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POWER QUALITY ENHANCEMENT USING DUAL-STRATEGY SPIDER WASP OPTIMIZATION ALGORITHM IN PHOTOVOLTAIC SYSTEMS

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Abstract

In Photovoltaic (PV) system, power quality enhancement emphases on minimizing voltage fluctuations and harmonic distortions caused by intermittent solar energy generation. It ensures reliable and stable power delivery by enhancing voltage regulation and balancing power flow. Effective power quality management increase overall effectiveness and PV lifespan system while maintaining grid stability. However, power quality in PV system arises from voltage fluctuations and harmonics caused by solar energy intermittency that affects grid stability and equipment performance. This research proposes Dual-Strategy Spider Wasp Optimization Algorithm (DS-SWOA) to enhance power quality in PV system. In traditional SWOA, circle map and dynamic adaptive boundary adjustment are the dual strategies considered which optimize system parameters by effectively initializing population and dynamically adjusting boundaries. A 3-level Neutral Point Clamped (NPC) inverter is used which enhance voltage quality and minimize harmonic distortions. Boost DC-DC converter improve power quality by effectively stepping up voltage which ensures stable power delivery to grid despite fluctuations in solar generation. The proposed DS-SWOA obtains a less Total Harmonic Distortion (THD) of 0.04% compared to existing methods like Third-Order Sliding Mode Control (TOSMC).

Keywords: Boost DC-DC converter, Dual-Strategy Spider Wasp Optimization Algorithm, Photovoltaic, Power quality enhancement, 3-level Neutral Point Clamped.

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1. Introduction

The growing integration of renewable energy resources such as photovoltaic (PV) and wind systems has transformed modern distribution networks. While these technologies significantly reduce dependency on conventional fossil-fuel generation and enhance system sustainability, they also introduce new challenges to the stability and quality of power supply [1], [2]. Power quality (PQ) disturbances—such as voltage fluctuations, harmonic distortion, and reactive power imbalance—can negatively affect both utilities and consumers, leading to reduced efficiency, equipment failures, and operational risks [3], [4]. Maintaining acceptable PQ has therefore become a critical research domain, particularly in systems with high penetration of distributed energy resources (DERs). Several studies have focused on advanced control and optimization strategies to mitigate harmonics and stabilize voltage profiles [5]–[8]. Techniques such as sliding-mode control, predictive filtering, and hybrid compensation approaches have been widely investigated for enhancing PQ in PV-based systems and microgrids [9]–[13]. These methods aim to balance the trade-off between fast dynamic response and robustness against nonlinear and uncertain operating conditions.

Recent developments have emphasized the role of artificial intelligence (AI)-driven and bio-inspired optimization algorithms in improving PQ performance. Algorithms such as swarm-based metaheuristics, fuzzy logic-based maximum power point tracking (MPPT), and hybrid neural-network controllers have been successfully applied to ensure reliable operation under varying load and environmental conditions [14]–[18]. Compared with conventional techniques, these methods exhibit stronger adaptability to system uncertainties and better convergence toward optimal PQ indices [19], [20]. In addition, the placement of compensating devices—such as distribution static compensators (D-STATCOM), shunt active power filters, and multilevel inverters—has proven effective in mitigating PQ issues [21]–[25]. Optimal allocation of such devices, combined with intelligent control, ensures reduced harmonic distortion, stable voltage regulation, and enhanced energy efficiency across the grid.

Thus, the motivation of this study is to address the persistent PQ challenges in renewable-integrated systems by applying an advanced optimization framework. By combining intelligent placement of compensating devices with robust control strategies, the proposed work aims to enhance overall PQ indices while supporting stable and sustainable power system operation.

The primary contribution of this research is explained as

- The circle map and dynamic adaptive boundary adjustment are the dual strategies incorporated in conventional SWOA to initialize population, solves local optima issue, and enhance convergence. This increase voltage stability, overall power quality, and minimize harmonics.
- The P&O based MPPT effectively tracks the MPP by continuously adjusting operating voltage which ensures optimal extraction from PV systems.
- Boost DC-DC converter stabilize and regulates voltage to minimize power fluctuations whereas 3-level NPC inverter reduce switching losses and THD that leads to enhanced PQ and efficiency in PV systems.

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The remainder of this paper is structured as follows: Section 2 reviews the relevant literature on power quality improvement methods. Section 3 outlines the proposed methodology, while Section 4 presents the simulation scenarios and results. Finally, Section 5 concludes the work with key findings and future research directions.

2. Literature Survey

Ehsan Akbaria and Abbas Zare Ghaleh Seyyedi [19] introduced a SOSF with Proportional Integral (PI) controller using 3-level NPC inverter to enhance the power quality. A PV system employs P&O approach for tracking MPPT and utilize boost DC/DC converter. A SOSF generate green output by employing PV arrays associated with HAPF via DC link. With greater accuracy and fewer mathematical procedures, this technique helps to obtain the fundamental real term of imbalanced load current. However, SOSF-PI minimized dynamic response and sensitivity to parameter variations due to SOSF introduce phase delay which affect transient performance whereas PI struggles with harmonic distortion.

