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Enhancement of Power Quality using Solar Photovoltaic System with Universal Active Filtering

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ABSTRACT
This work proposes a unique method for controlling the universal active power filter integrated with PV array system (UAPF-PV) using a proportional resonant controller and a second order sequence filter. The active component of the distorted load current is estimated using a second order sequence filter, and this value is then used to generate a reference signal for a shunt active filter at the instant of zero crossing of the load voltage. With fewer mathematical calculations, the suggested method extracts the essential active component of distorted and unbalanced load currents with good accuracy. In addition to enhancing power quality, the system produces clean energy thanks to the PV array system that is built into its DC-bus. The benefits of distributed generation and power quality improvement are combined in the UAPF-PV system. MATLAB/Simulink is used to analyze the system performance under a range of disturbance scenarios, including changes in solar irradiation, load unbalancing, and PCC voltage rise and fall.

Keywords: *power quality, universal active power filter, adaptive filtering, photovoltaic system, maximum power point tracking, sequence filter.*

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I. INTRODUCTION

The integration of renewable energy sources, such as solar photovoltaic and wind energy systems, into the grid has been receiving increasing attention [1]. This trend has been driven by advancements in reliable and efficient power electronics, improved efficiency of PV panels, and declining manufacturing costs. However, the rising penetration of these intermittent renewable energy sources has led to greater voltage fluctuations at the point of common coupling (PCC), particularly in low voltage distribution systems. Another significant issue in modern distribution systems is the widespread use of nonlinear power electronic systems, which draw highly distorted currents. These distorted currents can cause voltage distortion at the PCC, depending on the current magnitude and grid impedance [2]. Additionally, these loads contribute to losses in feeders and distribution transformers and are sensitive to voltage dips/rises at the PCC, leading to frequent tripping and increased maintenance costs. Consequently, a primary requirement of modern distribution systems is the integration of renewable energy systems alongside power quality improvement.

Recent advancements have focused on multifunctional renewable energy systems that provide clean energy while addressing power quality issues from both the load side and the PCC side. A solar photovoltaic integrated distribution static compensator (PV-DSTATCOM) has been proposed, offering the dual benefits of power generation from renewable sources and compensation for load current harmonics generated by nonlinear loads [3]. Similarly, a single-phase multifunctional solar energy conversion system has been developed, combining clean energy generation with active filtering for a single-phase distribution system [4]. Another innovation is a variable DC-link voltage grid-interfaced converter for three-phase supply systems, which combines clean energy generation, active filtering, and an adjustable DC-link voltage to improve efficiency and harmonic compensation of load current [5].

While much research has focused on shunt-compensated systems integrating clean energy with active filtering, there has been a growing interest in incorporating distributed generation capabilities with universal active power filters. A unified power quality conditioner (UPQC), also known as a universal active power filter (UAPF), integrated with PV systems, and has been proposed [6, 7]. The UAPF system enhances both voltage and current quality by incorporating shunt and series active power filters. However, the shunt active power filter requires reactive power to regulate the PCC voltage, making it challenging to simultaneously achieve voltage regulation and maintain unity power factor (UPF) for grid current. The solar-integrated UAPF (UAPF-PV) system addresses this by regulating load voltage while injecting or drawing grid current at UPF.

The UAPF-PV has two main functions: mitigating voltage and current quality issues and injecting PV array power into the grid. Accurate and fast reference signal generation for the shunt and series active filters is crucial for these functions. Extracting the fundamental component of a distorted signal is a key task in reference generation, with commonly used control algorithms including the p-q and d-q theory reference frame transform techniques [2]. However, these techniques involve multiple transformations and their dynamic performance can degrade under unbalanced load conditions.

Advanced techniques for fundamental component extraction include the least mean square (LMS) technique and adaptive notch filter (ANF) [8, 9], which are inherently single-phase and require complex structures and operations to extract fundamental positive sequence components. The damped SOGI technique has also been proposed for reference signal generation in PV systems, extracting the fundamental active component of load current using damped SOGI filters [10]. Additionally, inherently three-phase filters, such as sequence filters and complex filters, can directly extract fundamental positive sequence components [11]. Other advanced techniques include adaptive linear element (ADALINE) and wavelet transforms [12-14], which, despite their accuracy, impose a higher computational burden.

This work proposes a novel control technique for the UAPF-PV system, utilizing proportional resonant control for the series active filter and a second-order sequence filter for the shunt active filter [11]. The second-order sequence filter estimates the fundamental positive sequence component of distorted load current, which is then sampled to extract the magnitude of the fundamental active component of load current. These components are used to generate reference signals for the shunt active filter operation, enhancing precision in extracting the active component of distorted load current with good dynamic performance. The series active filter regulates load voltage by introducing the necessary voltage in series with the PCC voltage during voltage dips and rises.

II. PROPOSED CONTROL TECHNIQUE

In this work, a novel control technique is introduced for the UAPF-PV system, utilizing proportional resonant control for the series active filter and a second-order sequence filter [11] for the shunt active filter. The second-order sequence filter estimates the fundamental positive sequence component of the distorted load current. By sampling these fundamental positive sequence components at appropriate moments, the magnitude of the fundamental active component of the load current is extracted. These values are then used to generate reference signals for the shunt active filter's operation. This method enhances the precision of extracting the active component of the distorted load current, providing good dynamic performance. The series active filter regulates load voltage during PCC voltage dips and rises by introducing the necessary voltage in series with the PCC voltage.

