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A Control Strategy for Three-Phase PV-Grid Inverter with Active Filtering under Various Load Conditions

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Abstract: A unified dq-frame-based control strategy for a three-phase grid-connected photovoltaic (PV) inverter that serves as a flexible power-conditioning device is presented in this study. The proposed technique enables a multifunctional inverter design to simultaneously inject active power, reduce harmonic current, and compensate for reactive power. This differs from earlier systems that required multi-conversion structures or independent active power filters. The method is governed by the synchronous reference frame. It uses the DC link's instantaneous power balance to regulate the flow of bidirectional active power when there is either too much or too little PV power. The load current is divided into its basic and oscillating components using the dq-frame instantaneous power representation. Because of this, it can handle loads that are not straight lines or that combine curves and straight lines. Only the reactive and harmonic currents fluctuate, and the grid interface's unity power factor. The proposed approach has been tested under a wide range of conditions, including nonlinear, capacitive, and inductive loading. The findings demonstrate that regardless of how the system is configured, the grid current remains sinusoidal and in sync with the grid voltage. Additionally, the inverter side has very little harmonic distortion. These findings demonstrate that adding features that directly enhance the power quality of grid-connected PV inverters is simple and efficient with the suggested control framework.
Keywords: PV-grid systems, Park Transformation, Active filtering, Reactive power compensation, Harmonic mitigation, dq control.

I. INTRODUCTION

The rapid global shift toward low-carbon energy systems has significantly accelerated the deployment of photovoltaic (PV) grid-connected generation as a cornerstone technology in modern power networks. Countries with high solar irradiation, such as Indonesia, possess considerable potential to increase PV penetration in distribution systems while simultaneously strengthening long-term energy security and reducing dependence on fossil fuels. Despite these advantages, the large-scale integration of PV systems into medium- and low-voltage distribution networks remains constrained by strict grid code requirements, particularly those related to power quality and grid support functionality [1], [2].

As more and more PV systems are connected to the grid, distribution networks are more likely to have problems when inverter-based generation interacts with existing load characteristics. There are two power quality problems that are critical. First, most commercial PV inverters are mainly made for injecting active power and only provide a small amount of reactive power support. This is a problem because most residential, commercial, and industrial loads are inductive and need dynamic reactive power compensation to keep voltage profiles and power factor levels at acceptable levels [3], [4]. Second, the widespread use of nonlinear loads, like diode rectifiers, adjustable-speed drives, and switch-mode power supplies, creates many harmonic currents that change the shape of grid waveforms. These harmonics, along with the high-frequency switching behavior of PV inverters, cause equipment to overheat, losses to go up, sensitive devices to stop working, and the overall system to work less efficiently [5], [6]. As a result, modern grid codes are requiring more and more that distributed energy resources not only deliver active power and take part in reactive power regulation and harmonic mitigation [7].

PV-grid inverters that can inject active power, compensate for reactive power, and reduce current harmonics all at the same time. Synchronous reference frame (SRF) control combined with proportional-integral (PI) regulators is still widely used because it is easy to understand, works well for controlling DC-like quantities in the dq-domain, and works with industrial-grade digital controllers [8], [9]. However, traditional SRF-PI control has built-in problems when it comes to compensating for harmonic components, especially when the load is nonlinear and changes over time.

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Harmonic currents show up as oscillating parts in the synchronous reference frame, which means that PI-based regulators can't accurately follow these parts. This leads to incomplete compensation and worse filtering performance [10].

Some of the more complex approaches that have been proposed to address these issues include resonant-based approaches, repetitive control, and model predictive control (MPC). Although MPC has a stronger dynamic response and harmonic rejection, it is difficult to use due to its high setup costs and lack of utility for low-cost embedded platforms, which are frequently utilized in distributed photovoltaic systems [11], [12]. Additionally, many reported multifunctional inverter solutions rely on two-stage converter architectures—typically consisting of a DC–DC stage and a grid-side inverter—which increase switching losses, complicate DC-link energy management, and reduce overall system efficiency. In contrast, single-stage inverter configurations offer lower hardware complexity, improved efficiency, and reduced cost, provided that an appropriate control strategy can guarantee power balance and high-quality current injection. A lot of people talked about multifunctional inverter solutions that use multi-stage converter topologies. Inverters and DC-DC stages are common parts that go on the grid side. These designs make it more challenging to control DC link energy, lower system efficiency, and increase switching losses. Nevertheless, if there is an effective method to control the power and current, multifunction inverter setups are cheaper, more efficient, and far simpler to use. This underscores a research deficiency: an absence of a cohesive control architecture that maintains the robustness and computational efficiency of SRF-based methodologies while delivering precise harmonic compensation for multifunctional PV inverters. This paper presents an optimized dq-frame control architecture for a PV-Grid inverter designed to deliver active power, compensate for reactive power, and mitigate harmonic distortion caused by nonlinear loads. The proposed reference current generation scheme combines current decomposition, instantaneous power theory, and synchronous reference frame transformation. This lets you do exact harmonic compensation without having to do much work on the computer. To make sure the proposed control method is useful in real life, it is tested under composite load conditions, where nonlinear harmonic-producing loads run alongside linear inductive and capacitive loads. This is very similar to how distribution systems work in real life. We do a full simulation-based study to see how well the proposed multifunctional control strategy meets current grid power quality standards and improves dynamic performance, robustness, and power quality.

