

Article

Optimized PI Control of a PV-STATCOM for Power Oscillation Damping in Grid-Connected Photovoltaic Systems

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Abstract

This paper presents an optimized control strategy that enables a grid-connected photovoltaic (PV) system to operate as a static synchronous compensator (PV-STATCOM) to damp power oscillations in the transmission system, using an arithmetic optimization algorithm (AOA). The key contribution of this work is a synchronized, AOA-optimized multi-mode switching approach that includes standard PV operation, Full STATCOM, and Partial STATCOM with ramp-rate recovery, rather than relying solely on PI-gain adjustment. This is accomplished across the complete pre-fault, fault, and post-fault cycle. Under the proposed strategy, the PV system temporarily curtails its real power output when power oscillations arise following a system disturbance, thereby releasing the full inverter capacity for STATCOM operation and, hence, for oscillation damping. Once the oscillations are damped, the PV system ramps its real power back to the pre-disturbance level; at night, the inverter's full capacity remains available for damping oscillations. The control scheme is implemented with a set of proportional–integral (PI) controllers whose parameters are tuned with the AOA, and its performance is benchmarked against tuning with the cuckoo search (CS) algorithm. Simulation results demonstrate that the AOA-tuned PV-STATCOM significantly improves damping, reduces oscillation amplitudes, maintains the point-of-common-coupling voltage within the low-voltage ride-through envelope, and keeps the system frequency within grid-code limits, thereby ensuring stable grid operation. Compared to a CS-tuned benchmark, the AOA-tuned design keeps the frequency continuously within the grid code band, settles at nominal 50 Hz, and reduces the maximum voltage overshoot from 20% to 15%.

Keywords: PV system; STATCOM; PV-STATCOM; power oscillation damping; PI controller; arithmetic optimization algorithm



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1. Introduction

Power system oscillations (PSOs) have become a significant concern in power systems with high shares of renewable generation, as they threaten the stability and security of system operation [1]. PSOs are inherent phenomena in electrical power systems, characterized by periodic variations in electrical quantities such as voltage, current, and power [2]. If inadequately managed, these oscillations can lead to sustained instability, equipment damage, and widespread blackouts, underscoring their impact on overall system performance [1].

Mitigating PSOs is therefore imperative for a stable and secure power network, since poorly damped oscillations jeopardize the coordinated operation of interconnected systems. Moreover, the global transition toward renewable energy sources has made oscillation

control increasingly challenging [3]. Hence, the development of advanced analytical tools, control strategies, and monitoring systems is crucial [4].

Designing systems capable of withstanding both routine disturbances and infrequent severe events require a thorough understanding of PSO characteristics. Accordingly, this study examines the sources, impacts, and mitigation strategies of PSOs, with the aim of enhancing stability assessment and improvement in modern electrical networks [5].

Flexible AC transmission system devices have become integral to modern power systems, substantially improving their efficiency, stability, reliability, and operational flexibility [6]. These devices have proven highly effective in attenuating PSOs, which is critical for the long-term stability of interconnected grids.

Integrating FACTS devices into power networks markedly improves system stability, particularly by damping oscillations. Such devices provide dynamic control of power flows, thereby enhancing voltage regulation and reactive power compensation [7,8]. As demonstrated by an extensive body of literature on their applications, FACTS devices can also mitigate the risk of instability by actively compensating for load imbalances [6,9,10]. Among shunt-connected FACTS devices, the static synchronous compensator (STATCOM) is one of the most effective and widely deployed [11–13]. It provides essential support for voltage regulation and PSO damping through fast, precisely controlled dynamic exchange of reactive power. Owing to their rapid response times, STATCOMs can quickly mitigate transient disturbances and preserve grid voltage stability [14]. The principal barrier to STATCOM deployment, however, is cost: the high capital cost stems from the power-electronic equipment, control systems, and advanced materials used in its fabrication, while the installation cost arises from siting requirements and grid-integration activities [15]. A common shortcoming across this body of work, however, is that the reported cost and siting barriers are typically discussed qualitatively, with comparatively little attention paid to control-parameter design procedures that could make dedicated STATCOM installations more cost-effective; this observation motivates the search for lower-cost alternatives.

The high cost of FACTS devices has strongly motivated the development of alternatives that deliver comparable performance at lower cost. One strategy is to exploit assets already present in the generation system to provide this functionality, particularly during fault events. Employing photovoltaic (PV) systems, one of the most widely deployed renewable energy sources, to operate as a STATCOM during network disturbances, a concept known as the PV-STATCOM, is a key solution that avoids the cost and implementation challenges of a dedicated STATCOM [16,17]. The PV-STATCOM leverages the PV inverter's dual functionality to generate real power while providing ancillary services, including voltage regulation, reactive power support, and PSO damping. This configuration maximizes the utilization of existing solar infrastructure, reduces the need for additional equipment, simplifies the overall system, and contributes to a more resilient and sustainable energy system.

The PV-STATCOM concept has been applied in several modern applications by endowing the inverter control with smart functionality [16]. In this arrangement, the PV system behaves like a STATCOM by supplying reactive power during abnormal operating conditions. The PV-STATCOM operates in two distinct modes, Partial and Full STATCOM, both of which materially affect PSO damping. In Partial STATCOM mode, the inverter prioritizes real power production from the PV array; during periods of high solar irradiance, this leaves little or no spare capacity for reactive power control [17]. This constraint renders the system ineffective at damping oscillations during peak solar hours, because the inverter's entire capacity is committed to active power injection, leaving no margin for damping support through reactive power modulation [17]. Consequently, networks with significant PV penetration may experience poorly damped oscillations during daytime op-

eration, aggravating stability concerns [18]. To address this limitation, the Full STATCOM mode enables the PV plant to dynamically reallocate its inverter capacity to reactive power control, even during peak solar generation. This mode is particularly valuable during grid disturbances, when a rapid reactive power response can mitigate inter-area oscillations and improve transient stability [19].

The research supporting the Partial/Full STATCOM concept elucidates the operational principle but typically does not address the controller-design issue: PI gains are either determined through trial and error or remain undefined, resulting in a lack of systematic correlation between achievable damping performance and tuning methodology. This represents a considerable constraint, as the damping efficacy is largely determined by the controller gains rather than by the switching logic alone.

PV-STATCOMs have been employed for power oscillation damping [20] and for increasing transmission capacity [21]. A landmark contribution to PV-STATCOM technology, particularly for PSO damping, is reported in [16]; that work demonstrated the efficacy of the PV-STATCOM in mitigating PSOs and improving grid stability, and it has catalyzed substantial follow-on research. Its main limitation, however, is the absence of a systematic procedure for tuning the PI controllers that enable the PV system to operate as a STATCOM.

In contrast to [16], which fails to delineate the method for acquiring PI gains, and in distinction from analogous metaheuristic-optimized STATCOM investigations [22], this study articulates a definitive optimization problem for the PV-STATCOM controller and illustrates, thru a direct comparison with CS tuning, that the selection of the tuning algorithm significantly influences grid-code adherence and voltage overshoot—beyond merely affecting convergence velocity on a benchmark function.

Relative to existing PV-STATCOM oscillation-damping strategies including the hybrid metaheuristic-tuned wind-PV-STATCOM scheme of [22] and fuzzy/PSO-based PV-STATCOM voltage-support schemes such as [23], the presented study differs in two respects: (i) it targets the specific PI-tuning gap left open in the seminal PV-STATCOM formulation of [16] rather than proposing a new switching topology, and (ii) it benchmarks a recent, few-parameter metaheuristic (AOA) against an established one (CS) on the same PV-STATCOM plant and fault scenario, isolating the effect of the tuning method itself on damping performance.