Brahim Deffaf *et al*. [20] presented a Synergetic Control with PLL for three phase 3-level NPC based SAPF for power quality enhancement. The 3-level NPC has the ability in managing higher power levels by maintaining fewer switching losses that leads to high reliability and efficiency. The 3-level NPC represents a less harmonic distortion in output waveform that results in good filtering performance in SAPF. Moreover, the SC-PLL obtains a better performance while the source voltage was distorted or unbalanced. Nevertheless, SC-PLL suffer from increased THD under rapid load changes due to dynamic adaptation introduce oscillations which degrade harmonic performance.

Zoubida Amrani *et al.* [21] developed a Finite Control Set- MPC based on 3LNPC with SAPF in PV for power quality enhancement. Initially, PV was applied associated with DC/DC boost converter handled by MPPT which ensures optimized power extraction. This converter controls 2-split DC link capacitor associated with input side of 3-level NPC that act as primary part of shunt active power. Moreover, coupling inductors was used containing low-pass filter by enabling the harmonic suppression which ensures the combination of 3-level NPC to grid. However, FCS-MPC suffer from high computational complexity which lead to slow response in practical applications.

Fatiha Bouhadji et al. [22] proposed a 3rd Order Sliding Mode Control approach to achieve MPPT in PV systems, aiming to improve overall power quality. The method utilizes a three-level NPC inverter along with a PLL to convert DC power to AC, while a DC–DC converter controlled by TOSMC optimizes the PV power output. The PV system was connected to the AC grid, and a Shunt Active Power Filter (SAPF) was employed to supply power to a nonlinear load efficiently. However, the TOSMC method exhibited high sensitivity to parameter variations and system uncertainties, which could negatively affect the accuracy of power tracking.

Abdelouahad May *et al.* [23] suggested a two-phase grid tied PV using high-gain DC-DC converter managed by FCS-MPC to enhance power quality. A DC link based control was employed to ensure accurate grid reference generation in current and high dynamic

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performance. This balances DC link with high reference voltage than grid current's peak value. Nonetheless, the proposed method is susceptible to variations in grid voltage, which can adversely affect the stability and effectiveness of the control strategy.

From the overall analysis, the existing methods had limitations like minimized dynamic response and sensitivity to parameter variations, increased THD under rapid load changes, and challenges in grid voltage fluctuations which affects grid stability and equipment performance. To solve this issue, the DS-SWOA is proposed to enhance power quality effectively by optimizing control parameter. By ensuring optimal power and stabilizing grid voltage, the DS-SWOA effectively improves equipment performance and grid stability.

3. Proposed Methodology

In this research, the DS-SWOA is proposed to enhance the power quality system effectively. Initially, PV module is optimized to minimize energy cost which covers load demand and voltage as well as capacity are identified by connecting PV panel neither series nor in parallel connection. DC-DC boost converter is performed to regulate and stabilize PV's output voltage. In PV system, MPPT is considered to maximize power extraction whereas 3-level NPC inverter is applied to balance neutral point. Fig.1 shows a block diagram of DS-SWOA under numerous loads.

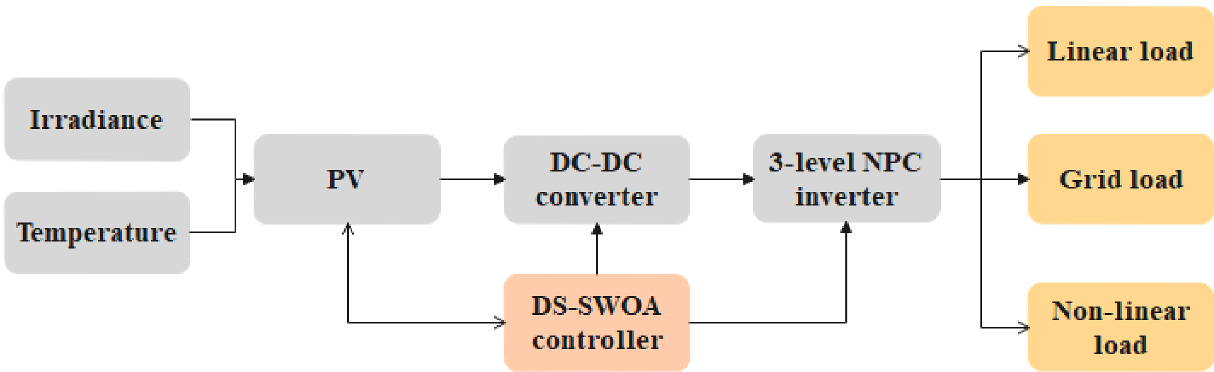

Figure .1 DS-SWOA proposed Block diagram under numerous loads

3.1 PV Array Modeling

PV array is essential to precisely model the PV system's response under changing conditions. A solar cell is a primary unit of PV array acts as semiconductor PN junction. The most of the PV array has an inverter for transforming DC into AC which is utilized to power loads such as lights, motors, and another appliance. The separate component of PV array is connected normally in parallel and series combination to attain required voltages. The mathematical formula for PV current is represented in eq.(1)

$$I = I_{pv} - I_{sh} - I_D \quad (1)$$

Where I_{pv} indicates insolation current, I represents cell current and Table.1 demonstrates the PV array specification and then PV output is fed into DC-DC boost converter.

