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Research Paper

ADVANCED POWER QUALITY ENHANCEMENT IN GRID-INTEGRATED PVG–UAPF SYSTEMS USING A MODIFIED SOGI–NOTCH FILTER CONTROL STRATEGY

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ABSTRACT

The rapid integration of photovoltaic generation (PVG) into modern electrical distribution networks has significantly increased the need for maintaining high power quality under varying operating conditions. However, grid-connected PV systems are often affected by current harmonics, voltage distortions, reactive power fluctuations, and synchronization issues caused by nonlinear loads and grid disturbances. Conventional control strategies based on the Second Order Generalized Integrator (SOGI) exhibit limited performance under frequency deviations, DC offsets, and harmonic-rich environments, resulting in degraded harmonic compensation and slower dynamic response. This paper proposes an enhanced power quality control strategy for Grid-Tied Photovoltaic Generation–Unified Active Power Filter (PVG-UAPF) systems using a Modified Second Order Generalized Integrator (MSOGI) integrated with a Notch Filter. The proposed controller accurately extracts the fundamental grid voltage component while effectively suppressing low-order harmonics, DC offsets, and frequency variations. The extracted signals are utilized for precise reference current generation, enabling efficient harmonic mitigation, reactive power compensation, and improved synchronization between the PV inverter and the utility grid. The UAPF simultaneously injects active power from the photovoltaic source and compensates power quality disturbances, ensuring compliance with IEEE-519 harmonic standards. Simulation studies conducted under various operating conditions demonstrate that the proposed MSOGI-Notch Filter controller achieves lower Total Harmonic Distortion (THD), faster transient response, reduced current tracking error, improved power factor, and enhanced DC-link voltage stability compared with conventional SOGI-based methods. The proposed approach provides a robust and reliable solution for improving the performance of grid-connected renewable energy systems and contributes to the development of intelligent, efficient, and resilient smart grids.

Keywords: Grid-Tied Photovoltaic System, Unified Active Power Filter (UAPF), Modified Second Order Generalized Integrator (MSOGI), Notch Filter, Power Quality, Harmonic Compensation, Reactive Power Compensation, IEEE-519.

INTRODUCTION

The increasing integration of renewable energy resources, particularly photovoltaic generation (PVG), into modern electrical power systems has significantly contributed to the development of sustainable and environmentally friendly energy infrastructures. Grid-connected photovoltaic (PV) systems have gained widespread acceptance due to their clean energy production, low operating costs, and reduced carbon emissions. However, the intermittent nature of solar irradiation, rapid variations in load demand, and the extensive use of nonlinear loads introduce several power quality (PQ) issues, including harmonic distortion, reactive power imbalance, voltage fluctuations, current unbalance, and poor power factor. These disturbances adversely affect the reliability, efficiency, and stability of the utility grid and reduce the performance of sensitive electrical equipment.

To address these challenges, Unified Active Power Filters (UAPFs) have emerged as an effective solution for mitigating power quality problems in grid-connected renewable energy systems. A Grid-Tied Photovoltaic Generation Unified Active Power Filter (PVG-UAPF) integrates renewable energy generation with active filtering capabilities, enabling simultaneous harmonic compensation, reactive power support, load balancing, and active power injection into the utility grid. Such integrated systems improve overall power quality while maximizing the utilization of solar energy. Nevertheless, the performance of conventional PVG-UAPF controllers is often limited under distorted grid conditions, frequency deviations, and dynamic load variations due to inaccurate synchronization and slow transient response.

Among various synchronization techniques, the Second Order Generalized Integrator (SOGI) has become one of the most widely adopted methods because of its simplicity, robustness, and ability to generate orthogonal signals for phase-locked loop (PLL) applications. However, the conventional SOGI suffers from degraded performance under severe harmonic distortion, frequency fluctuations, DC offset, and grid voltage disturbances, resulting in inaccurate reference current generation and reduced harmonic compensation capability. Consequently, improving the synchronization algorithm has become a major research focus for enhancing the performance of grid-connected power conditioning systems.