This study addresses that gap by optimally coordinating the PV-STATCOM strategy to mitigate PSOs in a grid-connected PV system. The optimization refines the gains of the PI controllers that drive the grid-tie inverter, using the AOA. To assess the effectiveness of the proposed approach, its performance is compared with that of tuning using the CS algorithm.

The main contributions of this paper may be outlined as:

- Developing an AOA-based optimal tuning procedure for the PI controllers of a PV-STATCOM performing PSO damping, addressing the tuning gap identified in the literature.
- Implementing a coordinated multi-mode control scheme, with normal PV operation, Full STATCOM, and Partial STATCOM with ramp-rate power restoration.
- Verifying the PV-STATCOM function over the complete pre-fault, fault, and post-fault cycle, including an improved fuzzy self-tuned MPPT for normal operation.
- Comparing the AOA-tuned controller against a CS-tuned counterpart in terms of frequency excursions, voltage recovery, and oscillation damping, demonstrating compliance with the applicable grid codes.

To clarify the attribution: the DC–DC MPPT stage, the dq inner current-control loop, and the abc/dq-PLL implementation adhere to recognized methodologies documented in [15,24,25], respectively, and are utilized here as conventional components rather than

introduced as novel findings. The contribution of this paper lies in the layer constructed atop those blocks: the synchronized multi-mode switching mechanism among normal, Partial-STATCOM, and Full-STATCOM operations, and crucially, the AOA-based optimal design of the damping-controller gains that dictate the efficacy of the switching logic in mitigating oscillations, a topic not explored in [15,24].

The remainder of this paper is organized as follows. Section 2 describes the system under study. Section 3 presents the system modeling and the proposed multi-mode control scheme. Section 4 presents and discusses the simulation results, and Section 5 concludes the paper and outlines directions for future work.

2. System Description

A conventional grid-connected PV system consists of PV modules interfaced to the grid through a DC–DC converter and a DC–AC inverter, as shown in Figure 1; the system data are given in the Appendix A (Table A1) [26]. The grid is modeled as an infinite bus at 400 V and 50 Hz. A boost-type DC–DC converter steps up the DC output of the PV array; a key feature of this stage is its ability to track the maximum available PV power through maximum power point tracking (MPPT). Numerous MPPT strategies have been documented and implemented in the literature [27].

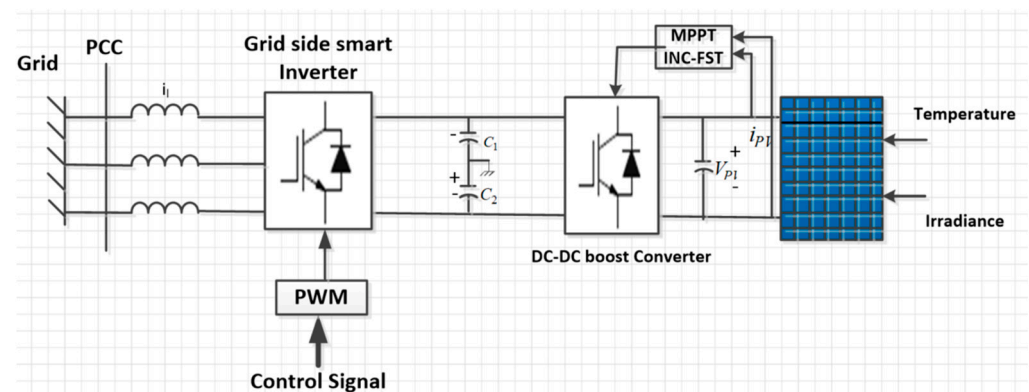


Figure 1. Configuration of the grid-connected PV system.

The DC–DC stage is a boost converter, selected for its step-up characteristic, which matches the PV array's operating-voltage range to the DC-link voltage required by the inverter.

3. System Modeling and Control

The aggregated PV panels are modeled as an equivalent array that generates DC current based on the module V–I characteristics and prevailing environmental conditions. The array is connected to the grid through a DC–DC converter, a DC link, and a three-phase six-pulse voltage-source inverter.

The PV-STATCOM concept relies fundamentally on smart inverter control, achieved by selecting an operating mode and its criteria based on prevailing system conditions. This section describes the modeling of the system components and the associated control mechanisms.

The modeling of PV systems has been thoroughly examined in the literature [27,28] and is therefore not discussed in depth here. Central to the proposed scheme is the oscillation detection unit (ODU), which is essential in contemporary power systems for monitoring and detecting the low-frequency oscillations that may compromise network stability. In this work, the ODU selects the operating mode by triggering switches S1 and S2, as shown in the control block diagram in following Figure.

The fault-management logic executed by the ODU is structured as follows. In optimal operation, the ODU maintains S1 in an asserted state while S2 is de-asserted. Upon detecting a disturbance-induced fluctuation (oscillation), the ODU negates S1 and activates S2, thereby transitioning the inverter into STATCOM mode. After the oscillation is mitigated, the ODU retracts S2; subsequently, S1 is reinstated, but rather than promptly returning to MPPT, the real-power controller implements the ramp-rate restoration rule defined in (1) until the power level prior to the disturbance is attained, at which point standard MPPT functionality resumes.

3.1. First Mode: S1 Activated

This mode is engaged when the ODU detects no disturbance, so the smart-inverter (STATCOM) functionality is not invoked. The active power is controlled by generating the direct-axis reference current, I_{d_ref} , and the inverter performs its conventional role of converting the PV array's DC output into grid-synchronized AC power. Switch S1 is asserted under two conditions: healthy operating conditions and the period immediately following disturbance clearance.

Under healthy operating conditions, the DC-voltage controller regulates the DC-link voltage so that the PV array tracks the maximum power available at the prevailing temperature and irradiance. The MPPT scheme adopted in this paper is an improved incremental conductance (INC) method in which the PID controller parameters are updated online by a fuzzy self-tuning mechanism (INC-FST) to accommodate variations in environmental conditions [17]. Since MPPT is not the primary focus of this work, only representative results of this technique are reported in the results section; full details are available in [17].

A further scenario arises when the ODU is deactivated after fault clearance while S1 remains on. In this case, the MPPT is not immediately re-engaged; instead, the real-power control mode is activated. In accordance with several grid codes, this controller restores the PV real power to its pre-disturbance level after the oscillations have been mitigated in PV-STATCOM mode [29]. In this study, the ramp-rate power restoration scheme of [30] is adopted:

$$P_{ref} = K_{sl}P_{pr}u(t - t_s) \quad (1)$$

Here, P_{ref} is the restored real-power command applied to the real-power controller; K_{sl} is the ramp-rate (slope) coefficient that sets how quickly power is restored; P_{pr} is the pre-disturbance real power level; and $u(t - t_s)$ is the unit-step function initiated at t_s , the instant at which the ODU de-asserts S2 following successful oscillation damping.