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Table 1. PV array specifications

Parameters	Values
Temperature coefficients	-0.27269 (%/°C)
Voltage at maximum power point	54.7 V
OC voltage	64.2 V
Diode saturation current	0.000063×10^{-5} A
Current at MPP	5.58 A
Diode ideality factor	0.93504
Maximum power	305.226 W

3.2 Modeling of Boost Converter

After PV modeling, DC-DC boost converter is applied for regulating and stabilizing output voltage of PV system which ensures consistent power supply to grid or load. It enhances low voltage generated by PV to required level at DC-link side of inverter which eliminates requirement for transformer at inverter's output when connected to grid. Boost converter is based on PWM to increase power extraction from Photo voltaic source. The inductor, switching device, diode, and capacitor are used to determine voltage level which is represented in Fig.2

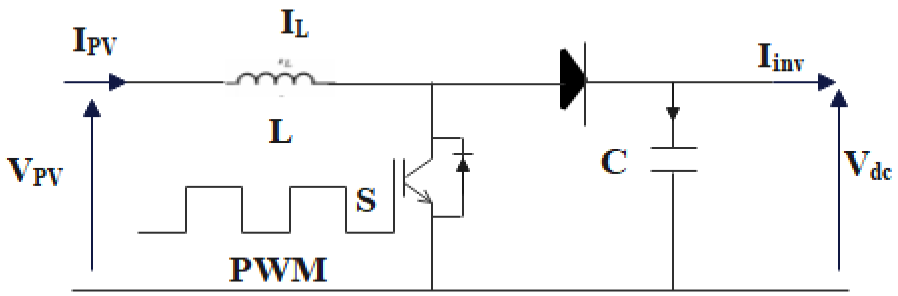

Figure 2. Structure of Boost converter

A converter is indicated by a different system of equation known as instantaneous model where the switch state is defined as 1 when closed (S=1) and 0 when opened (S=0). In this evaluation, ideal switches are analyzed in equations (1) and (2)

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$$\frac{d}{dt}I_L = -(1-S)\frac{1}{L}V_{dc} + \frac{1}{L}V_{PV}$$
(2)

$$\frac{d}{dt}V_{dc} = (1-S)\frac{1}{C}I_L - \frac{1}{C}I_{inv}$$
(3)

Where I_L indicates boost input I, V_{PV} represents boost input V, I_{inv} denotes inverter input I, V_{dc} illustrates boost output V, L depicts boost inductance, and C determines boost capacitance. The relationship among PV array output voltage V_{pv} and boost converter output voltage V_0 is calculated in eq.(4) for continuous current conduction whereas based on equation (5), the DC bus capacitor is sized.

$$\frac{V_0}{V_{pv}} = \frac{T}{t_{off}} = \frac{1}{1-D}$$
(4)

$$C_{cc} = \frac{P_{PV}}{2.\omega.V_{cc}^{*}.\triangle V}$$
(5)

Where $\triangle V$ denotes voltage ripple amplitude that is equivalent to 10% of peak grid voltage V_g, ω determines generated sine wave's frequency pulsation, P_{PV} represents nominal PV module power, and V_{cc}^{*} depicts average voltage across capacitor using equation (6)

$$V_{cc}^{*} = \mu\sqrt{3V_m}.(\mu > 1)$$
(6)

Thus, the boost converter enhances power quality by stabilizing and regulating the DC voltage which ensures the consistent supply to grid and inverter. It minimizes ripple and voltage fluctuations that enhance the total reliability and effectiveness of power system. Moreover, the converter eliminates the need for bulky transformer which makes the system more cost-effective and compact. Also, it provides rapid dynamic response to varying solar irradiance that ensures stable power injection into grid. Then, the converter output is passed through MPPT control for extracting maximum possible power from PV by continuously adjusting operating point for matching optimal current and voltage.

3.3 MPPT using P & O Method

After modeling boost converter, P&O method for MPPT [24] is applied which enhance power quality by dynamically adjusting the operating point to maximize power extraction from renewable sources. It enhances voltage and current stability by minimizing fluctuations which ensures efficient energy conversion. Moreover, it reduces harmonic distortion and power losses contributes to overall grid stability and performance. Fig.3 depicts flowchart of P&O method

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via continuous observation cycle and adjustment to obtain MPP.The iterative procedure involves comparing voltage and power at successive intervals, K and k−1, to estimate the trajectory toward the Maximum Power Point (MPP). A small variation in voltage modifies the PV panel's power output—if the change is positive, the algorithm retains the adjustment direction, whereas a negative variation indicates divergence from the MPP, prompting a reduction in perturbation to guide the system closer to the optimal point.