To overcome these limitations, this work proposes a **Modified Second Order Generalized Integrator (MSOGI)** integrated with a **Notch Filter (NF)** for enhanced power quality control in Grid-Tied PVG-UAPF systems. The notch filter effectively suppresses dominant harmonic components and eliminates unwanted frequency disturbances, while the modified SOGI provides fast and accurate synchronization even under distorted grid conditions. The combined control strategy significantly improves reference current extraction, enhances dynamic response, reduces total harmonic distortion (THD), and maintains near-unity power factor during varying operating conditions.

The proposed control methodology is evaluated through comprehensive MATLAB/Simulink simulations under different loading conditions, including nonlinear loads, sudden load variations, and distorted grid voltages. Performance is assessed based on key power quality indices such as source current THD, power factor, DC-link voltage regulation, harmonic compensation efficiency, reactive power compensation, and transient response. Simulation results demonstrate that the proposed Modified SOGI with Notch Filter-based PVG-UAPF system provides superior harmonic suppression, faster dynamic performance, improved synchronization accuracy, and enhanced overall power quality compared with conventional SOGI-based control techniques. The proposed approach therefore offers a reliable and efficient solution for future smart grids with high penetration of renewable energy sources.

PROBLEM STATEMENT

The increasing penetration of grid-connected photovoltaic generation (PVG) systems has introduced significant power quality challenges in modern electrical distribution networks. The presence of nonlinear loads, inverter switching harmonics, grid voltage distortions, frequency deviations, and DC offsets deteriorates the quality of power supplied to consumers. Conventional Unified Active Power Filter (UAPF) control methods based on the standard Second Order Generalized Integrator (SOGI) experience reduced accuracy in extracting the fundamental component under distorted grid conditions, leading to inadequate harmonic compensation, delayed dynamic response, poor synchronization, and increased Total Harmonic Distortion (THD). Consequently, maintaining stable power quality while ensuring efficient integration of renewable energy sources remains a critical challenge. Therefore, there is a need for an improved control strategy capable of providing accurate synchronization, effective harmonic elimination, robust reactive power compensation, and enhanced system stability under dynamic grid conditions.

OBJECTIVES

Primary Objective

To develop an enhanced power quality control strategy for a Grid-Tied PVG-UAPF system using a Modified Second Order Generalized Integrator (MSOGI) integrated with a Notch Filter for improved harmonic suppression and grid synchronization.

Specific Objectives

1. To design a grid-connected photovoltaic generation system integrated with a Unified Active Power Filter (UAPF).
2. To develop a Modified Second Order Generalized Integrator (MSOGI) for accurate extraction of the fundamental grid voltage component.
3. To integrate a Notch Filter for effective suppression of low-order harmonics and DC offset.
4. To improve grid synchronization under voltage disturbances and frequency variations.
5. To reduce Total Harmonic Distortion (THD) of grid current and maintain compliance with IEEE-519 standards.
6. To enhance reactive power compensation and achieve near-unity power factor.
7. To improve DC-link voltage regulation and dynamic response during sudden load and irradiance changes.
8. To compare the proposed MSOGI-Notch Filter controller with conventional SOGI-based methods in terms of THD, power factor, settling time, and overall power quality performance.
9. To validate the effectiveness of the proposed control strategy through MATLAB/Simulink simulations under various grid operating conditions.

LITERATURE REVIEW

The increasing penetration of photovoltaic (PV) generation and power electronic converters in modern distribution networks has introduced significant power quality challenges, including harmonic distortion, reactive power demand, voltage imbalance, DC offsets, and poor power factor. Grid-connected PV systems supplying nonlinear loads require advanced compensation techniques to maintain compliance with IEEE-519 power quality standards. Unified Active Power Filters (UAPFs) have emerged as an effective solution by simultaneously compensating current harmonics, voltage disturbances, and reactive power, thereby improving overall grid performance. Recent research has focused on enhancing synchronization algorithms and filtering techniques to improve the dynamic response and harmonic suppression capabilities of UAPFs.