3.2. Second Mode: S2 Activated

This mode enables smart-inverter operation, enabling the PV system to function as a STATCOM during PSOs. This is accomplished by controlling the inverter reactive power through updating and determining the quadrature-axis reference current, I_{q_ref} . Two scenarios are considered—Partial and Full PV-STATCOM—classified by the reactive power required to damp oscillations during fault events. In the Partial mode, the inverter capacity remaining after PV real-power production is allocated to STATCOM operation; this mode is activated during the daytime. In the Full PV-STATCOM mode, the entire inverter capacity is dedicated to STATCOM operation: during daylight hours, the PV real-power output is suspended upon detection of undesirable low-frequency oscillations caused by system disturbances, and the full inverter capacity is then used to provide reactive power support to mitigate these oscillations. Once the oscillations are damped, real-power generation is restored, and the plant ramps its output back to the pre-disturbance level while continuing to damp any residual oscillations in Partial PV-STATCOM mode. At night,

the Full STATCOM mode remains permanently available for oscillation damping using the entire inverter capacity.

The two operating modes are summarized in Table 1.

Table 1. Summary of PV-STATCOM operating modes.

	S ₁	S ₂
Healthy operation	✓	✗
PSO fault	✗	✓
daytime	✗	✗
Smart inverter	✗	✓
Full-STATCOM	✗	✓
Partial-STATCOM	✗	✓

✓ indicates the mode is active/applicable; ✗ indicates the mode is inactive/not applicable.

During grid faults, the operating mode switches from normal PV production to Full STATCOM operation; standard PV power injection is then restored automatically after fault clearance, ensuring system stability throughout the disturbance cycle. This behavior is illustrated for a fault applied between $t = 2$ s and $t = 2.25$ s in Figure 2.

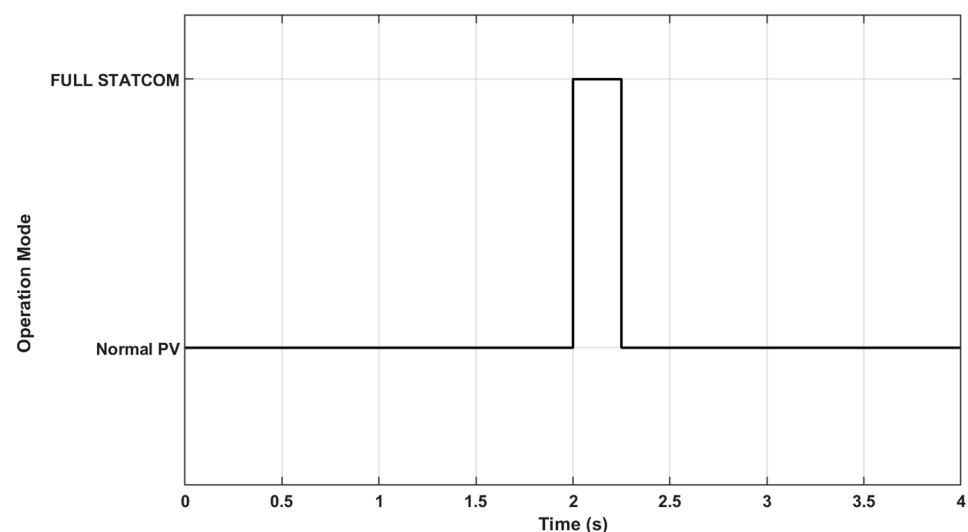


Figure 2. PV-STATCOM operating modes during a fault event.

3.3. Inner-Loop Control

The inner control loop independently controls real and reactive power in the d–q reference frame, using the d-axis reference current (I_{d_ref}) and the q-axis reference current (I_{q_ref}) as inputs. The controller generates the modulation indices m_d and m_q , which are transformed into the three-phase modulation indices (m_a , m_b , and m_c) in the dq/abc block; these, in turn, generate the inverter gating pulses through pulse-width modulation (PWM) [24]. The abc/dq transformation and the phase-locked loop (PLL) are implemented as described in [24]. As shown in the control block diagram in Figure 3.

3.4. Q-PSO Controller

This controller regulates the PV-STATCOM's reactive power output to damp low-frequency electromechanical oscillations. Following [15], the magnitude of the line current, i_l , at the point of common coupling (PCC) is adopted as the damping-control signal.

Effective damping is achieved by introducing sufficient phase lead or lag at the targeted oscillatory mode, and the controller gains are optimized using the AOA.

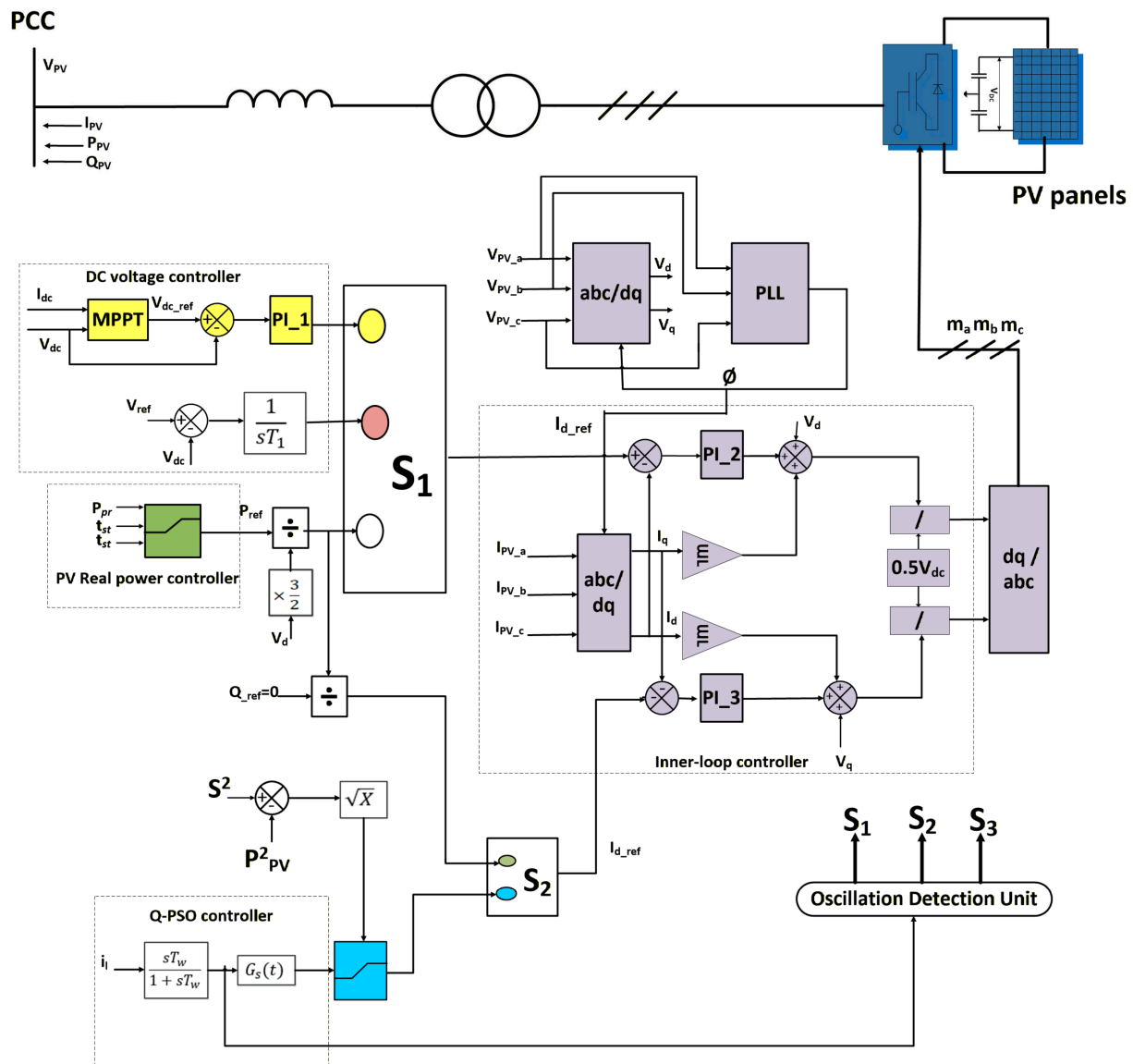


Figure 3. PV-STATCOM control block diagram.