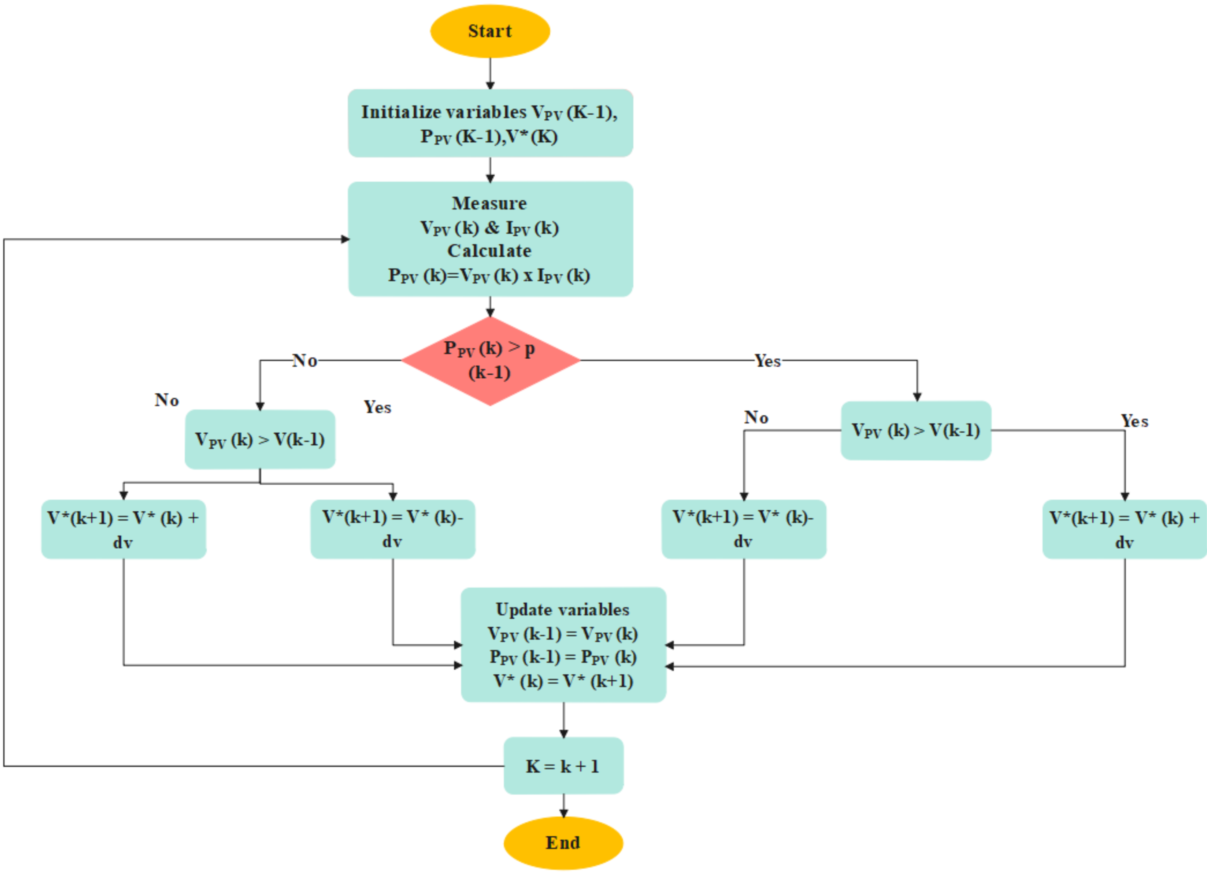

Figure 3. Flowchart of P&O method

The flowchart in figure 3 contains previous and actual values of photo voltaic panel voltage, power, and current represented as $V_{pv}(k), V_{pv}(k-1), P_{pv}(k), P(k-1), I_{pv}(k)$. Moreover, the output voltage perturbation is denoted as dV and V^* which is an updated value utilized to track the optimal voltage of photo voltaic panel. Then, the 3-level NPC inverter is performed to minimize distortion, enhance output voltage quality, and efficiency.