II. RESEARCH METHOD

PV-grid systems are commonly utilized to transmit electrical energy produced by PV modules into the utility grid, primarily delivering active power during linear load circumstances. However, nonlinear loads are making modern power systems worse by causing harmonic distortion and reactive power consumption. To fix these problems, Shunt Active Power Filters (SAPFs) have been widely used as a good way to reduce harmonics and improve power factor. A voltage source inverter with a DC-link capacitor is a common part of a SAPF. However, if there is no external DC energy source, it can only compensate for harmonic and reactive currents and not add active power to the grid. The combination of PV-grid inverters is a promising way to get around this problem by allowing both active power injection and power quality improvement at the same time. To rectify harmonics and increase power, most of the time, classic PV-grid systems require external active filtering gear and a grid-side inverter. This setup lets you easily change the PV operating point, but it also makes the system more complicated, expensive, and less efficient. Also, inverters that work as voltage sources need to be perfectly synced with the grid, which makes the control structure even more complicated. To solve these problems, this study uses a single-stage three-phase PV-grid inverter that works as a regulated current source (Fig. 1). In this setup, the inverter connects the PV array directly to the grid with a DC-link capacitor whose voltage is kept above the peak grid voltage. Using the inverter as a control current source makes it much easier to connect to the grid because the current control loop already has synchronization needs built in, so it doesn't need to match voltages. This feature makes it possible to use a single control approach in which the inverter does all three things at once: injects active power from the PV source, compensates for harmonic current, and controls reactive power.

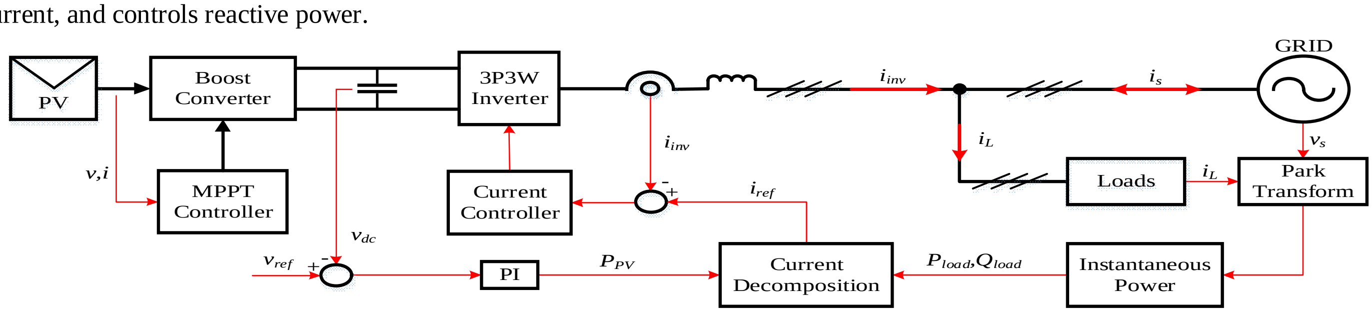

Fig 1. Blocks of the proposed control scheme for a three-phase PV-grid system

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According to Fig. 1, the three-phase inverter is utilized as a connection between the PV system and the grid. Which would cause the output voltage to be synchronized with the grid voltage. All energy generated by the PV must flow into the grid, so the inverter needs to detect power flow. By measuring the DC-link voltage (v_{dc}), the power balance can be found. Zero average power being absorbed or released by the inverter can be indicated by the steady DC-link voltage through the voltage controller. To minimize the harmonic components generated by nonlinear loads, the grid current needs to be sinusoidal at a unity power factor.

The reference current (i_{ref}) is generated by scaling the PV output current (i_{temp}) using the signal produced by the DC-link voltage controller. This controller regulates the DC-link voltage to a predefined reference level, known as the reference grid voltage (V_{ref}) which is set higher than the maximum grid voltage to ensure proper inverter operation. Any deviation between the actual and reference DC-link voltages, seen through the voltage controller (e_v) can be obtained using (1).

$$e_v = V_{ref} - v_{dc} \tag{1}$$

If the modulated factor is k, then by using the PI controller we have

$$k(s) = \left(K_p + \frac{K_i}{s}\right) e_v(s) \tag{2}$$

where K_p and K_i are the proportional and integral constants, the instantaneous value of the output power of the PV as fundamental power ($\bar{P}$) can be determined by

$$P_{PV} = \bar{P} = k \cdot i_{temp} \tag{3}$$

Currently, if P_{PV} exceeds P_{grid}, the DC-link voltage will rise, whereas the opposite scenario will result in a decrease in the DC-link voltage. The voltage controller needs to maintain this voltage almost constant to enable bidirectional active power exchange between the PV source and the utility grid.