3.5. Optimized Controller Design Using AOA

The AOA was selected over other recent metaheuristics for three practical reasons. First, it exposes very few control parameters (essentially α and μ , in addition to the population size and iteration budget shared by all population-based methods), which reduces the risk of poor performance due to mistuned optimizer settings, a known drawback of algorithms with many internal coefficients. Second, its exploration and exploitation phases are explicitly governed by the MOA coefficient in (3), yielding a transparent, analytically defined transition between the two search regimes rather than a heuristic one. Third, the AOA has demonstrated competitive or superior performance compared with other recent optimizers (e.g., Harris Hawks, sine-cosine, and swarm-based variants) on PI/PID controller-tuning problems in closely related power-system applications [31], supporting its suitability for the PV-STATCOM damping problem addressed here.

This decision was further corroborated empirically: comparing the AOA with the CS on the same PV-STATCOM damping-controller tuning issue across 20 independent,

variably seeded trials revealed that both algorithms yield similar optimal controllers, yet the AOA exhibits significantly greater consistency across runs and a reduced average computation time compared to the CS.

The AOA, a recent metaheuristic optimization technique, is used in this paper to design the controller parameters optimally [25].

The controller-design problem is posed as minimizing the deviation between the actual and reference line-current envelopes over the disturbance window, since this deviation directly reflects the residual, undamped oscillatory content that the PV-STATCOM is intended to suppress; integrating its square over the fault-observation window penalizes both the magnitude and the persistence of the oscillation, yielding the objective function below.

The objective function, OJ , is expressed as:

$$OJ = \min \int_{T_1}^{T_2} (i_l - i_{l_ref})^2 dt \quad (2)$$

In this expression, OJ is the objective (cost) function minimized by the optimizer; i_l and i_{l_ref} are, respectively, the instantaneous and reference magnitudes of the PCC line current introduced above; and T_1 and T_2 are the start and end times of the fault-observation window over which the transient response is evaluated.

The AOA minimizes this objective function, thereby determining the optimal gains and lag-compensator settings of the Q-PSO controller.

The AOA is inspired by the basic arithmetic operators used to solve arithmetic problems. Its search process comprises two principal phases: exploration and exploitation. During exploration, the search agents cover a large portion of the search space to avoid premature convergence to local solutions, while exploitation subsequently refines the solutions found. The choice between the exploration and exploitation phases is governed by the math optimizer accelerated (MOA) coefficient, computed as [25]:

$$MOA(C_{Iter}) = Min + C_{Iter} \times \left(\frac{Max - Min}{M_{Iter}} \right) \quad (3)$$

Here, $MOA(C_{Iter})$ is the math-optimizer-accelerated coefficient that governs the exploration/exploitation switch; C_{Iter} and M_{Iter} are the current and maximum iteration counts; and Min and Max bound the MOA function, conventionally set to 0.2 and 0.9, respectively, per the original AOA formulation [25].

The exploration operators of the AOA employ a random strategy—based on division and multiplication—to search widely dispersed regions of the search space in pursuit of better solutions. The corresponding position-update equations are expressed as:

$$xi, j(C_{Iter} + 1) = \begin{cases} \frac{best(x_j)}{MOP + \epsilon} \times ((UB_j - LB_j) * \mu + LB_j), & r2 < 0 \\ otherwise, best(x_j) \times MOP \times ((UB_j - LB_j) * \mu + LB_j) \end{cases} \quad (4)$$

In (4), $xi, j(C_{Iter} + 1)$ is the updated position (candidate gain value) of the i -th search agent along the j -th decision variable (Kp_3 or Ki_3); $best(x_j)$ is the best solution found so far for that variable; MOP is the math-optimizer-probability coefficient, which decreases with the iteration count to narrow the search as the algorithm converges; UB_j and LB_j are the upper and lower bounds of the search space for that gain; μ is a fixed control parameter (conventionally 0.5 [25]) that adjusts the search step; ϵ is a small constant added to avoid division by zero; and $r2$ is a uniformly distributed random number in $[0, 1]$ that selects between the division and multiplication search strategies.

The search space for the AOA and the CS optimization was constrained as follows: both gains were restricted to positive values, with $Kp_3 \in [0, 20]$ and $Ki_3 \in [0, 1000]$, where the upper bounds were chosen to keep the closed-loop PI controller within its linear operating region and avoid actuator (modulation-index) saturation. Both algorithms used an identical population size of 20 search agents and a maximum of 30 iterations per run, to ensure a fair, side-by-side assessment for the two optimizers.

Figure 4 illustrates the flowchart of the AOA-based procedure for optimizing the PI controller to enable optimal PV-STATCOM operation under fault conditions.