3.4 3-Level NPC Inverter

It is a multilevel inverter topology that generates three voltage levels (positive, negative, and zero) by utilizing clamping diodes to balance neutral point. The primary concern of 3-level NPS is balancing and stabilizing capacitor's DC voltage. Moreover, single supply performs DC-bus to converter causing issues with lower and upper arms of DC-link capacitor. To solve this issue, numerous solutions are introduced, for example, DC link of converter is supplied with two segregated DC sources by installing voltage balance regulation circuitry. Figure 4 shows a 3-level NPC inverter which is an altered 2-level inverter by including 2 updated switches in all stage. The C1 and C2 are the two capacitors to isolate DC bus voltage that causes neutral point P which generates an additional voltage level for creating 3-level inverter. Clamp diode confines the voltage stress over the switches via voltage across capacitor which is equivalent to $U_{dc}/2$. When switches T1 and T2 are "on", the output of inverter is equivalent to $U_{dc}/2$ whereas T3 and T4 are "on", the output is $-U_{dc}/2$. While the T2 and T3 are "on", the 3-level inverter produce zero level and Table 2 represents the 3-level inverter switching modes in detail. Then, due to attaining the maximum power from PV exposed to non-uniform solar irradiance, a metaheuristic algorithm is proposed to design global MPPT.

Table 2. Switches states of 3-level inverter

Inverter output voltage	Phase "A" switches states				Switching states
	T1	T2	T3	T4	
$U_{dc}/2$	On	On	Off	Off	1
$-U_{dc}/2$	Off	Off	On	On	-1
0	Off	On	On	Off	0

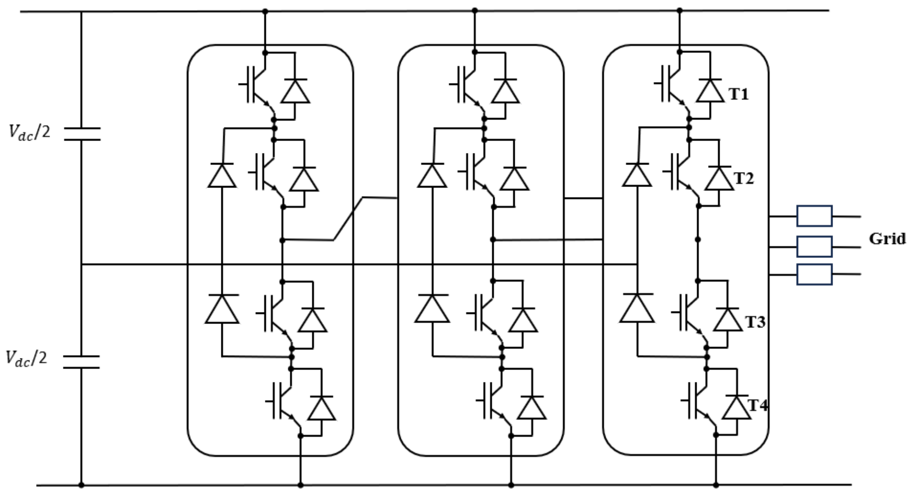

Figure 4. Structure of 3-level NPC inverter

3.5 Proposed DS-SWOA

The DC-DC converters are controlled by utilizing DS-SWOA which is easy to implement with fewer parameters and efficiency for combining PV into grid which obtains smooth power quality. Furthermore, it has a superior fitness solution with better convergence speed and a response of controller is analyzed under changing irradiance and constant temperature. This leads to represent the proficiency of controller at enhancing the system performance. Initially, global MPPT is performed by DS-SWOA to solve mismatching phenomena issues associated with partial shading. The performance of DS-SWOA based MPPT is able to attain global MPP which allows to enhance in PV system effectiveness. The input of DS-SWOA computes PV

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power and conversion rate where the variation in reference current is represented as output. DS-SWOA is applied to achieve maximum global point that exploits the enhanced power extracted in PV. Compared to existing methods like Coyote Optimization Algorithm (COA) and Hunter Prey Optimization Algorithm (HPOA), the SWOA [25] provides better convergence speed and accuracy in power quality enhancement. SWOA effectively balances exploitation and exploration which shows better stable solutions in complex environments. Unlike COA and HPOA, SWOA's co-operative search mechanisms performs effective for optimizing power systems with varying operational conditions. The Spider Wasp Optimization Algorithm (SWOA) draws inspiration from the natural behaviors of female spider wasps, including nesting, hunting, and mating, and incorporates distinctive update mechanisms to tackle Nondeterministic Polynomial (NP)-hard problems.

Initialization: In addressing the optimization issue, it is required for generating initialized individuals among problem boundaries which is represented in equation (7)

$$SW_i = LB + r \odot (ub - lb)$$
(7)

Where SW_i represents information of i^{th} female individual, lb and ub denotes lower and upper bound, and r determines D-dimensional random vector in [0,1] range. A N individuals are established into initialized population for following iterative process is indicated in equation (8)

$$SW_{Pop} = \begin{bmatrix} sw_{1,1} & sw_{1,2} & \cdots & sw_{1,D} \\ sw_{2,1} & sw_{2,2} & \cdots & sw_{2,D} \\ \vdots & \vdots & \vdots & \vdots \\ sw_{N,1} & sw_{N,2} & \cdots & sw_{N,D} \end{bmatrix}$$
(8)