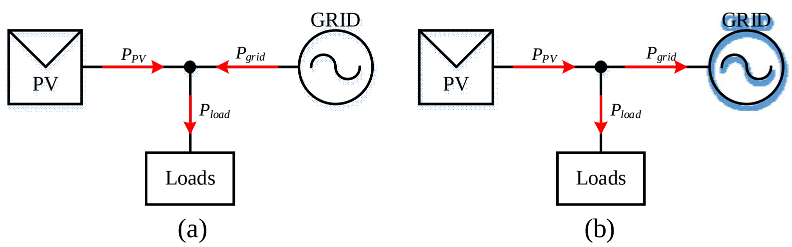


Fig 2. Power flow among the P_{load}, P_{PV}, and P_{grid} under various operating conditions (a) P_{PV} is less than P_{grid} (b) P_{PV} is greater than P_{grid}

According to the previous method of analysis, we can obtain the power flow. Hence, the power equilibrium (Fig. 2) can be analyzed using the relationship between P_{grid}, P_{load}, and P_{PV}, described in (4)

$$P_{grid} = P_{load} - P_{PV} \tag{4}$$

A positive value of P_{grid} indicates power absorption from the utility grid, whereas a negative value corresponds to power injection into the grid.

The proposed control framework is formulated in the Synchronous Reference Frame (dq-frame), allowing decoupled regulation of active and reactive power components under various operating conditions, including both power deficit ($P_{PV}<P_{load}$) and power surplus ($P_{PV}>P_{load}$) scenarios. Through regulation of current and power management, the inverter will maintain a sinusoidal grid with a unity power factor while effectively utilizing the available PV energy.

Grid phase alignment is achieved when a Synchronous Reference Frame Phase-Locked Loop (SRF-PLL) is utilized. The SRF-PLL will track the phase angle of the grid voltage, making sure synchronization is occurring despite distorted and unbalanced operating conditions.

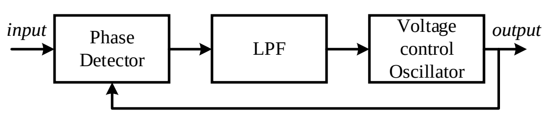


Fig 3. General block diagram of PLL

The measured three-phase grid voltages are first transformed into the stationary $\alpha\beta$ reference frame using the Clarke Transformation stated in (5).

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{5}$$

Subsequently, the stationary voltage components are mapped into the dq-frame using the estimated phase angle θ through the Park Transformation, as expressed in (6).

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \cdot \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \tag{6}$$

From (6), the quadrature-axis voltage component (v_q) directly indicates the phase discrepancy between the estimated reference frame and the actual grid voltage. The grid voltage is processed by a PI controller to generate the angular frequency and phase angle corrections,

$$e = v_q = -v_\alpha \sin(\theta) + v_\beta \cos(\theta) \tag{7}$$

the grid angular frequency (ω) and phase angle (θ) are then obtained as

$$\omega = K_p \cdot e + K_i \int e \cdot dt \tag{8a}$$

$$\theta = \int \omega \cdot dt \tag{8b}$$

As shown in Fig. 3, the SRF-PLL aligns the rotating reference frame by regulating v_q as the phase error signal. When the PLL is locked, v_q is regulated to zero, thereby aligning the rotating reference frame with the fundamental grid voltage vector, as depicted in Fig. 4.

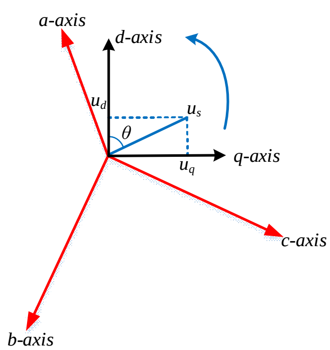


Fig 4. Vector diagram for abc-dq axis

The three-phase voltages (v_a, v_b, v_c) can be calculated by substituting (8) into (6), and the currents (i_a, i_b, i_c) as shown in (9) are stated in terms of dq.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{9}$$

Nonlinear loads, such as diode rectifiers, can be effectively represented as harmonic current sources that inject distorted currents into the point of common coupling (Fig. 5). These distorted currents contain significant high-order harmonic components, which appear in the dq-frame as oscillatory variations in both $\tilde{P}$ and $\tilde{Q}$. If these oscillatory components are not compensated, they propagate into the grid, leading to current distortion and degradation of power quality.

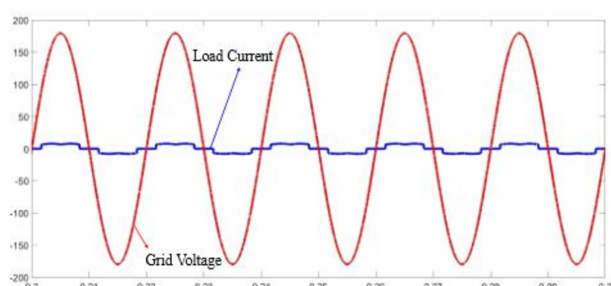
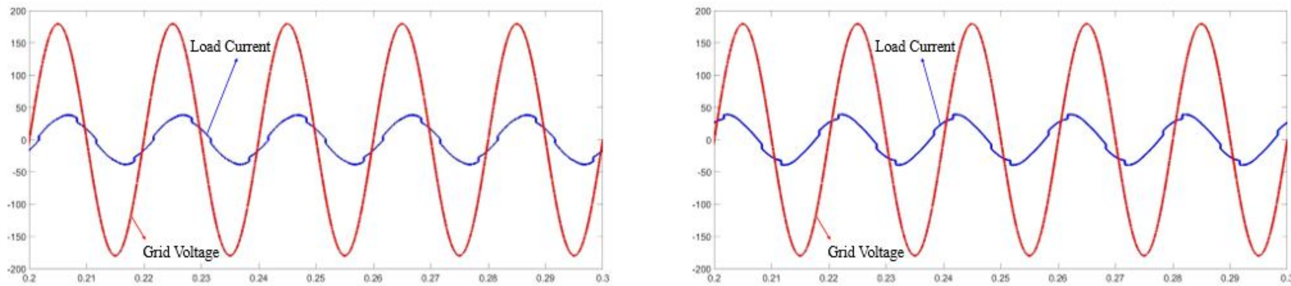