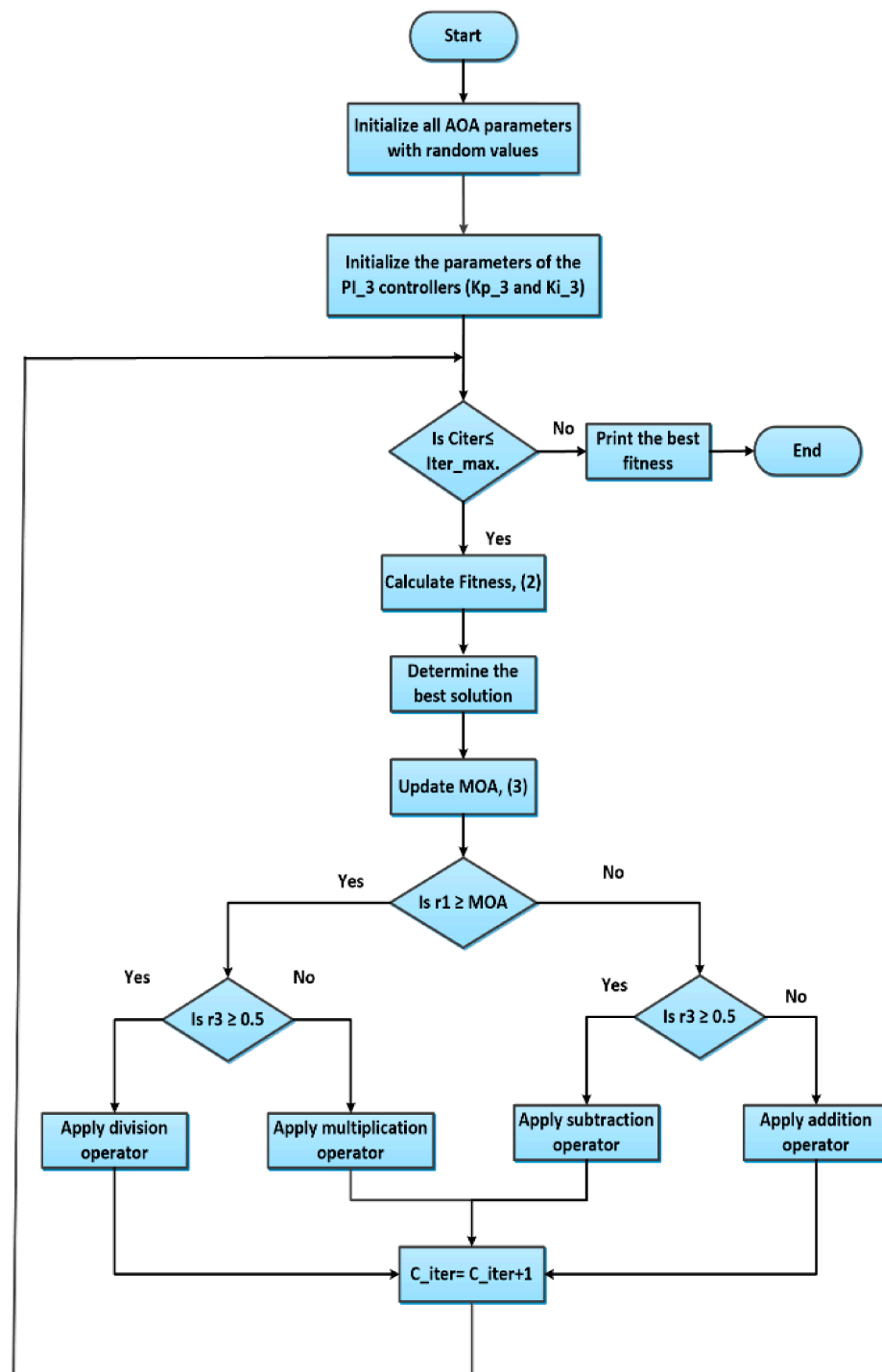


Figure 4. Flow chart of the AOA-based controller tuning procedure.

The AOA-centric calibration method depicted in Figure 4 is encapsulated in pseudocode (Algorithm 1).

Algorithm 1. AOA-based tuning algorithm of the PV-STATCOM PI controller (Kp_3 , Ki_3)