The major focus and advantages of this research work are summarized as follows:

Multifunctional Topology: Integrates clean energy generation with comprehensive power quality improvement.

Load Protection: Shields sensitive loads from PCC voltage dips/rises while compensating for nonlinear current drawn by the load.

Enhanced Accuracy: Employs a second-order sequence filter combined with zero-cross detection technique for improved accuracy in extracting the load current active component across all three phases using a single sample and hold operation.

Performance Evaluation: Assesses both dynamic and steady-state performance of the UAPF-PV system under conditions such as PCC voltage dips/rises, unbalanced load removal, and variations in solar irradiation intensity.

The system's response has been validated on an experimental prototype. The control algorithm is digitally implemented in a DSP-based controller, which generates the necessary control signals for the UAPF-PV system. The steady-state performance of the system is verified to ensure compatibility with the IEEE-519 standard. Additionally, the dynamic performance of the system is analyzed under various conditions, including changes in PCC voltages, unbalanced nonlinear loads, and variations in solar irradiation.

III. STRUCTURE OF UAPF-PV SYSTEM

Figure 1 presents the structure of the UAPF-PV system. The topology features a three-phase double-stage configuration, where a boost DC-DC converter interfaces the PV array with the DC-bus of the UAPF. The compensators are connected to the distribution system through filter inductors. The series active filter introduces voltage in series with the PCC via series transformers. Ripple filters, which consist of resistors and capacitors in series, are used in both the series and shunt voltage source converters (VSCs) to filter out higher-order harmonics generated by the switching actions of the series and shunt active filters.

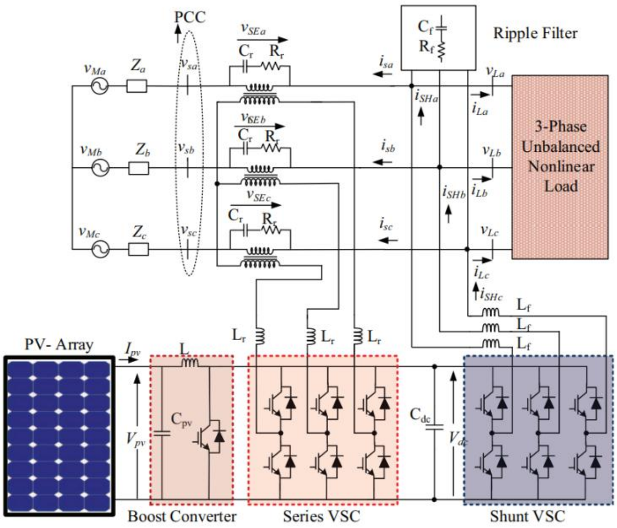


Figure 1: System configuration of UAPF-PV

IV. OBJECTIVES AND CONTROL ASPECTS OF UAPF-PV SYSTEM

The primary objective of the UAPF-PV system is to compensate for harmonics caused by nonlinear loads and protect sensitive loads from PCC voltage dips and rises. In addition to enhancing power quality, the UAPF-PV system generates clean energy by supplying PV power to the distribution system. The control aspects of the shunt active filter and the series active filter are explained further as follows:

Shunt Active Filter Control: The shunt active filter is responsible for compensating the harmonic currents drawn by nonlinear loads. It ensures that the current drawn from the grid remains sinusoidal and at unity power factor.

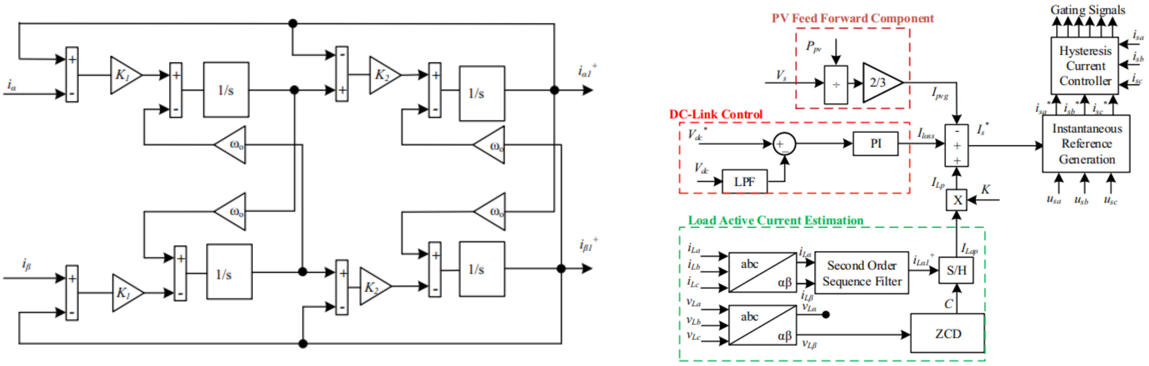
Series Active Filter Control: The series active filter manages the voltage quality at the PCC. It injects or absorbs the necessary voltage in series with the PCC to mitigate voltage sags, swells, and other disturbances, thereby protecting sensitive loads.