Fig 5. Load characteristics under nonlinear operating conditions

Linear loads with controlled impedance are introduced alongside the nonlinear load. An inductive load is employed to generate a lagging power factor condition (Fig. 6a), whereas a capacitive load produces a leading power factor (Fig. 6b).



(a) (b)

Fig 6. Load characteristics under nonlinear operating conditions connected in parallel with inductive load

This configuration allows for a methodical performance evaluation of the controller in both inductive and capacitive reactive power scenarios prior to implementing current decomposition for harmonic and reactive power compensation.

The dq-based power formulation serves as a crucial link between DC-link power management and load characterization. This is done by disclosing the oscillatory power elements that are linked to nonlinear loads. The inverter can be instructed to deliver harmonic and reactive currents while regulating active power transfer with the grid to be stable.

In the proposed control scheme, the electrical characteristics of the connected loads are analyzed through their instantaneous power characteristics in the SRF. The instantaneous load active (P_{load}) and reactive (Q_{load}) powers employ the grid voltage component (v_{ds}, v_{qs}) and the load current components (i_{dL}, i_{qL}). Therefore, both the instantaneous active and reactive powers are articulated as

$$\begin{bmatrix} P_{load} \\ Q_{load} \end{bmatrix} = \begin{bmatrix} \bar{P} \\ \tilde{Q} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} v_{ds} & v_{qs} \\ v_{qs} & -v_{ds} \end{bmatrix} \cdot \begin{bmatrix} i_{dL} \\ i_{qL} \end{bmatrix} \tag{10}$$

this dq-frame formulation establishes a direct relationship between load currents and power flow, allowing for a clear distinction between active and reactive power components under synchronized conditions.

The dq-frame power representation and previous load characteristics can be used to look at the proposed system's power flow in Fig. 2 by using power equilibrium at the DC-link stage. The inverter makes current that can be controlled, and the DC-link capacitor stores energy to even out the power from the PV system, the load, and the utility grid. The average energy stored in the DC-link capacitor stays the same when the system is in steady state, which means that the DC-link's instantaneous powers must be balanced. So, (4) can still be used to figure out the instantaneous power relationship between grid power, load power, and PV-generated power. Instantaneous total energy, contributed by active power P, flowing from the grid to the load or the other way around in a certain amount of time. But instantaneous reactive power Q shows how energy moves between the phases of a system.

After the established power balance and dq-frame power representation, the load current can be broken down into fundamental and oscillatory components to enable selective harmonic and reactive power compensation. Equation (10) shows that all components contained in the phase currents will contribute to any type of instantaneous power in the dq frame. However, we cannot infer which current components are responsible for fundamental power transfer and which components originate from harmonic and reactive effects. Since only the fundamental active current component should be supplied by the grid, it becomes necessary to decompose the dq-frame currents into components corresponding to different power contributions. This decomposition is applied to the dq-frame currents through their contribution to instantaneous power, rather than directly to the phase currents.

$$\frac{2}{3}\begin{bmatrix} v_d & v_q \\ v_q & -v_d \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \bar{P} + \tilde{P} \\ \bar{Q} + \tilde{Q} \end{bmatrix} \tag{12}$$

by applying the inverse Park Transformation, the current components corresponding to the instantaneous power terms in (12) can be obtained as

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{3}{2}\begin{bmatrix} v_d & v_q \\ v_q & -v_d \end{bmatrix}^{-1} \cdot \begin{bmatrix} \bar{P} + \tilde{P} \\ \bar{Q} + \tilde{Q} \end{bmatrix}$$

$$\begin{bmatrix} i_{d,pf} + i_{d,ph} + i_{d,qf} + i_{d,qh} \\ i_{q,pf} + i_{q,ph} + i_{q,qf} + i_{q,qh} \end{bmatrix} = \frac{3}{2(v_d^2 \cdot v_q^2)}\begin{bmatrix} v_d & v_q \\ v_q & -v_d \end{bmatrix} \cdot \begin{bmatrix} \bar{P} + \tilde{P} \\ \bar{Q} + \tilde{Q} \end{bmatrix} \tag{13}$$

This step is essential for distinguishing between fundamental and oscillatory current components prior to current synthesis. Decomposition current stated as