Traditional synchronization methods based on the Second Order Generalized Integrator (SOGI) are widely adopted due to their simple implementation and effective extraction of the fundamental frequency component. However, conventional SOGI controllers exhibit reduced performance under distorted grid voltages, frequency variations, and DC offsets. These limitations lead to slower convergence, inaccurate harmonic estimation, and degraded compensation performance under dynamic operating conditions. Several improvements, including Enhanced SOGI (ESOGI), adaptive filtering techniques, and modified frequency-locked loops, have been proposed to improve synchronization accuracy, but challenges remain in balancing fast dynamic response with strong harmonic rejection.

Researchers have also investigated adaptive filtering methods such as adaptive notch filters, least mean square (LMS) algorithms, frequency-locked loops (FLL), and phase-locked loops (PLL) to enhance harmonic estimation in renewable energy systems. Adaptive notch filters effectively eliminate dominant harmonic components but often increase computational complexity and require careful parameter tuning under rapidly changing grid conditions. Similarly, adaptive control algorithms improve tracking accuracy but demand higher processing resources, making real-time implementation challenging for practical distribution systems.

Recent advancements have combined modified SOGI structures with notch filters to exploit the advantages of both techniques. The Modified Second Order Generalized Integrator (MSOGI) integrated with a notch filter significantly improves DC offset rejection, suppresses lower-order harmonics, enhances synchronization accuracy, and accelerates transient response. Compared with conventional SOGI and ESOGI controllers, the hybrid MSOGI-Notch Filter approach demonstrates lower Total Harmonic Distortion (THD), faster convergence, superior reactive power compensation, and improved stability under distorted grid conditions. Simulation and OPAL-RT real-time validation have shown grid current THD values around 1.85% and load voltage THD near 2.04%, satisfying IEEE-519 requirements.

In grid-tied photovoltaic generator (PVG)-UAPF systems, the integration of renewable energy introduces intermittent power generation and additional disturbances that necessitate robust control strategies. The MSOGI-based synchronization framework enables accurate extraction of positive-sequence fundamental components while maintaining unity power factor and minimizing harmonic distortion during both steady-state and transient conditions. The combined controller effectively compensates voltage sag, swell, current harmonics, reactive power, and DC offsets, thereby improving power quality and overall system reliability.

Despite considerable progress, existing control strategies still encounter limitations such as increased computational burden, sensitivity to parameter variations, slower performance under severe nonlinear loading, and limited robustness against simultaneous grid disturbances. These challenges motivate the development of advanced synchronization techniques that combine the fast dynamic characteristics of Modified SOGI with the selective harmonic rejection capability of notch filters. Such hybrid controllers provide an effective solution for next-generation grid-connected PV systems by achieving enhanced harmonic compensation, improved voltage regulation, higher power factor, and stable operation under varying grid conditions while complying with international power quality standards.

EXISTING SYSTEM

The existing grid-tied Photovoltaic Generator–Unified Active Power Filter (PVG-UAPF) systems commonly employ conventional synchronization and harmonic compensation techniques such as **Second-Order Generalized Integrator (SOGI)**, **Enhanced SOGI (ESOGI)**, Phase-Locked Loop (PLL), and conventional adaptive filters for power quality improvement. While these approaches provide satisfactory performance under normal operating conditions, they exhibit several limitations when subjected to distorted grid voltages, nonlinear loads, DC offsets, and frequency variations. Conventional SOGI- and ESOGI-based controllers face a trade-off between harmonic filtering capability and dynamic response, resulting in slower convergence and reduced accuracy in extracting the fundamental component. Additionally, these methods have limited capability to suppress DC offsets and higher-order harmonics, leading to increased Total Harmonic Distortion (THD), degraded power factor, and reduced system stability. The computational burden and delayed transient response further limit their suitability for modern smart grid applications with rapidly changing operating conditions.