A. Control Techniques Of UAPF-PV System

Shunt Active Filter Control:

The block diagram for the control of the shunt active filter is presented in Figure 2(b). In this control structure, a second-order sequence filter is employed to extract the fundamental positive sequence component of the distorted load current. The structure of the second-order sequence filter is shown in Figure 2. Sequence filters are inherently suitable for three-phase systems as they extract the fundamental positive sequence components. The open-loop transfer function of the second-order sequence filter and detailed analysis regarding the filter gain selection is provided in [11]. The shunt compensator's reference signal is essentially the desired grid current, meaning it should be balanced and at unity power factor. The grid current magnitude consists of three fundamental active components: grid current due to fundamental active load power (I_{Lp}), grid current corresponding to PV power (I_{pvg}), and the loss component corresponding to losses from switching actions and filters. This is expressed as:

$$I^*_s = I_{Lp} - I_{pvg} + I_{loss} \qquad \dots (1)$$



(a) **Structure of second order sequence filter** (b) **Shunt Compensator Control Structure**

Figure 2: Shunt Compensator Control Based on second order sequence filter

The fundamental frequency positive sequence component (FPSC) of the load current is estimated using the second-order sequence filter. Once the FPSC of the load current is estimated, the magnitude corresponding to the load active current is extracted by sampling the current at the zero crossing of the β component of the load voltage. Since a magnitude-invariant transformation is used in the Clark transform of load voltages and currents, the sampled value of the FPSC of the load current corresponds to the magnitude of the active component of the load current. When the PCC voltage decreases and the load remains constant, the grid current drawn increases to maintain power balance. The equivalent grid current corresponding to load active power is given by:

$$I_{Lp} = K \times I_{Lap} \qquad \ldots (2)$$

where

$$K = \frac{V_L}{V_s} \qquad \ldots (3)$$

Here, (V^*_L) is the magnitude of the reference load voltage and (V_s) is the magnitude of the PCC voltage.

The grid current magnitude corresponding to PV power is obtained by:

$$I_{pvg} = \frac{2}{3}\frac{P_{pv}}{V_s} \qquad \ldots (4)$$

where (P_{pv}) is the PV array power.

A proportional-integral (PI) controller regulates the DC-bus voltage of the UAPF-PV to the desired value. The controller provides the component corresponding to losses in the converter and filter circuits. The control equation for the DC-link PI controller is:

$$I_{loss}(n) = I_{loss}(n-1) + K_p(\Delta e_{vdc}) + K_i\, e_{vdc}(n) \qquad \ldots (5)$$

where (I_{loss}) is the output of the PI controller, (K_p) and (K_i) are the gains of the PI controller, (Δe_{vdc}) is the difference in DC-link voltage error between the present and past sampling times, and (e_{vdc}) is the DC-link voltage error. The magnitude of the PCC voltage (V_s) and the PCC voltage in-phase templates are extracted using the following equations.

$$V_s = \sqrt{\frac{2}{3}(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)} \qquad \ldots (6)$$

$$u_{sa} = \frac{v_{sa}}{V_s},\ u_{sb} = \frac{v_{sb}}{V_s},\ u_{sc} = \frac{v_{sc}}{V_s} \qquad \ldots (7)$$

The reference magnitude is multiplied by the templates of PCC voltages to generate the instantaneous shunt active filter reference currents:

$$i_{sa}^* = I_s^* \times u_{sa},\ i_{sb}^* = I_s^* \times u_{sb},\ i_{sc}^* = I_s^* \times u_{sc} \qquad \ldots (8)$$

The error between (i_{sa}^*, i_{sb}^*, i_{sc}^*) and (i_{sa}, i_{sb}, i_{sc}) is passed through a hysteresis controller, which generates gating pulses for controlling the shunt compensator.

Series Active Filter Control:

The control configuration of the series active filter is presented in Figure 3. The series active filter is controlled in the α-β domain to ensure that the PCC and load voltages are in phase. The instantaneous reference load voltages are generated as:

$$v_{La}^* = V_L^* \times u_{sa} \qquad \ldots (9)$$

$$v_{Lb}^* = V_L^* \times u_{sb} \qquad \ldots (10)$$

$$v_{Lc}^* = V_L^* \times u_{sc} \qquad \ldots (11)$$

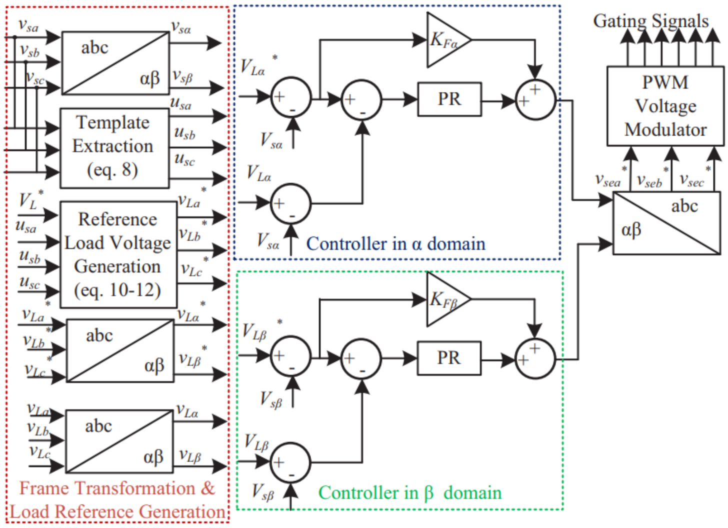


Figure 3: Series Active Filter Control Structure

These reference load voltages are then converted to the α-β domain. For the control of the series active filter, two sets of damped proportional controllers along with a feedforward path are implemented for the α and β components. In the α domain, the reference series active filter voltage ($v_{se\alpha}^{*}$) is obtained as:

