even when supplied with sinusoidal voltages, thereby introducing current harmonics that degrade power quality in distributed generation systems.

4. VOLTAGE AND CURRENT SENSORS:

Voltage and current sensors continuously measure three-phase voltages and currents at the PCC. These measured signals act as real-time inputs for harmonic detection and control. Accurate sensing is essential for effective implementation of PQ theory and precise harmonic compensation.

5. CLARKE TRANSFORMATION BLOCK:

The Clarke transformation converts three-phase (abc) voltages and currents into two-axis stationary reference frame (α–β) quantities. This transformation simplifies the mathematical analysis by eliminating phase dependency and enables instantaneous power calculation, which is the core principle of PQ theory

6. INSTANTANEOUS POWER (REFERENCE POWER BLOCK):

This block computes instantaneous active power (p) and reactive power (q) using α–β components of voltage and current. The total power is separated into average and oscillating components. The oscillating part corresponds to harmonic and reactive power, which must be compensated to improve power quality.

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7. REFERENCE COMPENSATING CURRENT CALCULATION:

Based on the calculated p and q components, this block generates reference compensating currents (i*ca, i*cb, i*cc). These currents represent the harmonic and reactive portions that need to be injected by the compensator to ensure sinusoidal source currents and unity power factor operation.

8. HYSTERESIS CURRENT CONTROLLER (HCC):

The HCC compares the actual compensating current with the reference current and generates appropriate switching signals. It offers fast dynamic response, simple implementation, and high accuracy, making it suitable for real-time harmonic compensation in DG systems.

9. PULSES TO VOLTAGE SOURCE INVERTER (VSI):

This block applies the switching pulses generated by the HCC to the Voltage Source Inverter. The VSI injects compensating currents into the system to cancel harmonics and reactive components drawn by nonlinear loads.

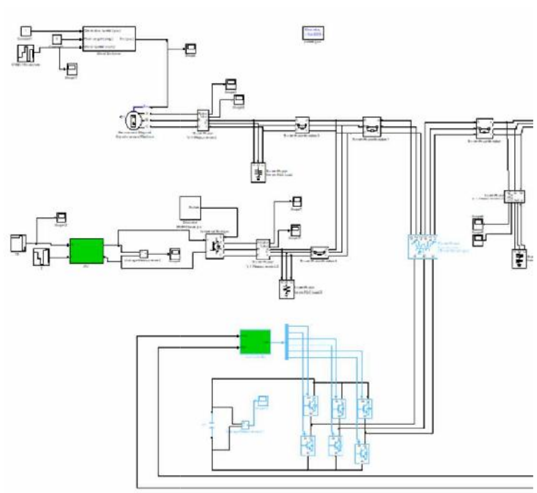
10. FILTERS:

The filter (typically an LC or LCL filter) is used to smooth inverter output currents and suppress high-frequency switching harmonics. It ensures that only the desired compensating current components are injected into the grid.

11. DG POWER REFERENCE BLOCK:

This block defines the active power reference of the distributed generation unit. It ensures coordinated operation between power injection and harmonic compensation, maintaining system stability and compliance with grid codes.

B. CIRCUIT DIAGRAM



Input Wind Speed Vs Time

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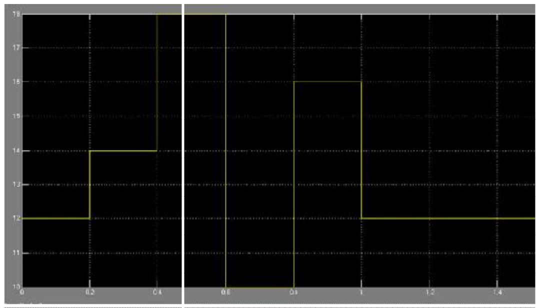
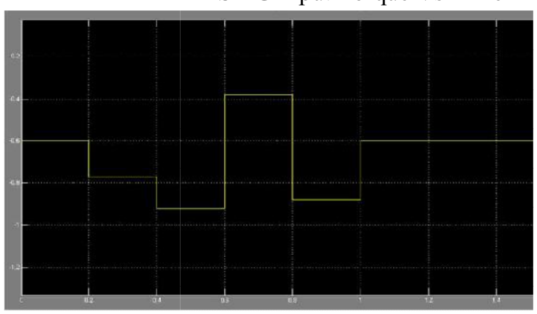


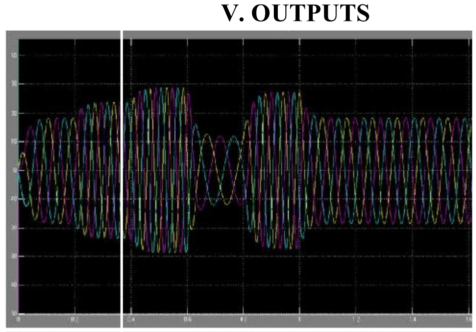
PSMG Input Torque Vs Time



IV. RESULT

The proposed harmonic analysis and mitigation strategy was tested on a grid-connected distributed generation system comprising solar photovoltaic (PV) and wind energy sources. The integration of these renewable sources through power electronic converters introduced nonlinear characteristics, resulting in noticeable current harmonics at the point of common coupling (PCC). Fast Fourier Transform (FFT) analysis was employed to evaluate the harmonic spectrum of the system currents. Before compensation, the total harmonic distortion (THD) was observed to be 5.78%, exceeding the limits prescribed by IEEE-519 standards. An instantaneous PQ theory–based control algorithm was then implemented to generate appropriate compensating reference currents for harmonic suppression. The controller dynamically separated the active and reactive power components and effectively eliminated the harmonic content. After compensation, the THD was significantly reduced to 1.2%. The results confirm that the proposed PQ theory–based approach provides efficient harmonic mitigation and substantial power quality improvement in hybrid solar PV and wind-based distributed generation systems..