Searching stage: In this stage, a female spider wasp haphazardly explores the population space at constant step size to determine appropriate spiders for feeding larvae using equation (9). Assume that sometimes female spider wasp loses spider track falling from sphere, The female wasp explores the vicinity surrounding the location where a spider is found, as represented by equation (10).The mathematical formula for search stage is represented in equation (11) to determine more significant areas.

$$SW_i^{t+1} = SW_i^t + \mu_1.(SW_a^t - SW_b^t)$$
(9)

$$SW_i^{t+1} = SW_c^t + \mu_2.(LB + r \odot (ub - lb))$$
(10)

$$SW_i^{t+1} = \begin{cases} Equation\ (8) & r_2 < r_3 \\ Equation\ (9) & otherwise \end{cases}$$
(11)

Where SW_c^t represents random individual in population, μ_2 indicates search direction, r_2 and r_3 denotes random number in [0,1] range.

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Following and escaping behavior: After determining prey location, prey is hunted by female spider wasp using equation (12). The trade-off among fleeing and hunting behaviors by randomization is represented in equation (13).

$$SW_i^{t+1} = SW_i^t + C.|2.r \odot SW_a^t - SW_i^t| \quad (12)$$

$$SW_i^{t+1} = SW_i^t \odot vc \quad (13)$$

$$SW_i^{t+1} = \begin{cases} Equation\ (12) & r_2 < r_3 \\ Equation\ (13) & otherwise \end{cases} \quad (14)$$

Where C indicates distance control factor that minimize linearly from two to zero. The searching behavior is utilized to determine region which involves global optimal solution and then following and escaping behavior is employed. Equation (15) is applied to weigh these two behaviors

$$SW_i^{t+1} = \begin{cases} Equation\ (11) & r_1 < k \\ Equation\ (14) & otherwise \end{cases} \quad (15)$$

Nesting behavior: Meanwhile, female spider wasp includes numerous nesting techniques, two process are determined in SWOA. Initial one is to pull a spider over most appropriate area for female spider wasp which is represented in equation (16). The next one is to choose female spider wasp randomly from construct nests and population depending on location using equation (17).

$$SW_i^{t+1} = SW^* + \cos(2\pi l).(SW^* - SW_i^t) \quad (16)$$

$$SW_i^{t+1} = SW_a^t + r_1|\gamma|.(SW_a^t - SW_i^t) + (1 - r_2).u \odot (SW_b^t - SW_c^t) \quad (17)$$

These two nesting approaches are weighted based on equation (18). At last, the three behaviors are weighted using equation (19)

$$SW_i^{t+1} = \begin{cases} Equation\ (16) & r_2 < r_3 \\ Equation\ (17) & otherwise \end{cases} \quad (18)$$

$$SW_i^{t+1} = \begin{cases} Equation\ (15) & r_2 < r_3 \\ Equation\ (18) & otherwise \end{cases} \quad (19)$$

Mating: The female spider wasp's mating behavior is considered to produce a new spider wasp using equation (20)

$$SW_i^{t+1} = Crossover(SW_i^t, SW_m^t, CR) \quad (20)$$

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Where $Crossover$ represents crossover operation among solution SW_i^t and SW_m^t with crossover probability CR and SW_m^t indicates i^{th}male and female spider wasp.

Population reduction and memory optimization: At last, number of female spider wasps is optimized which enable for better outcomes and rapid convergence using equation (21)

$$N = N_{min} + (N - N_{min})\, k$$
(21)

Where $N_{\,min}$ determines minimal population size. Later, updated individuals are compared with prior generation and global optimal individuals are stored.

3.5.1 Improved Strategies

However, the SWOA suffer from random initialization which leads to inefficient convergence or poor performance if initial values are far from optimal regions. Moreover, predation trap boundary minimizes linearly with no. of iteration increases and wandering boundary is moderately single that is easy to lose the population diversity and has local optima. Therefore, DS-SWOA is proposed to overcome this issue which enhance solves convergence and avoids local optima effectively which is described below in detail.

Circle Map: It is used to initialize the population which minimize probability of initializing boundary points and avoids out-of-bounds for updating position. This leads to enhance the initial population and increase search effectiveness. Both the pseudo-random and chaotic map have unpredictability and randomness but chaotic map contains some regularity instead of pseudo-random for obtaining better outcomes. Numerous chaotic maps are presented like circle, intermittency, Chebyshev, logistic, sinusoidal, singer, tent, and iterative map. To place spider's initial position as near to center as possible, circle map is employed for initialization which is expressed in equation (22)

$$X_{K+1} = mod(X_K + a - \frac{b}{2\pi}\sin(2\pi X_K), 1)$$
(22)

Where $mod()$ represents mod function, X_1 is acquired from random function with (0,1) function, and K indicates integer, $a = 0.5, b = 0.2$ respectively.