$$v_{se\alpha}^{*} = v_{L\alpha}^{*} - v_{s\alpha} \qquad \ldots (12)$$

The series active filter voltage ($v_{se\alpha}$) is obtained as:

$$v_{se\alpha} = v_{L\alpha} - v_{s\alpha} \qquad \ldots (13)$$

The error between ($v_{se\alpha}^{*}$) and ($v_{se\alpha}$) is given to a damped proportional resonant (PR) controller. The advantage of the PR controller is that it has a very high gain for the designed frequency, and its gain can be adjusted based on the cut-off frequency. The output of the PR controller is added to the output of the feedforward path. The major component of the control signal is obtained from the feedforward path, while the PR controller accounts for drops in filter circuits not considered in reference calculations. Similarly, control functions are implemented in the β domain. The control signals obtained in the α-β domain are then converted back to the stationary frame and passed to a PWM modulator to generate gating pulses for the series active filter.

B. Boost Dc-Dc Converter and MPPT Algorithm

The boost DC-DC converter is designed to operate the PV array at its peak power point. To achieve this, a Maximum Power Point Tracking (MPPT) algorithm is employed to control the boost converter. Common MPPT algorithms include the Perturb and Observe (P&O) technique, incremental conductance (INC) technique, and fractional open-circuit voltage method [15]. In this work, the P&O technique is used to track the maximum power operating point of the PV array. The algorithm measures the current and past power and voltage of the PV array and generates the appropriate duty ratio for controlling the boost converter.

The duty ratio for the next cycle in the P&O technique is determined by:

$$d_{boost}(n + 1) = d_{boost}(n) + D_{step}.\ \mathrm{Sgn}(\Delta P_{pv}) \qquad \ldots (14)$$

where, $d_{boost}(n + 1)$ is the duty ratio for the next MPPT sampling interval of the boost converter,($d_{boost}(n)$) is the duty ratio in the current MPPT sampling interval,(D_{step}) is the duty ratio step size, and (ΔP_{pv}) is the difference in PV array power between the current and past sampling intervals.

C. Evaluation of Dynamic Performance of UAPF-PV System

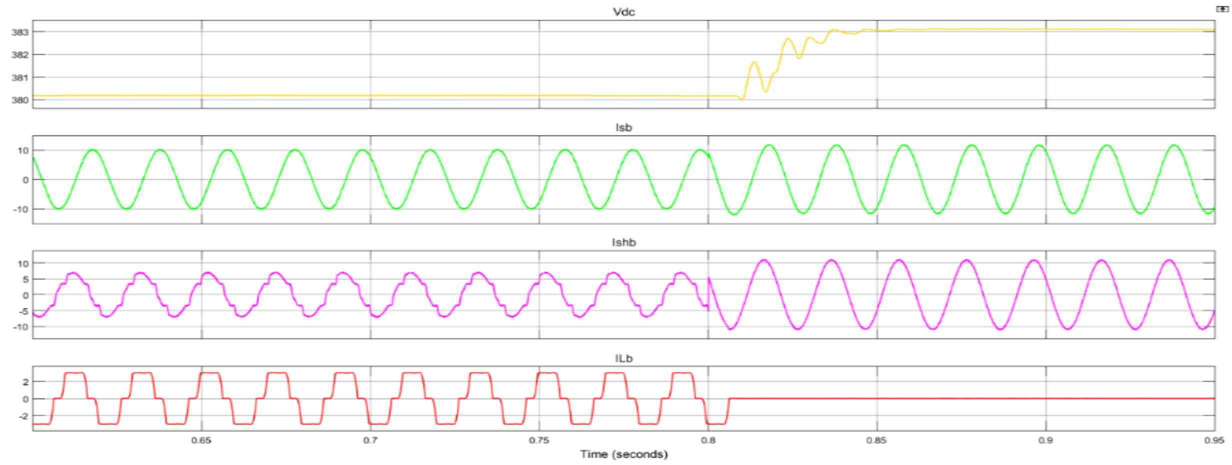
To evaluate the dynamic performance of the UAPF-PV system, it is subjected to typical disturbances encountered in distribution systems, and the system's response is recorded by taking the system parameter values from Table I.