V. OUTPUTS



PV Inverter Voltage Vs Time

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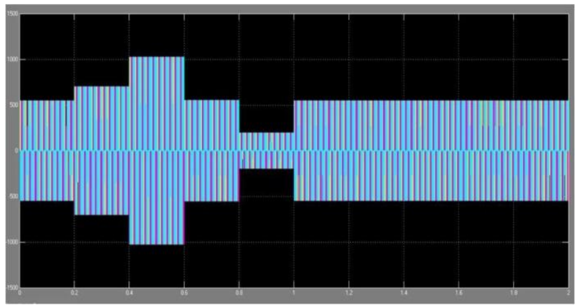
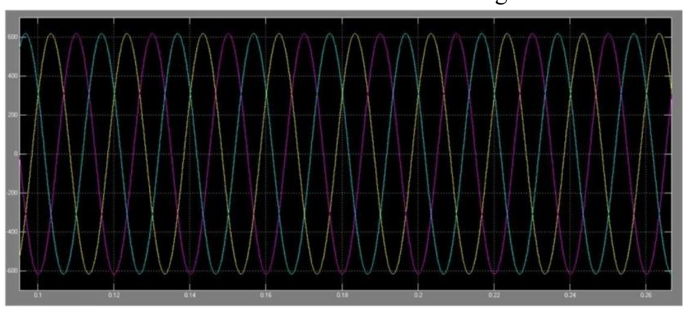
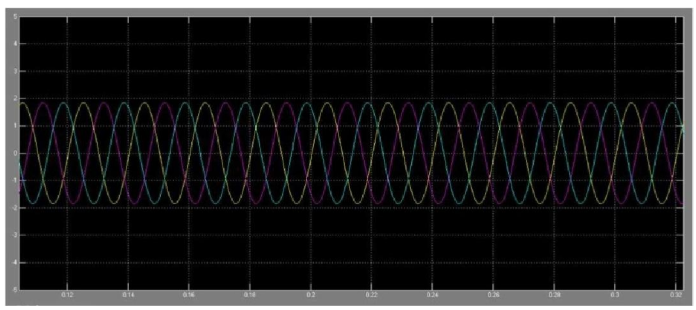


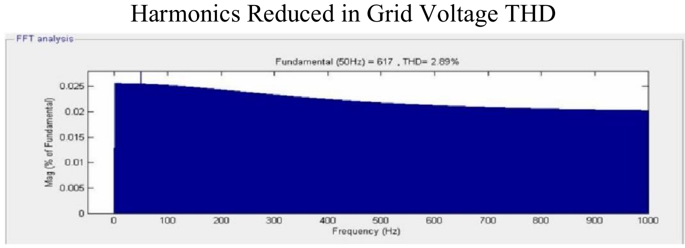
After Harmonics Reduced The Grid Voltage Vs Time



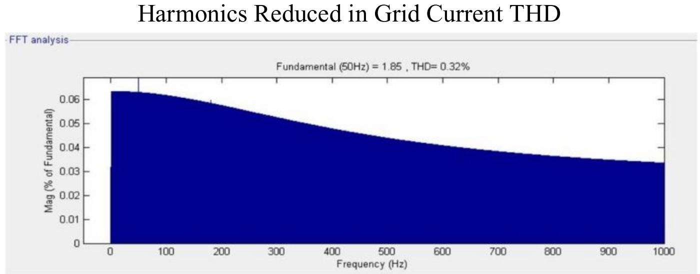
Grid Current Vs Time



Harmonics Reduced in Grid Voltage THD



Harmonics Reduced in Grid Current THD



VI. CONCLUSION

This project successfully demonstrates harmonic analysis and mitigation in a distributed generation system using Instantaneous Reactive Power (PQ) Theory implemented in MATLAB/Simulink 2023a. Simulation results clearly show that inverter-based DG and nonlinear loads introduce significant harmonic distortion, degrading power quality. By applying PQ theory–based control, effective harmonic compensation

is achieved, resulting in a substantial reduction in Total Harmonic Distortion (THD). The improved current waveforms and enhanced power quality validate the fast dynamic response and accuracy of the proposed method. Hence, the PQ theory–based approach proves to be a reliable and efficient solution for harmonic mitigation in modern distributed generation systems.

VII. FUTURE SCOPE

- Implementation of the proposed PQ theory–based harmonic mitigation technique on real-time hardware using DSP or FPGA platforms.
- Extension of the system to hybrid renewable energy sources such as solar–wind integrated DG systems.
- Performance analysis under unbalanced grid conditions and voltage sag/swell disturbances.
- Integration of advanced control strategies such asadaptive, fuzzy logic, or AI-based controllers for improved accuracy.
- Reduction of switching losses by employing optimised PWM or model predictive control techniques.
- Real-time monitoring and control using IoT-enabled smart grid architectures.
- Comparative analysis with other harmonic mitigation methods like SRF and repetitive control.
- Scalability study of the proposed approach for microgrid and utility-scale distributed generation systems.

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