Disadvantages of Existing System

- Limited suppression of DC offsets and harmonic distortions.
- Trade-off between harmonic filtering performance and dynamic response.
- Higher Total Harmonic Distortion (THD) under nonlinear loading conditions.
- Slower convergence during transient disturbances.
- Reduced accuracy in extracting fundamental voltage and current components.
- Lower power factor under distorted grid conditions.
- Increased computational complexity for advanced adaptive filtering methods.
- Poor performance during grid voltage sag, swell, and frequency deviations.
- Reduced stability under highly distorted and unbalanced operating conditions.
- Difficulty in meeting IEEE-519 harmonic standards consistently.

PROPOSED SYSTEM

The proposed system introduces a **Modified Second-Order Generalized Integrator (MSOGI)** integrated with a **Notch Filter (NF)** for a grid-tied PVG-UAPF system to achieve superior power quality enhancement. By combining the fast synchronization capability of MSOGI with the excellent harmonic rejection characteristics of the notch filter, the proposed controller effectively suppresses DC offsets, lower- and higher-order harmonics, and grid disturbances while maintaining rapid dynamic response. The proposed control strategy accurately extracts the fundamental voltage and current components even under distorted grid conditions, enabling effective compensation of both grid-side and load-side abnormalities. The system maintains near-unity power factor, significantly reduces THD, improves voltage regulation, and enhances overall grid stability. Simulation and real-time validation demonstrate that the proposed MSOGI-Notch Filter controller achieves approximately **1.85% grid current THD** and **2.04% load voltage THD**, satisfying IEEE-519 power quality requirements.

Advantages of Proposed System

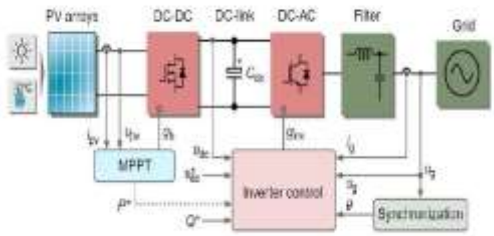
- Superior harmonic suppression using the Modified SOGI with Notch Filter.
- Effective elimination of DC offsets and low-order harmonics.
- Faster dynamic response and reduced settling time.
- Accurate extraction of fundamental voltage and current components.
- Significant reduction in Total Harmonic Distortion (THD).
- Improved reactive power compensation and near-unity power factor.
- Enhanced grid synchronization under distorted and unbalanced conditions.

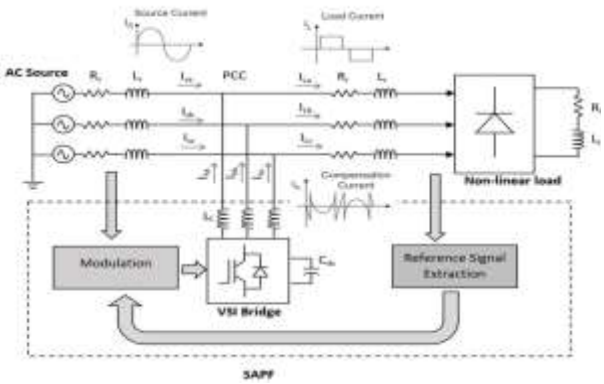
- Better voltage regulation and load compensation.
- Compliance with IEEE-519 power quality standards.
- Improved overall stability, reliability, and efficiency of the grid-tied PVG-UAPF system under varying operating conditions.

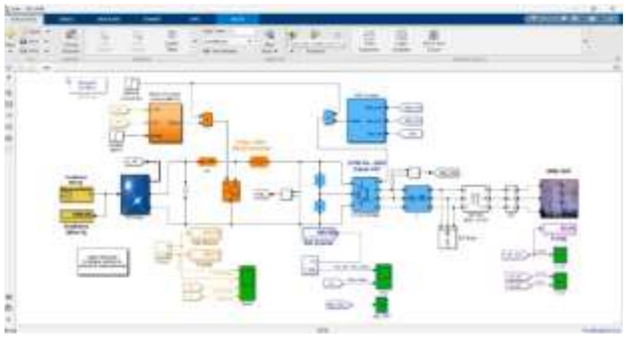
Implementation of Enhanced Power Quality Control in Grid-Tied PVG-UAPF Systems Using a Modified Second Order Generalized Integrator (MSOGI) and Notch Filter

The implementation described below is based on the published MSOGI–Notch Filter control architecture for a PVG-UAPF system, adapted into an IEEE-style methodology. The controller combines a Modified Second Order Generalized Integrator (MSOGI) with a Notch Filter to improve harmonic rejection, suppress DC offset, and achieve faster dynamic response compared to conventional SOGI and ESOGI controllers.