Table 1: Experimental Parameters

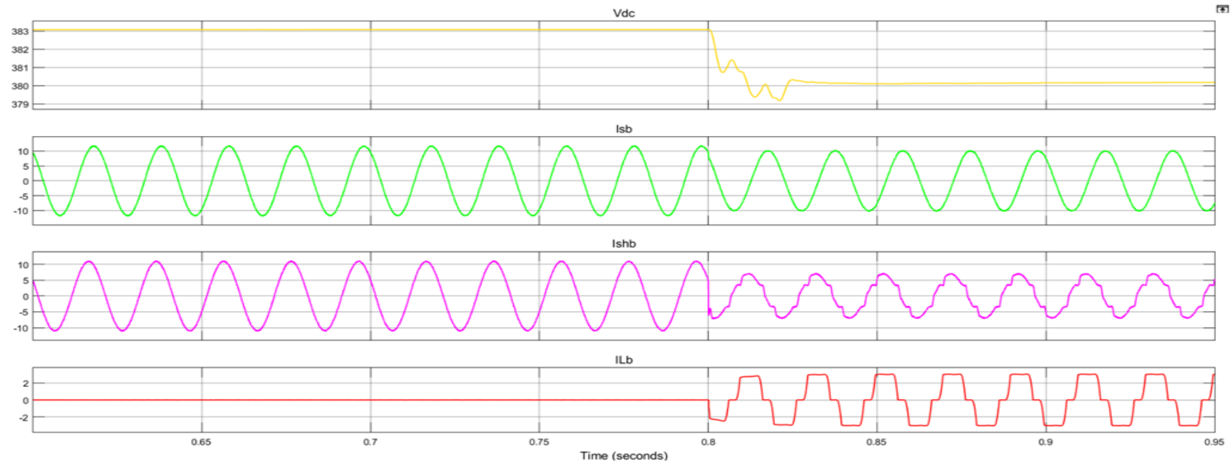
PARAMETER	VALUE	PARAMETER	VALUE
PCC voltage	V_s = 220 V, f = 50 Hz	Shunt Active Filter Inductor	L_s = 4 mH
Nonlinear Load	Rectifier with R-L: 1.12 kW	series active filter Inductor	L_{se} = 0.5 mH
DC-bus Voltage	V_{dc} = 380 V	Sampling Time	T_s = 33.33 µs
DC-bus Capacitor	C_{dc} = 3.3 mF	DC-bus PI contoller	K_p = 0.2, K_i = 0.15
Boost Inductor	L = 4mH	Second Order Sequence Filter Gains	K_1=100, K_2=250
PV array Capacitor	C_{pv} = 100µF	series active filter PR controller	$K_{P\,\alpha-\beta}$ = 1;
LPF cut off frequency	f_{LPF} = 10 Hz	PV Array	P = 4.0 kW, V_{oc} = 350 V, I_{sc} = 14 A V_{mpp} = 301 V, I_{mpp} = 13.272 A
$K_{R-\alpha-\beta}$ = 600, K_{FF} = 1			

Load Disturbance Condition:

The system's performance under load disturbance conditions is illustrated in Figure 4. In this test, the load in phase 'b' is completely removed or added, and the effect on the grid current in the same phase is observed. Figure 4(a) and Figure 4(b) depict the performance of UAPF-PV under load removal and load addition in phase 'b', respectively. The signals captured include (Vdc), (isb), (ishb), and (iLb), where all current signals are from phase 'b'. The shunt active filter of the UAPF-PV maintains the grid current as sinusoidal while the load current remains unbalanced and nonlinear. The DC-link voltage is regulated. There is an increase in (isa) due to the reduction in load demand while PV power generation remains constant.