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1: Initialize a population of candidate gain pairs ( $Kp\_3$ ,  $Ki\_3$ ) at random within [LB, UB]
2: Set  $Min = 0.2$ ,  $Max = 0.9$ ,  $\mu = 0.5$ , and the maximum iteration count  $M_{Iter}$ 
3:   for  $C_{Iter} = 1$  to  $M_{Iter}$  do
4:     Compute  $MOA(C_{Iter})$  and  $MOP(C_{Iter})$ 
5:   for each search agent  $i$  do
6:     if  $rand() > MOA(C_{Iter})$  then (exploration)
7:       Update  $x_{i,j}$  using the division/multiplication rule of Equation (4), selected by  $r2$ 
8:     else (exploitation)
9:       Update  $x_{i,j}$  using the corresponding subtraction/addition rule
10:    end if
11:    Evaluate the objective function  $OJ$  (Equation (2)) via closed-loop simulation of the PV-STATCOM with the candidate ( $Kp\_3$ ,  $Ki\_3$ )
12:    Update  $best(x\_j)$  if the candidate improves on the incumbent best solution
13:  end for
14: end for
15: return  $best(x\_j)$  as the tuned ( $Kp\_3$ ,  $Ki\_3$ )

```

To assess the effectiveness of the AOA, a comparison with the CS optimization technique is presented [25,26,32].

4. Results and Discussion

This section presents the simulation results for all operating modes of the proposed controller.

4.1. MPPT Technique

The healthy operating condition is examined first, in the absence of any PSO-inducing disturbance. In this case, $S1$ is active, and the smart-inverter (PV-STATCOM) functionality is disabled. The MPPT performance of the INC-FST scheme is presented and compared with that of the fuzzy-logic-based INC (INC-FL) technique.

In the first test, the irradiance is held constant at 1000 W/m^2 , while the temperature is increased from 25°C to 35°C over the interval from $t = 1 \text{ s}$ to $t = 1.25 \text{ s}$. The temperature rise reduces PV power generation, as shown in Figure 5a; the INC-FST scheme harvests more power with fewer oscillations than INC-FL.

A second test demonstrates the applicability and effectiveness of the proposed INC-FST under variable irradiance. Here, the temperature is held constant at 25°C while the irradiance is reduced from 1000 W/m^2 to 50 W/m^2 between $t = 1 \text{ s}$ and $t = 1.25 \text{ s}$. The reduction in irradiance lowers the generated PV power, as shown in Figure 5b; again, INC-FST outperforms INC-FL in terms of extracted power and reduced oscillations.

4.2. Power Oscillation Damping

A three-phase-to-ground fault is applied at the PCC between $t = 2 \text{ s}$ and $t = 2.25 \text{ s}$. The two optimization algorithms (AOA and CS) are employed to minimize the objective function in (2), thereby determining the optimal parameters of the PI controller (PI_3) that

governs PV-STATCOM operation for PSO damping. The tuned parameters obtained with the two optimization techniques are listed in Table 2.

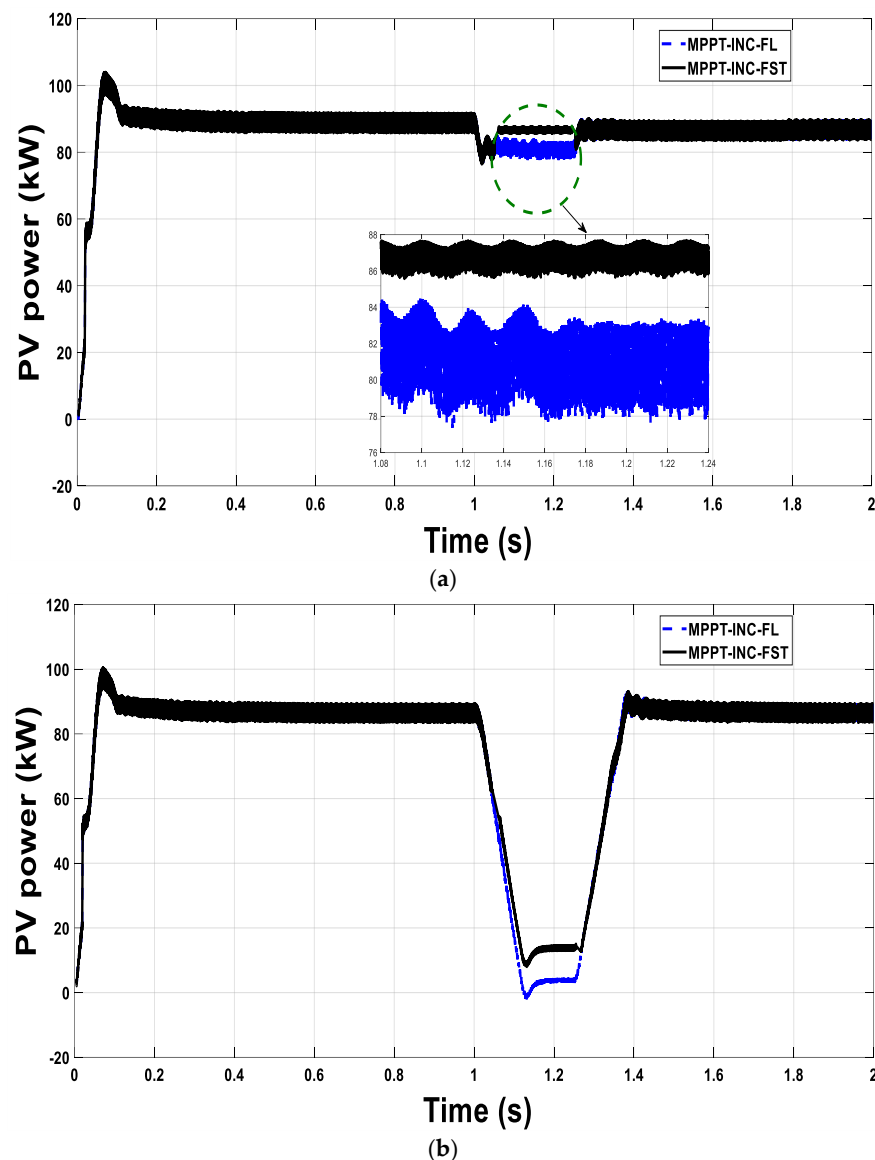


Figure 5. MPPT performance of the PV system. (a) Temperature change at constant irradiance; (b) irradiance change at constant temperature.

Table 2. Optimized PI controller parameters (PI₃).

Technique	K _p ₃	K _i ₃
CS	2.78	415
AOA	6.89	387

Figure 6 shows the dynamic frequency response of the system with and without PV-STATCOM operation during the fault event. Without the PV-STATCOM, the frequency exhibits severe excursions (46–53 Hz) that violate the permissible range specified in the frequency grid code [33]. Such non-compliant behavior would trigger protective islanding of the PV system from the grid, whose subsequent reconnection would require technically demanding resynchronization procedures.

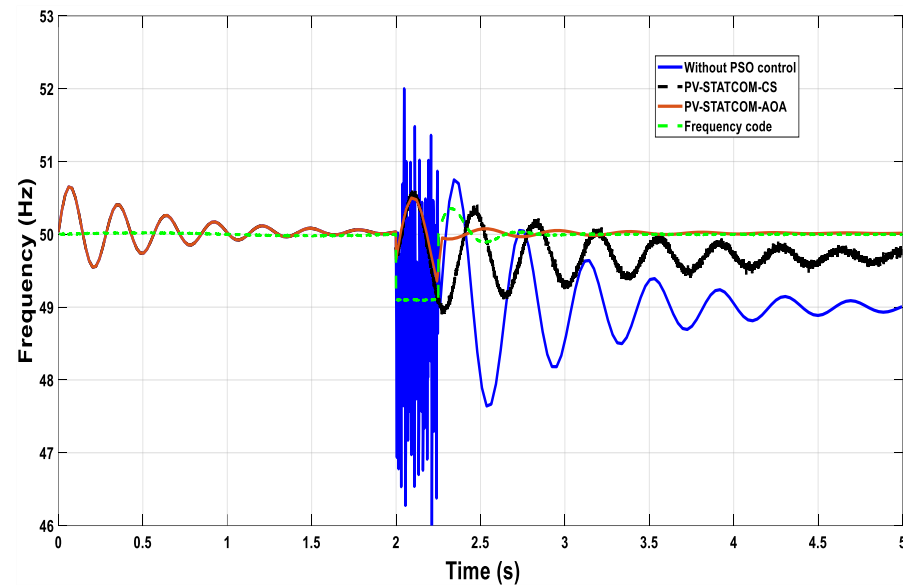


Figure 6. Frequency response during the fault event with and without PV-STATCOM control.

When PV-STATCOM operation is triggered during the fault event—detected through the increase in line current—with optimally tuned PI parameters, the frequency response improves markedly.

A comparative assessment of the two optimization approaches shows that the AOA provides superior frequency regulation compared with the CS. Although both methods improve system performance (CS: 49.35–50.6 Hz; AOA: 49.36–50.49 Hz), only the AOA maintains the frequency continuously within the grid code limits. After fault clearance, the AOA-tuned controller settles at the nominal 50 Hz, whereas the CS-tuned controller exhibits residual oscillations within 49.5–50.05 Hz.

Without PV-STATCOM functionality, the PCC voltage collapses to 0.15 p.u. and subsequently exhibits sustained instability with large oscillations. This voltage profile violates contemporary low-voltage ride-through (LVRT) requirements, taking the US code as an example, and such an event would therefore require disconnection of the PV system from the grid.