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} i_{d,pf} \\ i_{q,pf} \end{bmatrix} + \begin{bmatrix} i_{d,ph} \\ i_{q,ph} \end{bmatrix} + \begin{bmatrix} i_{d,qf} \\ i_{q,qf} \end{bmatrix} + \begin{bmatrix} i_{d,qh} \\ i_{q,qh} \end{bmatrix} \quad (14)$$

Equation (14) represents an analytical dq-frame current extraction based on instantaneous power components, which allows the identification of individual current components responsible for the instantaneous active and reactive power, the phase currents can be expressed as a superposition of four distinct components, each associated with a specific power contribution in (14), these are:

- $i_{dq,pf}$: contributes directly to the DC component of the instantaneous real power $\bar{P}$, these currents are active currents that have a fundamental frequency and are in phase with respect to contributes to the DC component of the instantaneous real power.
- the main voltage, it is in phase with respect to the main voltage
- $i_{dq,ph}$: contributes directly to the AC component of the instantaneous real power $\tilde{P}$, included as a current component
- $i_{dq,qf}$: contributes directly to the DC component of the instantaneous reactive power $\bar{Q}$, included as a current component with reactive currents, has a fundamental frequency, and is in quadrature with respect to the main voltage
- $i_{dq,qh}$: contributes directly to the AC component of the instantaneous reactive power $\tilde{Q}$, included as a current component

From a power quality perspective, only the fundamental active current component should flow from the utility grid, whereas all harmonic and reactive current components must be supplied by the inverter to prevent distortion and reactive power exchange with the grid. For filtering purposes, these current components can be separated into two parts:

- active current components that must flow in the grid side (15)

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} i_{d,pf} \\ i_{q,pf} \end{bmatrix} \quad (15)$$

- compensating current components which, are the sum of current components that contribute to reactive power and harmonic power (16)

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} i_{d,ph} \\ i_{q,ph} \end{bmatrix} + \begin{bmatrix} i_{d,qf} \\ i_{q,qf} \end{bmatrix} + \begin{bmatrix} i_{d,qh} \\ i_{q,qh} \end{bmatrix} \quad (16)$$

At this stage, the load current has been fully decomposed into its fundamental and oscillatory components. In the next step, these components are selectively recombined to generate the inverter reference currents for active power injection and power quality compensation.

Based on the current decomposition established in (15) and (16), the reference currents for the grid-connected inverter can be systematically synthesized. The objective of the reference current generator is to ensure that the utility grid supplies only the fundamental active current component, while all harmonic and reactive current components are locally compensated by the inverter.

Let i_{ds}^* and i_{qs}^* denote the reference grid current components in the dq frame. According to (15), the grid current component consists solely of the fundamental active current, which is responsible for the net transfer of real power between the grid and the load. Therefore, the reference grid current in the SRF is defined as

$$\begin{bmatrix} i_{ds}^* \\ i_{qs}^* \end{bmatrix} = \begin{bmatrix} i_{d,pf} \\ 0 \end{bmatrix} \quad (17)$$

where the q-axis grid reference current is set to zero to enforce unity power factor operation at the grid interface.

The compensating current reference for the inverter is given by (16) as the sum of all non-fundamental and reactive current components. This formulation ensures that the inverter supplies the oscillatory active current component associated with harmonic power and both the fundamental and harmonic reactive current components, preventing them from propagating into the utility grid.

To integrate P_{PV} injection into the control framework, the fundamental active current reference is modified based on the DC-link power equilibrium. According to the power equilibrium articulated in (4), the reference for the direct-axis grid current is obtained as

$$i_{ds}^* = i_{d,pf} = \frac{2}{3} \cdot \frac{P_{grid}}{v_{ds}} \quad (18)$$

P_{grid} denotes the reference grid power established by the DC-link voltage regulator. A positive value of i_{ds}^* indicates power absorption from the grid during power deficit conditions, whereas a negative value denotes active power injection into the grid during PV power surplus. The inverter reference current in the dq frame can be succinctly articulated as

$$\begin{bmatrix} i_{d,inv}^* \\ i_{q,inv}^* \end{bmatrix} = \begin{bmatrix} i_{dL} - i_{ds}^* \\ i_{qL} - i_{qs}^* \end{bmatrix} \quad (19)$$

This expression highlights that the inverter current is obtained directly from the difference between the load current and the desired grid current, consistent with Kirchhoff's current law at the point of common coupling.

$$\begin{bmatrix} i_{cd,inv} \\ i_{cq,inv} \end{bmatrix} = \begin{bmatrix} i^*_{d,inv} - i_{d,inv} \\ i^*_{q,inv} - i_{q,inv} \end{bmatrix} \tag{20}$$

Finally, the dq-axis compensating inverter currents are transformed back into three-phase quantities using the inverse Park Transformations to generate the switching signals for the inverter,

$$\begin{bmatrix} i_{ca,inv} \\ i_{cb,inv} \\ i_{cc,inv} \end{bmatrix} = [T_{Park}]^{-1} \cdot \begin{bmatrix} i_{cd,inv} \\ i_{cq,inv} \end{bmatrix} \tag{21}$$

The resulting three-phase currents enable the inverter to simultaneously perform active power injection, harmonic mitigation, and reactive power compensation within a unified control framework, without requiring any mode switching or auxiliary filtering hardware.