(a) Performance under Load Removal

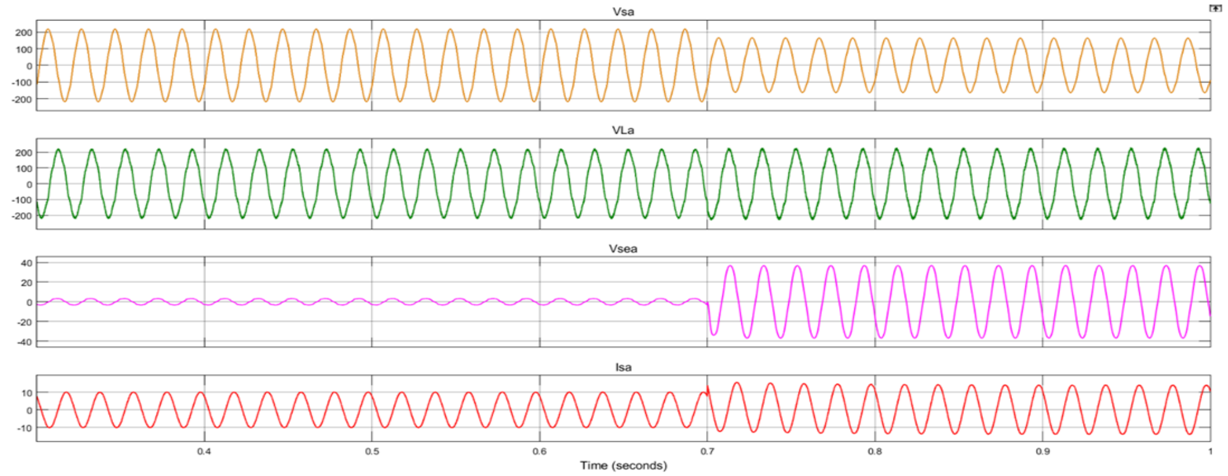


(b) Performance under Load Addition

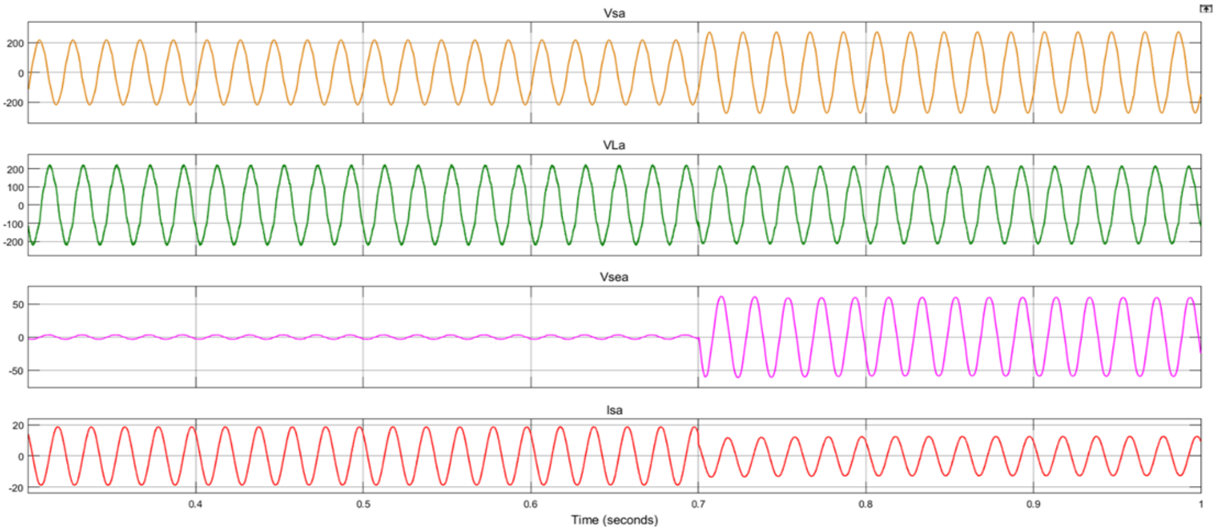
Figure 4: Dynamic Performance under load Unbalance Condition

PCC Voltage Dip/Rise Condition:

The behavior of UAPF-PV under PCC voltage dip and rise conditions is presented in Figure 5. Figure 5(a) and Figure 5(b) show the performance of UAPF-PV during voltage dip and rise conditions, respectively. The signals captured include (v_{sab}), (v_{Lab}), (v_{seab}), and (i_{sa}). During a voltage dip, the PCC voltage reduces to 0.75 pu, while during a voltage swell, the PCC voltage rises to 1.25 pu. The series active filter injects the appropriate voltage to maintain the load voltage at the desired value of 220 V, ensuring the load voltage remains in-phase with the PCC voltage.



(a) Performance under PCC Voltage Dip Condition



(b) Performance under Swell Condition

Figure 5: Dynamic Performance under PCC Voltage dip/rise Condition

Solar Irradiation Variation:

The system behavior under variation in solar irradiation is depicted in Figure 6. A solar array simulator produces the desired solar array characteristics. The performance of the system is captured under conditions when solar radiation intensity decreases from 1000 W/m² to 500 W/m². It is observed that the DC-link voltage remains stable under both conditions. The MPPT performance under irradiation conditions of 500 W/m² and 1000 W/m² is shown in Figure 6. The MPPT efficiency is above 99% under both these conditions.

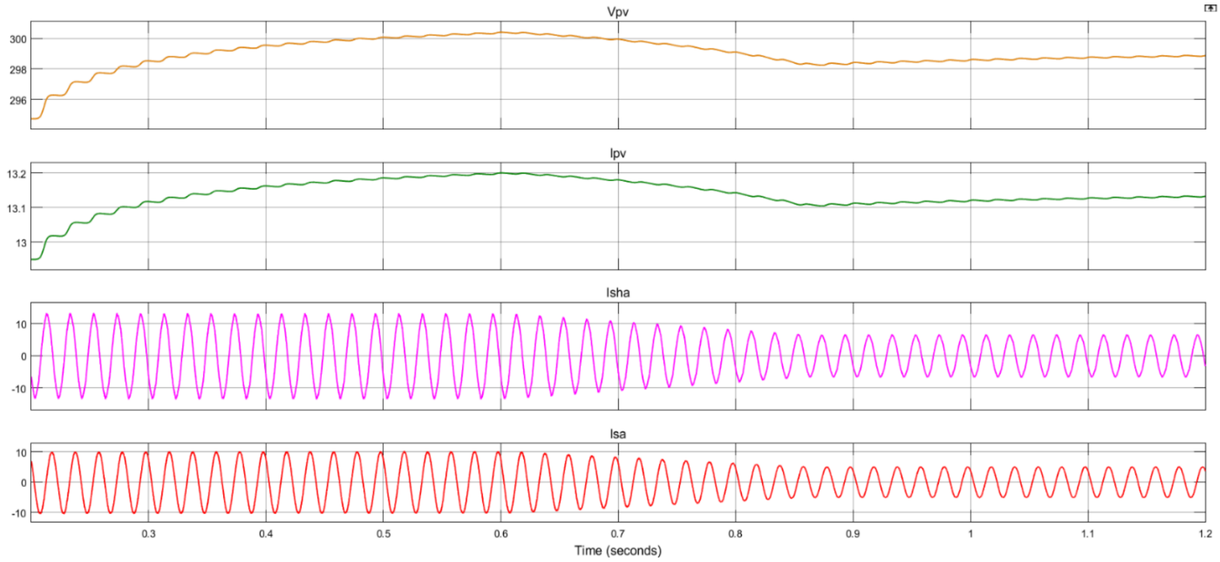


Figure 6: UAPF-PV Response under irradiation Change Condition

D. Control Signals of UAPF-PV

The control signals of the UAPF-PV system are illustrated in Figs. 7 and 8.