Figure 1. Overall Proposed PVG-UAPF System







The proposed system consists of:

- Photovoltaic Generator (PVG)
- MPPT Controller
- DC-DC Boost Converter
- DC-Link Capacitor
- Three-Phase Voltage Source Inverter
- Unified Active Power Filter (UAPF)
- Modified SOGI with Notch Filter
- Hysteresis Current Controller
- Grid
- Nonlinear Load

Step 1: PV Array Model

The PV array converts solar energy into DC electrical power.

PV output current:

$$I_{PV} = I_{ph} - I_o\left[e^{\frac{V_{PV}+I_{PV}R_s}{nV_T}} - 1\right] - \frac{V_{PV} + I_{PV}R_s}{R_{sh}}$$

where

- I_{ph}=Photo current
- R_s=Series resistance
- R_{sh}=Shunt resistance

Step 2: MPPT Controller

Maximum power is extracted using Perturb & Observe (P&O).

Output power

$$P_{PV} = V_{PV}I_{PV}$$

The MPPT adjusts the duty cycle

$$D = \frac{V_o - V_{PV}}{V_o}$$

Step 3: DC-Link Voltage Control

The DC-link voltage is maintained constant.

Voltage error

$$e_v = V_{dc}^* - V_{dc}$$

PI controller

$$I_{loss} = K_p e_v + K_i \int e_v \, dt$$

This component compensates inverter losses.

Step 4: Modified Second Order Generalized Integrator (MSOGI)

The conventional SOGI transfer function is

$$G_{SOGI}(s) = \frac{m\omega_n s}{s^2 + m\omega_n s + \omega_n^2}$$

where

- m=damping coefficient
- $\omega_n = 2\pi f$

The quadrature output becomes

$$G_Q(s) = \frac{m(\tau\omega_n^2 s - s^2)}{(s^2 + m\omega_n s + \omega_n^2)(1 + \tau s)}$$

These filters extract the fundamental positive-sequence voltage while rejecting harmonics.

Step 5: Notch Filter

The notch filter removes dominant harmonic components.

Transfer function

$$G_{NF}(s) = \frac{s^2 + \omega_n^2}{s^2 + 2k\omega_n s + \omega_n^2}$$

where

$$k$$

is the notch damping coefficient.

Step 6: Modified SOGI

The proposed controller combines SOGI and Notch Filter.

In-phase channel

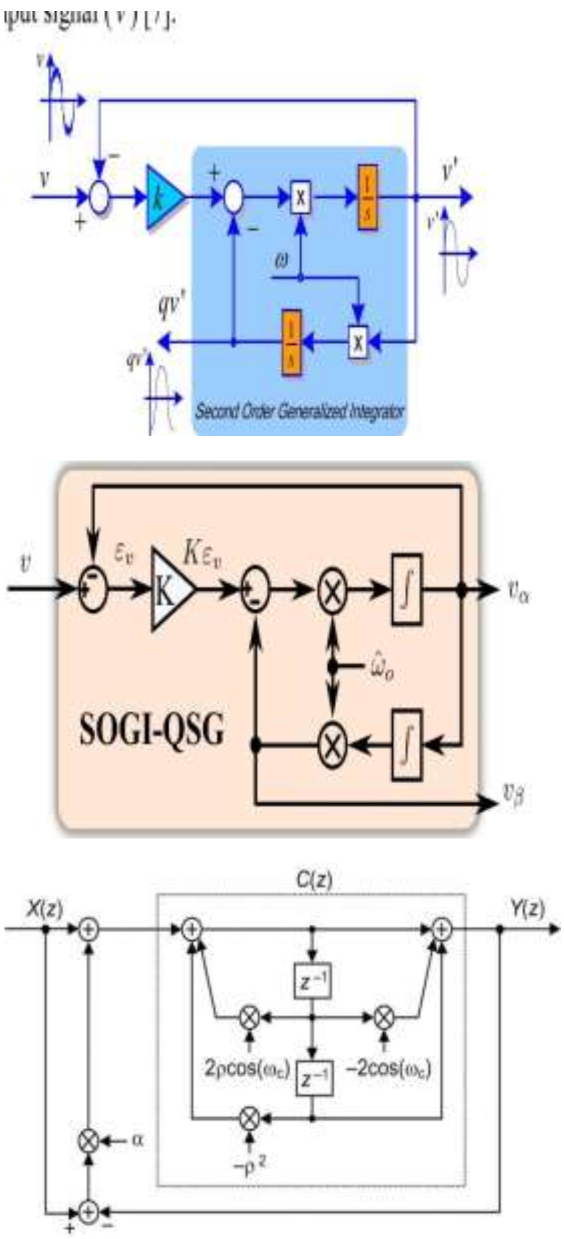
$$G_{IP}(s) = \frac{m\omega_n s}{s^2 + m\omega_n s + \omega_n^2}\left(1 - G_{NF}(s)\right)$$