III. RESULT AND DISCUSSION

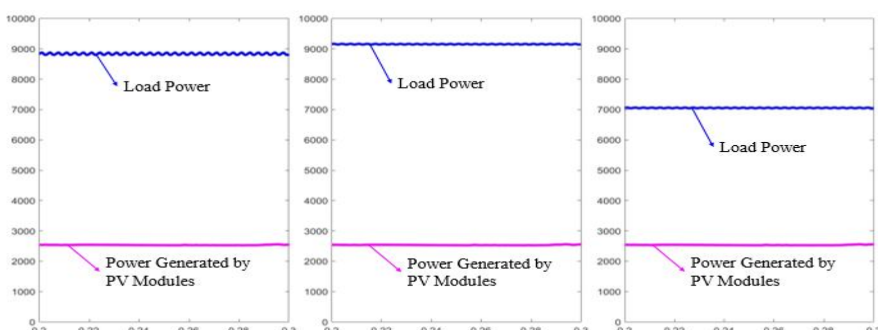
The analysis of proposed the control scheme above was verified through simulation based on Fig. 1. This system contains PV-Grid, and then a harmonic current source is used as the nonlinear load connected in parallel with inductive or capacitive load as the linear loads. The parameter used is represented in Table 1.

TABLE I
PARAMETER FOR SIMULATION WORKS

Parameters	Value
Photovoltaic	90 pieces of 200.07Wp PV modules (6 series, 15 parallel) V_{MPP} = 28.5 V, I_{MPP} = 7.02 A
DC-link Voltage	500 V_{dc}
Grid Voltage	220 V_{rms}
Nonlinear Load	Diode rectifier with inductive loads
Linear Loads	R = 5 Ohm, L = 10mH (for inductive loads) R = 10 Ohm, C = 470µF (for capacitive loads)
System	Three-Phase Three-Wire

The simulations were conducted under two scenarios, the first being when the load power (P_{load}) exceeds the power generated by the PV modules (P_{PV}) and the second one is vice versa. The results for discussion are focused on active filtering, power factor correction, and bidirectional active power flow.

First simulations were run to assess the reliability of the inverter control mechanism under the power deficit scenario (P_{PV}<P_{load}) condition depicted in Fig. 7.



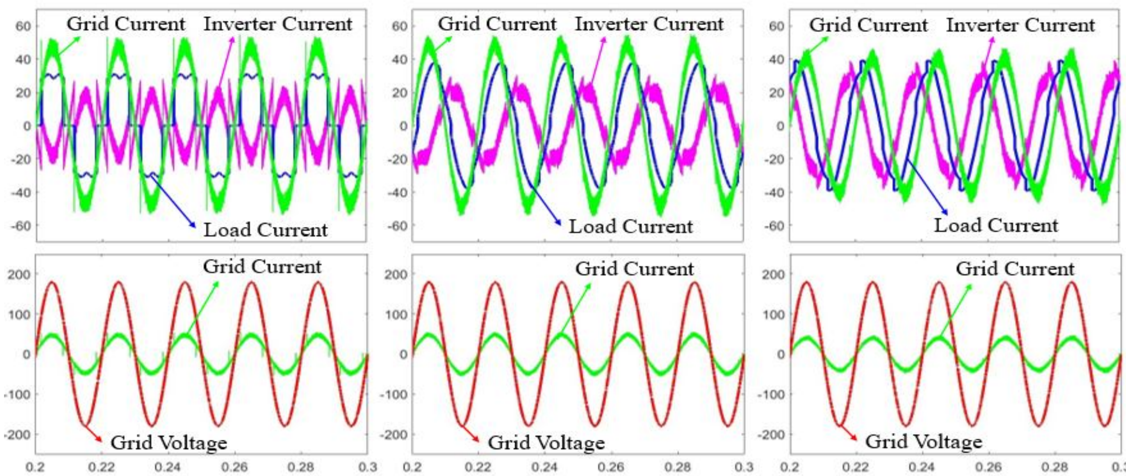
(a) (b) (c)

Fig 7. Simulation results for power generated when P_{PV}<P_{load} (a) under nonlinear load (b) under nonlinear load with inductive linear load (c) under nonlinear load with capacitive linear load

This operating condition corresponds to the scenario in which the PV generation is insufficient to supply the total load demand. As observed in Fig. 7, the load active power exceeds the PV-generated power, causing the reference grid power derived from the DC-link voltage regulator to assume a positive value.

According to (18), a positive reference grid power results in a positive d-axis grid current reference. This enforces active power flow from the grid to the load, ensuring power balance at the DC-link. The grid therefore supplies only the fundamental active current component required by the load, consistent with (4).

Simulation results under various loads are shown in Fig. 8. This load current shows harmonic and reactive power distortion. Grid current is sinusoidal and in phase with voltage. The load receives real power from the grid without harmonic and reactive components. Some load power comes from the inverter. Inverter current controllers match load currents to generate compensation current.