Second Order Sequence Filter Signals:

Figure 7 displays key signals within the second order sequence filter. The signals captured include the phase 'b' load current, the load current in the (α- β) domain ($i_{L\alpha}$, $i_{L\beta}$), and the α component of the fundamental positive sequence component ($i_{L\alpha}$+). It is observed that when the load in phase 'b' is instantaneously removed, the second order sequence filter extracts the fundamental positive sequence component (FPSC) of the load current within a cycle.

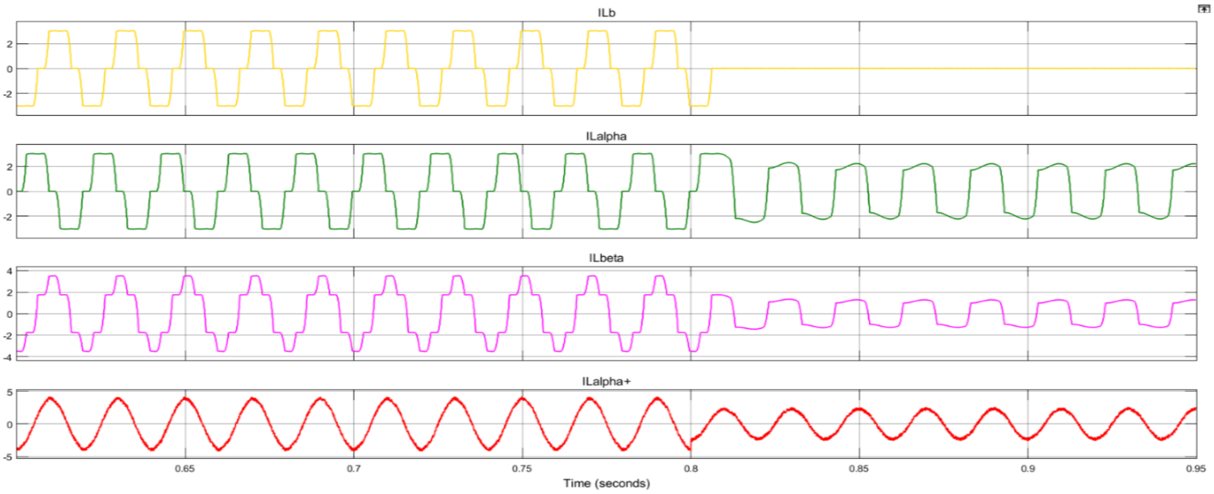
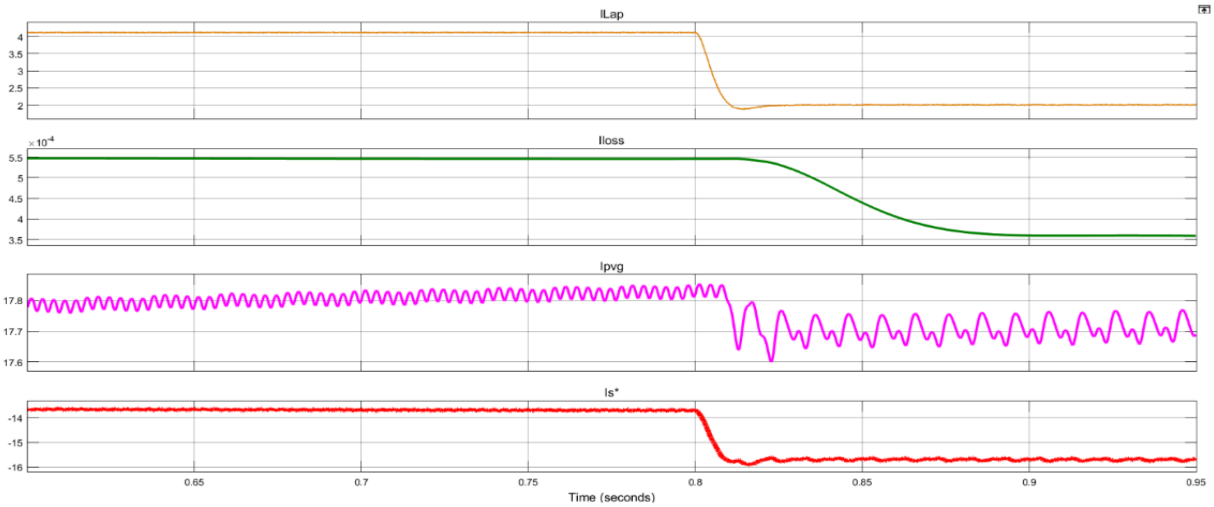
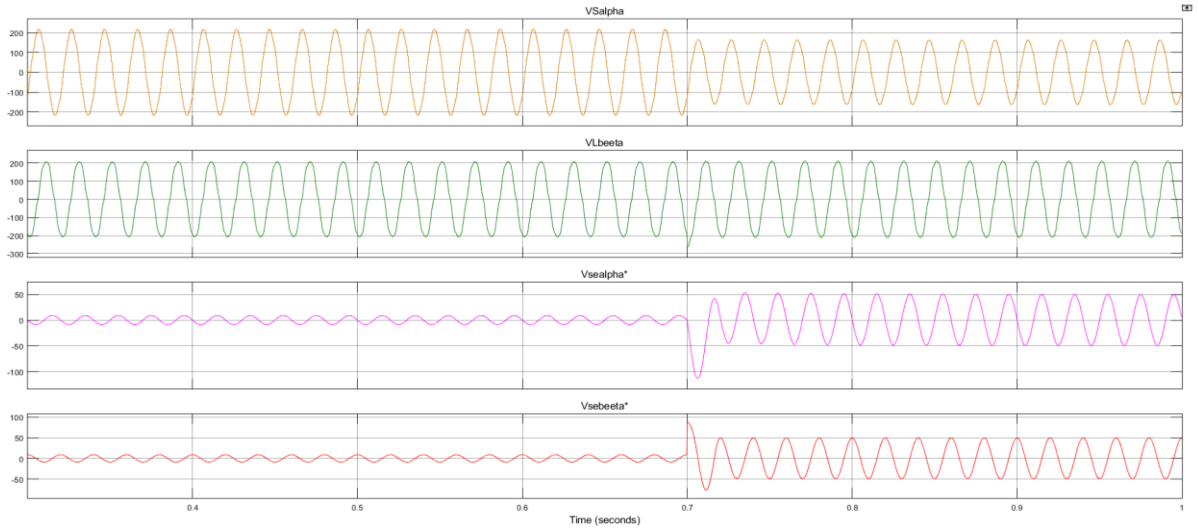