Dynamic adaptive boundary adjustment: In traditional SWOA, the trap boundary size is minimized linearly as no. of iteration maximize. Nevertheless, the mechanism does not reflect present performance dynamically and minimize the model's diversity. Therefore, dynamic adaptive boundary adjustment is applied to solve this issue using equation (23)

$$I = 10^w \frac{t}{T} \times (1.5 - \cos(\frac{t\pi}{2T} rand))$$
(23)

Where $rand$ indicates random number which is distributed uniformly among (0,1). The enhanced expression includes dynamic parameter that enable size of trap boundary represents a non-linear decreasing trend. By adjusting the trap boundary's range, randomness and diversity of random walk is maximized as well as global exploration is enhanced.

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Fitness function: Once, the difference of output power is fulfilled, the process is re-initialized that is represented in equation (24)

$$\left|\frac{P_{real}-P_m}{P_m}\right| > \triangle P$$
(24)

Where P_{real} denotes actual output power, P_m represents PV output power, and $\triangle P$ indicates output power change threshold that is fixed as 0.2. Then, the mathematical equation of duty cycle is formulated in equation (25)

$$D_i(k+1) = D_i(k) - B^t H^t$$
(25)

Where $D_i(k+1)$ determines new duty cycle value. The fitness function of proposed DS-SWOA is represented in equation (26)

$$Pd_k^i > Pd_k^{i-1}$$
(26)

Where d demonstrates duty cycle, P refers to power, i denotes number of present spider, and k represents number of iterations. Thus, the circle map ensures diverse and well-distributed initial solution and dynamic adaptive boundary fine-tunes the search space solves local optima issue which results in better power quality enhancement in Photo voltaic system.

4. Simulation Results

The presented DS-SWOA algorithm was implemented and simulated using MATLAB R2020b with 128 GB RAM, i7 intel processor, and windows 10 operating system. This section provides the simulation outcomes associated via PV which operates with proposed DS-SWOA to extract maximum power. A grid-tied PV was constructed and later PQ is determined by utilizing DS-SWOA optimization method. The proposed DS-SWOA manages the duty ratio of boost converter to improve the power quality effectively.

4.1 Performance Analysis

Figure 5 indicates a performance analysis of RMS voltage. RMS is an effective value of AC voltage that determines the equivalent DC voltage which delivers the same power to a load. Sustaining stable RMS voltage is vital to ensure reliable process of sensitive electrical equipment that minimize power losses. The analysis of RMS voltage in given plot represents the three-phase voltage variation over time. With minor fluctuations, a voltage remains stable at 6.35 kV which shows better voltage regulation. Moreover, a transient disturbance is observed at 1 second approximately in switching event or disturbance which is rapidly alleviated.

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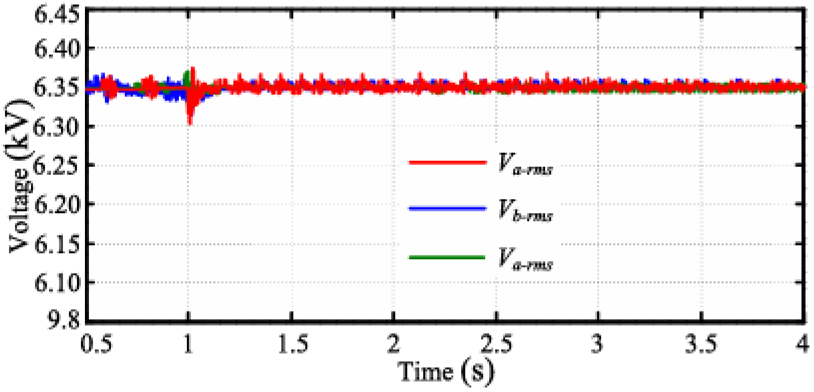
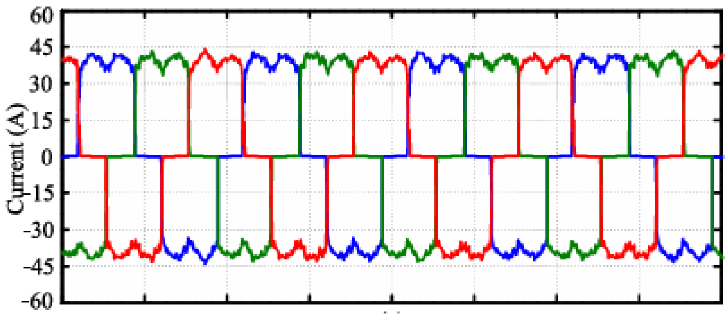


Figure 5. Analysis of RMS voltage

Figure 6 represents current waveforms of load, inverter, and grid under an unbalanced nonlinear loading condition. In the load current (fig. a) significant imbalance and distortions are observed because of non-linear loads which introduce harmonics into the system. The inverter current (fig. b) indicates that inverter actively compensates for these distortions by considering opposite-phase harmonics. Moreover, the grid current (fig. c) remains approximately sinusoidal and balanced despite of non-linear loads. This determines the inverter's role in the enhancement of power quality by functioning as an active power filter. It minimizes THD effectively which ensures cleaner power supply to the grid. Hence, it increases overall system efficiency and avoids adverse effect on electrical equipment. Furthermore, maintaining sinusoidal grid current assist in enhancing performance and reliability of power distribution network.