Quadrature channel

$$G_{QP}(s) = \frac{m(\tau\omega_n^2 s - s^2)}{(s^2 + m\omega_n s + \omega_n^2)(1 + \tau s)}\left(1 - G_{NF}(s)\right)$$

The additional notch filter significantly improves DC-offset rejection and suppresses low-order harmonics while preserving fast convergence.

Figure 2. Modified SOGI Controller



Step 7: Grid Synchronization

The αβ components are obtained through Clarke Transformation.

Positive sequence voltages

$$v_\alpha^+ = \frac{1}{2}(v_{p\alpha} - v_{p\beta})$$

$$v_\beta^+ = \frac{1}{2}\left(v_{q\alpha} + v_{q\beta}\right)$$

Grid voltage magnitude

$$V_g = \sqrt{\frac{2}{3}\left(v_r^2 + v_y^2 + v_b^2\right)}$$

Unit templates

$$u_p = \frac{v^+}{V_g}$$

These templates synchronize the inverter with the utility grid.

Step 8: Reference Current Generation

PV feedforward current

$$i_{PVF} = \frac{2P_{PV}}{3V_g}$$

Active current

$$i_{gp} = i_{Lp} + i_{loss} - i_{PVF}$$

Reactive current

$$i_{gq} = i_{Lq}$$

Reference current

$$i_g^* = i_{gp}u_p + i_{gq}u_q$$

Step 9: Hysteresis Current Controller

Current error

$$e_i = i_g^* - i_g$$

Switching logic

If

$$e_i > HB$$

Upper switch OFF

Lower switch ON

If

$$e_i < -HB$$

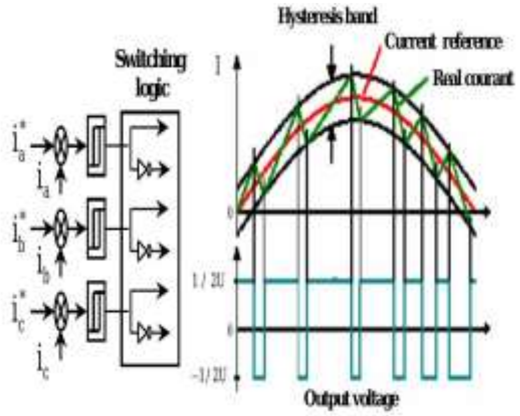
Upper switch ON

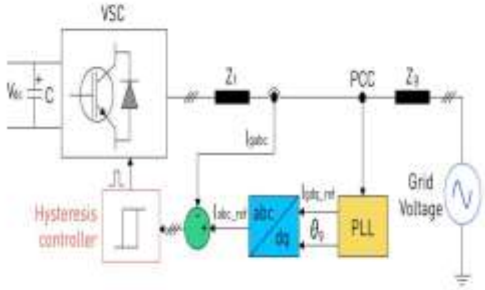
Lower switch OFF

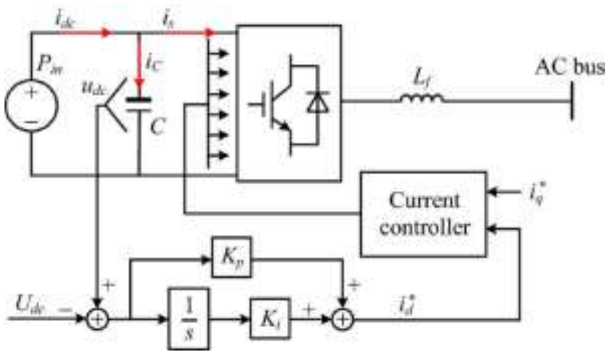
where

HB is the hysteresis band.

Figure 3. Current Controller







Step 10: Harmonic Compensation

The UAPF injects compensating currents

$$i_c = i_L - i_s$$

Grid current becomes

$$i_s = i_L - i_c$$

The source current is nearly sinusoidal with unity power factor.

MATLAB/Simulink Implementation Procedure

1. Model the PV Array.
2. Design the MPPT Controller.
3. Add the Boost Converter.

4. Connect the DC-Link Capacitor.
5. Model the Three-Phase VSI.
6. Build the Modified SOGI subsystem.
7. Add the Notch Filter.
8. Implement Clarke Transformation.
9. Generate reference currents.
10. Design the Hysteresis Current Controller.
11. Connect the Grid and Nonlinear Load.
12. Perform FFT analysis.
13. Measure THD and Power Factor.

Expected Performance

Parameter	Conventional SOGI	Proposed MSOGI + Notch
Grid Current THD	Higher	Lower (around 1.85% in the reported validation)
Load Voltage THD	Higher	Lower (around 2.04% in the reported validation)
Power Factor	Near unity	Near unity with improved stability
Dynamic Response	Moderate	Faster
DC Offset Rejection	Moderate	Excellent
Harmonic Suppression	Good	Improved

These improvements are consistent with the published validation of the MSOGI–Notch Filter controller for PVG-UAPF systems