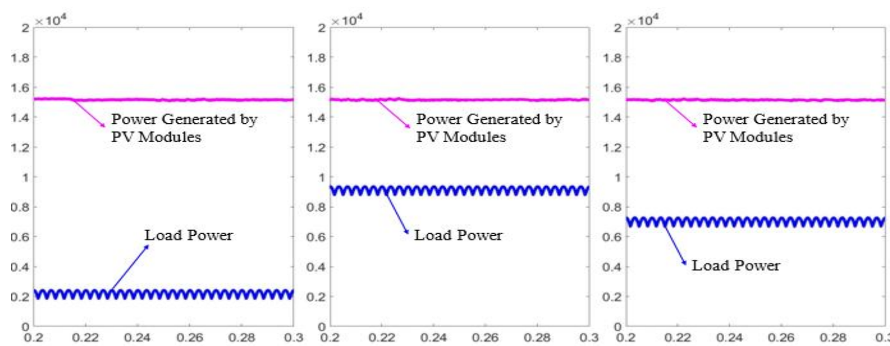


(a) (b) (c)

Fig 8. Simulation results of the current waveform when $P_{PV}<P_{load}$ (a) under a nonlinear load, (b) under a nonlinear load paired with an inductive linear load, (c) under a nonlinear load containing a capacitive linear load

Despite the severely distorted load current, the grid current is sinusoidal and in phase with the grid voltage. The current separation in (15) and (16) assigns only the fundamental active current component to the grid, while the inverter supplies all harmonic and reactive current components. Physically, the inverter acts as a local compensator that absorbs the oscillatory dq current components associated with harmonic and reactive power. As a result, the grid current waveform is effectively decoupled from the nonlinear load characteristics, demonstrating the inverter's active power filtering capability under power deficit conditions.

The second work of simulations was done to evaluate the effectiveness of the inverter control method when the power surplus ($P_{PV}>P_{load}$) condition depicted in Fig. 9.



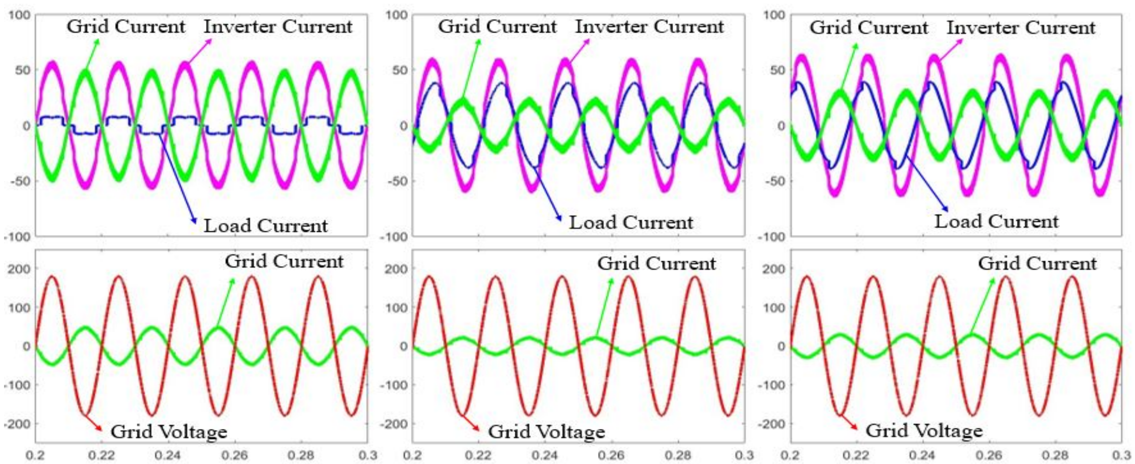
(a) (b) (c)

Fig 9. Simulation results for power generated when $P_{PV}>P_{load}$ (a) under nonlinear load (b) under nonlinear load with inductive linear load (c) under nonlinear load with capacitive linear load

Based on (18), a negative reference grid power leads to a negative d-axis grid current reference, reversing the direction of active power flow. Consequently, excess PV energy is injected into the utility grid without requiring any modification to the control structure or mode-switching logic.

The seamless inversion of the grid current phase relative to the grid voltage proves that the d-axis current reference manages bidirectional power flow. This behavior highlights a major benefit of the dq-based formulation, which regulates power flow direction using continuous control variables instead of discrete operating modes.

The grid current has a sinusoidal waveform and a unity power factor during power injection. The inverter persistently adjusts for harmonic and reactive current components as in (16), illustrating that active power injection and power quality enhancement are concurrently attained within an integrated control system.



(a) (b) (c)

Fig 10. Simulation results of the current waveform when $P_{PV}<P_{load}$ (a) under a nonlinear load, (b) under a nonlinear load paired with an inductive linear load, (c) under a nonlinear load containing a capacitive linear load

Fig. 10 shows simulation results with different loads. This load current shows harmonic and reactive power distortion. The grid voltage and sinusoidal grid current are oppositely polarized. We analyse the proposed control strategy to reduce harmonic distortion using load and grid current spectral analysis. Since the load is nonlinear, the load current has a lot of harmonic distortion, but the grid current after compensation has less. The inverter correctly compensates for the oscillatory dq current components found through current decomposition. The proposed method keeps harmonic currents on the inverter side to prevent grid spread. This enhances common coupling power quality.