With the PV-STATCOM function presented in this study, the PCC voltage profile improves substantially under both optimization techniques (CS and AOA). Both the CS- and AOA-tuned configurations maintain the voltage within a stable range of 1–1.2 p.u., with minimal sag and rapid recovery, in compliance with the US LVRT code, thereby keeping the PV system grid-connected. The AOA outperforms the CS in tuning the PI controller parameters, damping the oscillations, and reducing the maximum overshoot from 20% to 15%.

Based on the superior voltage and frequency profiles shown in Figures 6 and 7, the AOA is adopted as the representative tuning method for all subsequent analyses, and the CS approach is not pursued further.

The AC line-current profile in Figure 8 clearly demonstrates the essential role of the PV-STATCOM in preserving grid integrity during the fault. Under normal pre-fault conditions (0–2 s), both operating configurations deliver the nominal 1.0 p.u. current; the decisive difference emerges at fault inception at $t = 2$ s. The optimized PV-STATCOM-AOA applies a reactive-current support strategy comprising voltage stabilization, active damping of grid oscillations, and controlled oscillatory current injections. Without the PV-STATCOM, the current is unregulated and excessive, causing the protection devices to disconnect the PV system from the grid. After fault clearance, the proposed control gradually re-

stores the current to 1.0 p.u. by $t = 7.0$ s, enabling stable resynchronization and preventing prolonged disturbance—underscoring the PV-STATCOM’s role in converting a grid-tied PV inverter from a potential source of instability into a robust grid-supporting asset during contingencies.

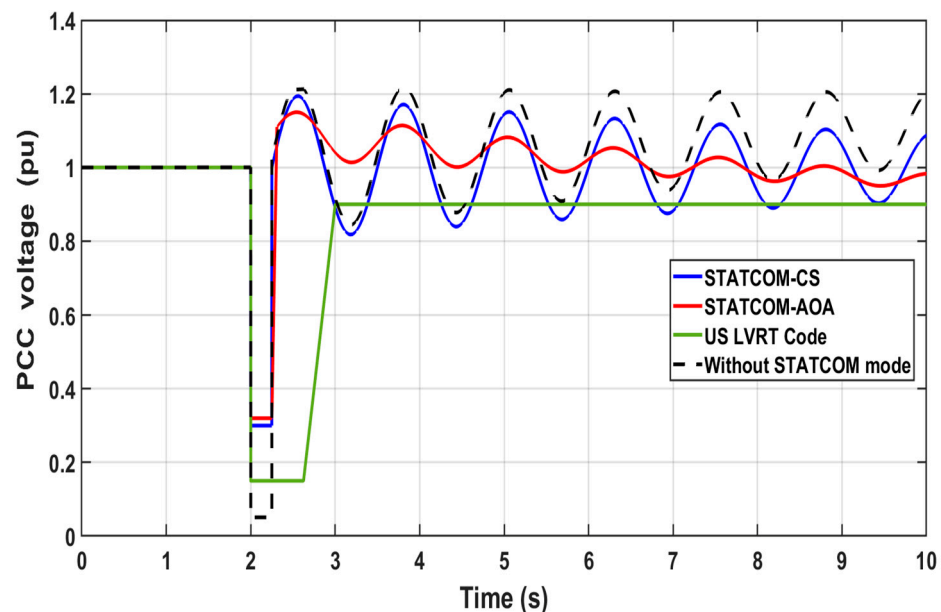


Figure 7. PCC voltage during the fault event with and without PV-STATCOM control.

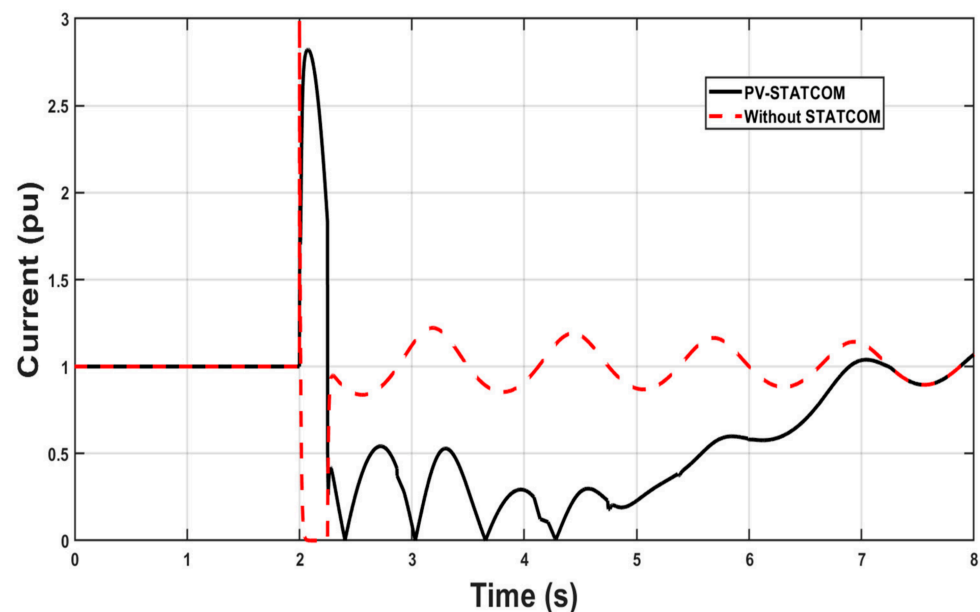


Figure 8. AC line current delivered by the PV inverter to the grid at the PCC.

Figure 9 illustrates the role of the proposed PV-STATCOM strategy before, during, and after the fault. To damp the power oscillations excited by the fault event (2–2.25 s) and ensure rapid grid recovery, the PV-STATCOM must traverse all its operating modes. During the pre-fault period (0–2.0 s), the inverter operates in normal PV mode, delivering its full 86 kW of active power at zero reactive power (unity power factor).

At fault inception ($t = 2.0$ s), the system instantaneously switches to Full STATCOM mode as the voltage sags: active power injection is suspended entirely (0 kW), and the full inverter capacity is devoted to generating the oscillatory reactive power that directly

damps the oscillations. Full STATCOM mode is maintained for 2 s after fault clearance (until $t \approx 4.25$ s) to continue providing the required dynamic voltage support.

The system then transitions to Partial STATCOM mode, in which the active power is ramped from 0 kW to its rated 86 kW over 3 s. During this restoration phase, the inverter capacity remaining after the increase in active-power injection continues to supply oscillatory reactive power, so damping support persists until full power recovery.

At approximately $t = 7.25$ s, the system returns to normal PV mode after stabilizing the grid, restoring nominal power generation, and resuming unity-power-factor operation. This sequential mode transition converts the PV system from a simple DC power source into a dynamic grid stabilizer and back again, highlighting its important role in strengthening system resilience.

4.3. Quantitative Performance Assessment

To consolidate the findings, Table 3 summarizes the key performance indicators extracted from Figures 6–9 for the three configurations: no PV-STATCOM, the CS-tuned PV-STATCOM, and the proposed AOA-tuned PV-STATCOM. Without the PV-STATCOM, the system fails on every criterion: the frequency deviates by up to 4 Hz from nominal, the PCC voltage collapses to 0.15 p.u., and the resulting grid-code violations would force disconnection of the PV plant. Both optimized PV-STATCOM configurations restore compliant operation; however, only the AOA-tuned controller keeps the frequency within the grid-code band throughout the entire disturbance cycle and settles exactly at the nominal 50 Hz after fault clearance.

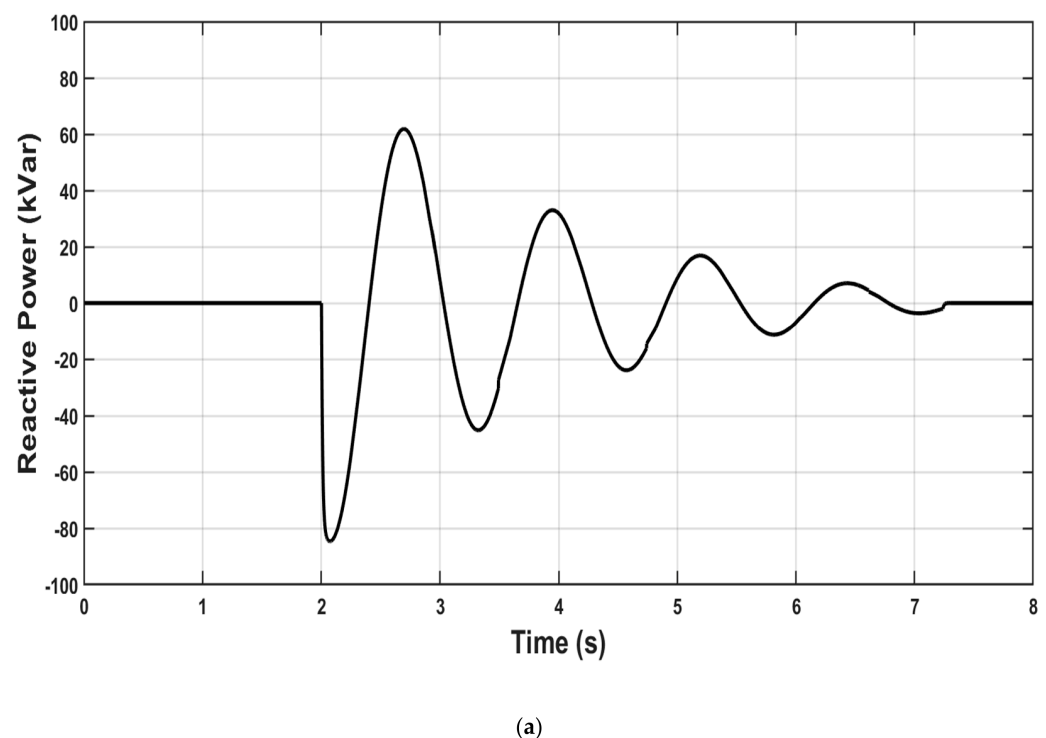


Figure 9. Cont.

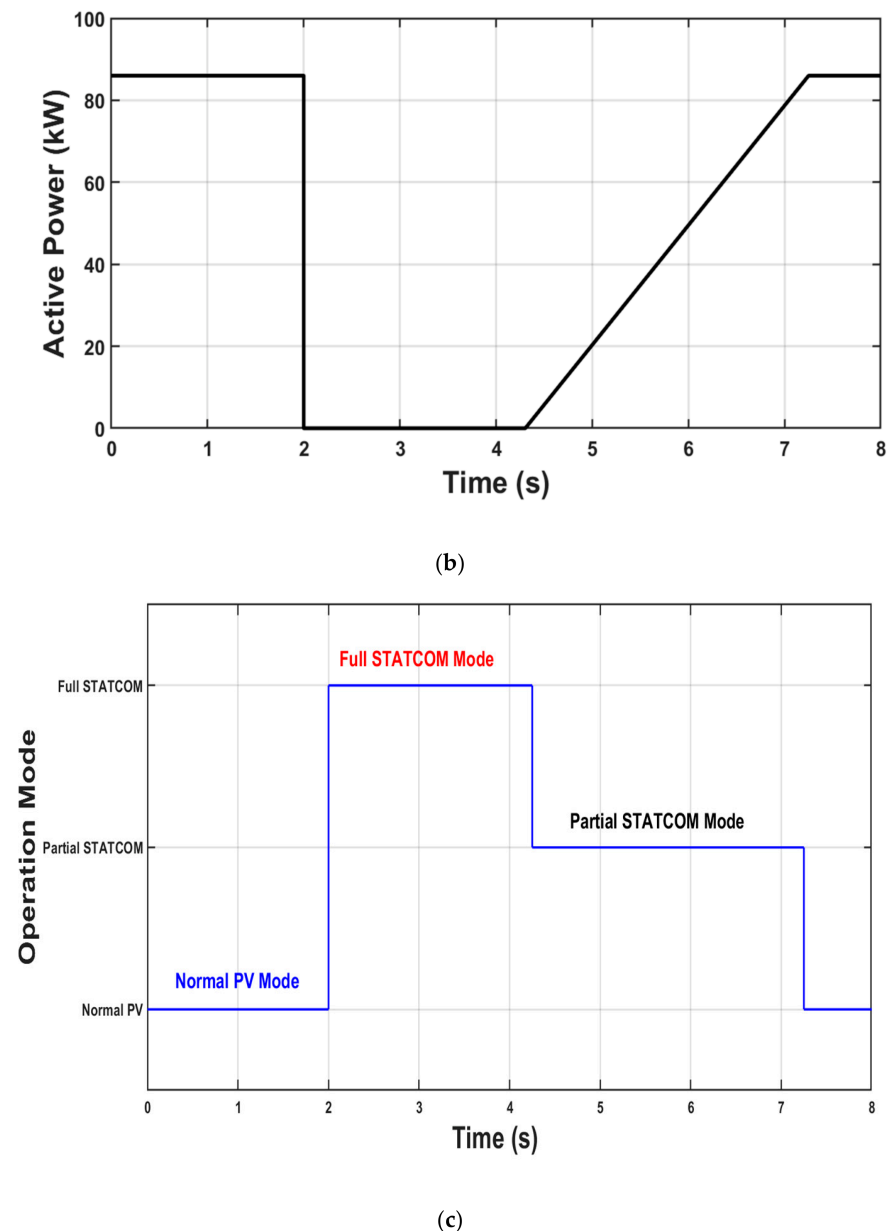


Figure 9. PV-STATCOM performance: (a) reactive power; (b) real power; (c) operating modes.