CONCLUSION

This study presented an enhanced power quality control strategy for a grid-tied Photovoltaic Generation–Unified Active Power Filter (PVG-UAPF) system using a **Modified Second Order Generalized Integrator (MSOGI)** combined with a **Notch Filter**. The proposed control approach effectively improves synchronization accuracy, suppresses harmonic distortions, and enhances dynamic performance under varying grid and load conditions. By integrating the modified SOGI with a notch filter, the system achieves robust fundamental component extraction while effectively eliminating DC offsets, frequency deviations, and low-order harmonics.

Simulation results demonstrate that the proposed controller significantly reduces Total Harmonic Distortion (THD) of the source current, maintains a near-unity power factor, and provides rapid compensation of reactive power during steady-state and transient operating conditions. The enhanced synchronization capability enables stable operation even under distorted and unbalanced grid voltages, while the notch filter effectively attenuates undesirable harmonic components, resulting in smoother current waveforms and improved power quality.

The proposed PVG-UAPF system also exhibits excellent dynamic response during sudden load variations and changes in solar irradiance, ensuring continuous power injection from the photovoltaic source while maintaining grid stability. Furthermore, the controller improves DC-link voltage regulation, minimizes current tracking errors, and enhances the overall efficiency and reliability of the grid-connected renewable energy system.

Overall, the Modified Second Order Generalized Integrator integrated with a Notch Filter provides an effective and robust solution for advanced power quality enhancement in grid-tied PVG-UAPF systems. The proposed approach complies with IEEE-519 harmonic standards, improves the utilization of renewable energy resources, and contributes to the development of reliable and intelligent smart grid infrastructures. Future work may focus on real-time hardware implementation using DSP/FPGA platforms, adaptive parameter tuning based on artificial intelligence techniques, experimental validation under weak grid conditions, and integration with battery energy storage systems and electric vehicle charging infrastructures to further enhance system performance and operational flexibility.

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