The proposed method achieves multifunctionality purely through dq-frame current decomposition and reference current synthesis, unlike previous systems that necessitate extra active filtering hardware. This makes the system less complicated while still keeping the power quality high in situations with nonlinear and mixed loads.

Simulations show that the proposed dq-framed control method allow a PV-Grid inverter inject power, mitigate harmonics, and adjust reactive power simultaneously. Because it can distinguish analytical current components from control reference signals, the inverter can adjust PV generation without changing the control framework.

IV. CONCLUSION

This study introduces a dq-frame-based unified control framework that turns a three-phase PV-Grid inverter into a multifunctional power conditioner. The proposed method allows seamless bidirectional active power flow using DC-link instantaneous power equilibrium and systematic dq-frame current decomposition. It reduces harmonic currents and compensates for reactive power in nonlinear or mixed loads. A single conversion stage with analytical current synthesis improves power quality. Traditional systems require active filtering hardware or complex predictive control schemes. The simulation shows that the inverter separates harmonic and reactive utility grid components well. Even with excessive or insufficient PV power, grid currents are sinusoidal and unity power factor. Thus, the suggested method can improve PV grid electricity quality in the future when distribution networks have many nonlinear loads.

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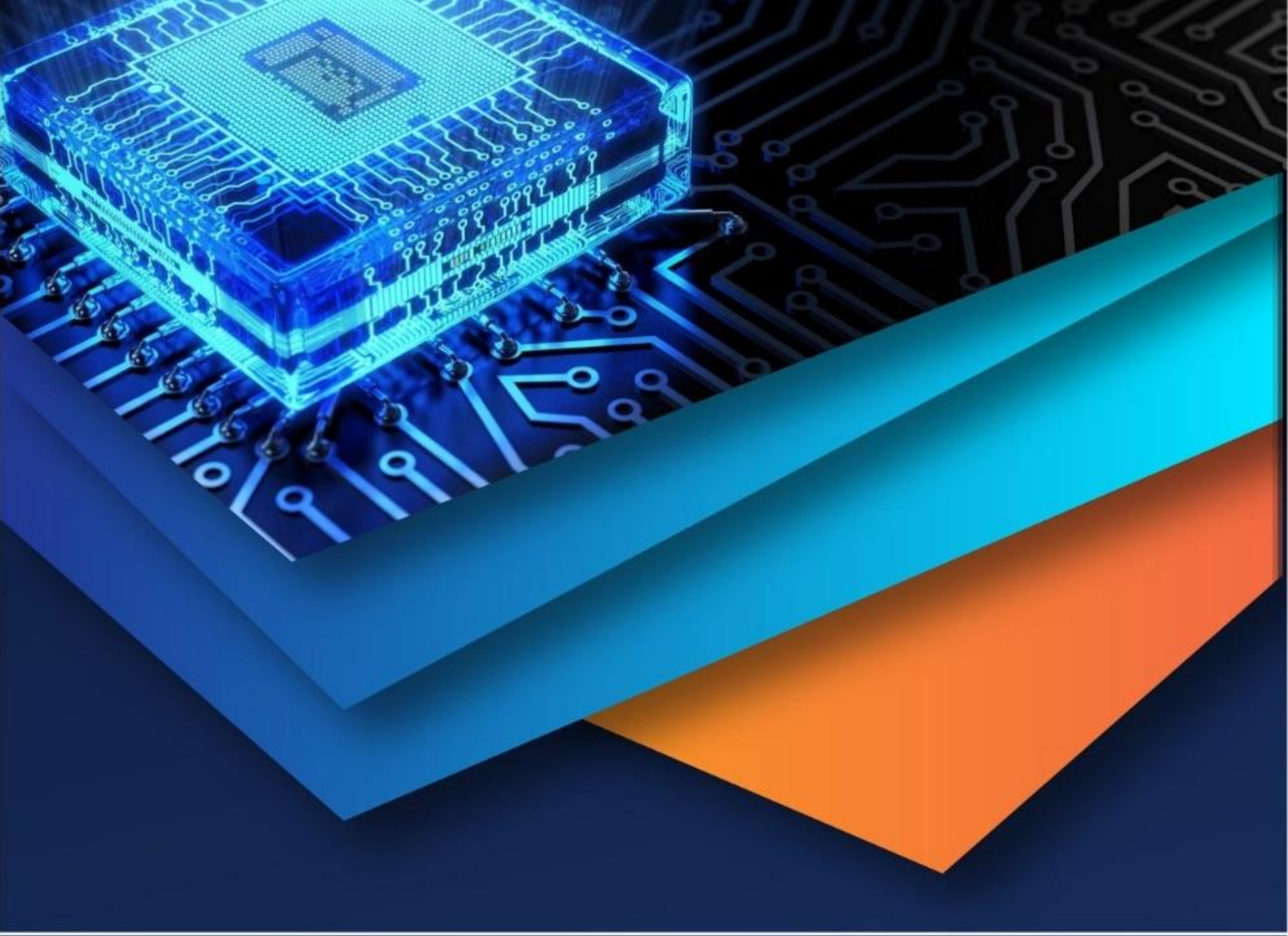

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