Relative to the CS-tuned controller, the AOA-tuned controller reduces the maximum voltage overshoot from 20% to 15%—a 25% relative improvement—and narrows the post-fault frequency band from 49.5–50.05 Hz to a monotonic settlement at 50 Hz. The tuned gains in Table 2 are consistent with this behavior: the AOA solution combines a higher proportional gain with a lower integral gain than the CS solution, thereby favoring stronger instantaneous damping and reducing integral-induced overshoot. It is also worth quantifying the cost of the Full STATCOM interval: assuming the pre-disturbance PV power of 86 kW remains available, the active power suspended between $t = 2.0$ s and $t \approx 4.25$ s, and the subsequent 3-s ramp, corresponds to a curtailed energy of only about 323 kJ (≈ 0.09 kWh). This negligible energy sacrifice is exchanged for preserving grid connection and averting the far larger production loss that a protective disconnection and resynchronization would entail. Collectively, the metrics of frequency, voltage, current, and energy cost (Table 3) encompass the parameters commonly used to demonstrate the superiority of AOA tuning over CS across certain control indices. Those include dynamic response characteristics (overshoot, stabilization behavior), adherence to grid codes (frequency and

low-voltage ride-through parameters), and the financial implications of the STATCOM intervention itself.

Table 3. Key performance indicators during the fault event.

Indicator	Without PV-STATCOM	PV-STATCOM-CS	PV-STATCOM-AOA
Frequency excursion during fault (Hz)	46–53	49.35–50.6	49.36–50.49
Frequency grid-code compliance	Violated	Marginal	Compliant
Post-fault frequency behavior	Islanding triggered	Oscillates, 49.5–50.05 Hz	Settles at 50 Hz
Minimum PCC voltage (p.u.)	0.15 (collapse)	Within 1–1.2	Within 1–1.2
Maximum voltage overshoot (%)	—	20	15
LVRT compliance	Violated (disconnection)	Compliant	Compliant
Line-current restoration to 1.0 p.u.	Not achieved	—	By $t = 7.0$ s
Full active-power restoration (86 kW)	Not achieved	—	By $t \approx 7.25$ s

5. Conclusions

This study developed and validated an improved control strategy that enables a grid-connected PV inverter to operate as a STATCOM during grid faults, thereby enhancing system stability through active power-oscillation damping. The core of the strategy is the optimal tuning of the PI controller parameters using the AOA. The AOA-optimized PV-STATCOM controller achieved seamless mode transitions from normal active power generation to full reactive power support during the fault, and back to normal operation through a controlled restoration phase. During the fault, it prevented voltage collapse, maintained the PCC voltage within the LVRT envelope, and injected precisely controlled oscillatory reactive current to damp the electromechanical oscillations. These time-domain signals are not the primary objective of this study; they serve as the clearest markers of its success. These responses demonstrate accelerated convergence with reduced transient peaks, providing definitive evidence that the control technique successfully reduces oscillation duration and magnitude, the primary aim of this research.

A comparative analysis with a controller tuned using the CS algorithm demonstrated the superiority of the AOA technique. While both methods provided essential STATCOM functionality and complied with the grid codes, the AOA-optimized controller exhibited better dynamic performance, achieving a more damped oscillation profile and reducing the maximum voltage overshoot from 20% to 15%. This tighter regulation reduces electrical stress on grid components and yields a smoother recovery trajectory.

Furthermore, the results confirmed that without STATCOM functionality, the PV system would experience severe voltage collapse, violate LVRT requirements, and risk disconnection, whereas the proposed scheme maintains a continuous, grid-supportive connection.

Future work will extend the proposed scheme to multi-machine and multi-inverter test systems, quantify the achieved damping ratios via modal (eigenvalue) analysis, benchmark the AOA against additional metaheuristic techniques via statistically repeated runs, and experimentally validate the controller through hardware-in-the-loop testing. The economic

implications of the temporary real-power curtailment during Full STATCOM operation will also be assessed.

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Conflicts of Interest: The author declares no conflicts of interest.

Appendix A

Table A1. PV system data.

Description	Specifications
PV Panel type	SunPower SRR-315E-WHT-D
Open circuit voltage	64.6 V
Short circuit current	6.14 A
The voltage at max power	54.7 V
Current at max power	5.76 A
The maximum output power	315 W

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