Figure 7: Salient Signals in Extraction of Fundamental Positive Sequence Load Current

Shunt and Series Active Filter Control Signals:



(a) Salient Signals in Shunt Active Filter Control



(b) Salient Signals in series active filter Control
Figure 8: Salient Signals in UAPF-PV Control

Shunt Active Filter Control (Figure 8a): This figure shows the critical internal signals for reference current generation for the shunt active filter. The captured signals include the grid current corresponding to load active current (K × I_{La}), loss component (I_{loss}), grid current corresponding to PV array power injection (I_{pvg}), and the magnitude reference grid current (Is*), which also serves as the reference for the shunt active filter. The reference current (Is*) is calculated based on Eqn.1. The signals are recorded when the load in phase 'b' is removed, showing a decrease in load current, which results in an increase in (Is*) as derived from Eqn 1.

Series Active Filter Control (Figure 8b): This figure presents the crucial internal signals for the control of the series active filter during a reduction in PCC voltage from 220 V to 160 V. The reference signals are generated immediately upon detecting a dip in PCC voltage.

These control signals illustrate the effective response of the UAPF-PV system to dynamic changes in load and PCC voltage, maintaining power quality and stability. The overall grid current Total harmonic distortion (THD) is being reduced from 20% to approximately less than 5% in all conditions as per the IEEE-519 standard of Harmonic Control in Electric Power Systems given in [16].

V. CONCLUSION AND FUTURE SCOPE

The performance of a novel control technique for a solar PV system with universal active filtering has been assessed. This technique utilizes a second order sequence filter combined with a zero-cross detection method to extract the fundamental positive sequence component of the nonlinear load current. The series active filter is managed using a proportional resonant controller implemented in the α- β domain, along with a feedforward component. The system demonstrates satisfactory performance under various disturbances, such as PCC voltage dips/rises, changes in solar radiation, and load disturbances.

In addition to enhancing power quality, the system also supplies power from the PV array to the grid. A comparison of the proposed control method indicates that the system achieves improved performance relative to conventional control techniques, while maintaining a slightly lower computational burden. This system successfully integrates distributed generation and enhances the power quality of the distribution system.

The future scope of this project involves exploring advanced methodologies and techniques to enhance the performance and efficiency of solar photovoltaic (PV) systems. Advanced Maximum Power Point Tracking (MPPT) methods, such as Fuzzy Logic Controllers (FLC), ANFIS, and neural networks, can significantly improve efficiency and accuracy. Various machine learning algorithms, including support vector machines, decision trees, and reinforcement learning, offer improved adaptability and optimization for MPPT. For DC link control, advanced controllers like FLC, Model Predictive Control (MPC), Sliding Mode Control (SMC), and H-infinity (H∞) control should be investigated to provide better dynamic response, robustness, and stability. Hybrid control strategies, combining techniques like neural networks with traditional controllers, can achieve optimal control and regulation of DC link voltage. Implementing these advanced techniques in real-time systems will provide valuable insights into their performance and highlight areas for further optimization. Additionally, integrating PV systems with other renewable energy sources and storage solutions can enhance the reliability and stability of the power supply, ensuring consistent energy output. Developing smart grids and microgrids will facilitate efficient energy distribution, balance supply and demand, and improve the overall efficiency and resilience of the power network.

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