a) Load

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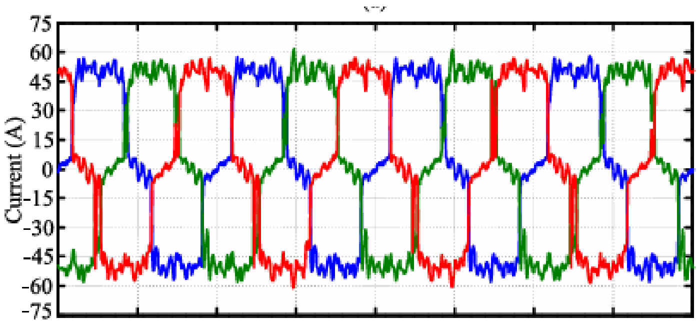
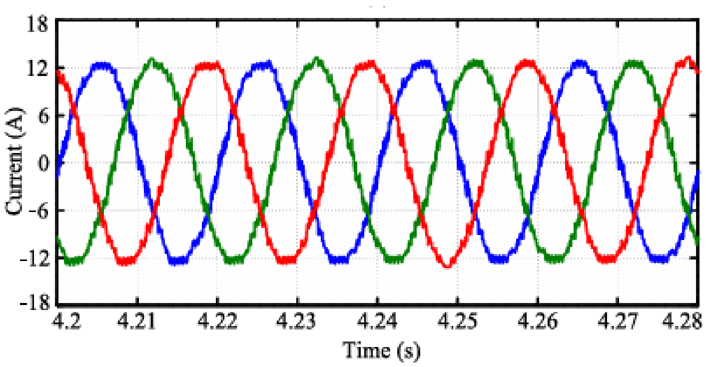


b) Inverter



C) Grid under unbalanced non-linear loading condition

Figure 6. Analysis of current waveforms

Figure 7 demonstrates the performance analysis of sharing reactive power between inverter, grid, and load over time. Initially, the reactive power is nearly zero for all components before 2 seconds. At around 2 seconds, load experience sudden enhancement in reactive power demand which reaches 80kVAR approximately. Subsequently, inverter immediately responds by supplying nearly whole reactive power requirement which is represented in violet color closely matching the load power. The grid produces only a less amount of reactive power which remains close to zero. Therefore, this determines that inverter effectively compensates for reactive demand in power which minimize burden on grid. Such, reactive power sharing increase power quality by minimizing losses and enhancing voltage stability in distribution network.

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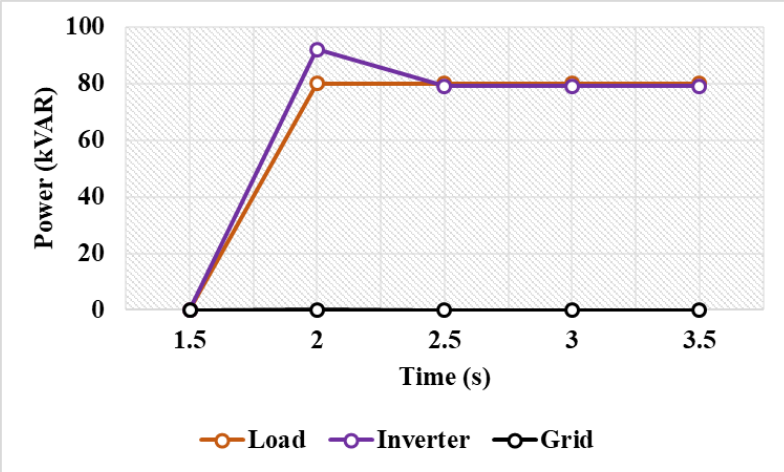

Figure 7. Analysis of sharing reactive power among load, inverter, and grid

Table 3 demonstrates the performance analysis of different optimization methods. The existing methods like COA, HPOA, and SWOA are compared with proposed DS-SWOA. While compared to these methods, the proposed DS-SWOA obtains a less performance of THD of 0.44% due to its adaptive and dual-strategy search mechanism. DS-SWOA effectively decrease harmonics by choosing optimal switching and controls reactive power. It has the ability in balancing global and local search that assist in fine-tuning power quality solutions. Moreover, it adapts to dynamic load changes, minimize voltage distortions, and ensures stable RMS voltage. This leads to enhance current and voltage waveforms and results in better overall power quality.

Table 3. Performance analysis of different optimization methods

Method	PV Efficiency	Response Time (s)	Boost Converter Efficiency	THD (%)
COA	0.897	0.12	0.76	0.64
HPOA	0.923	0.08	0.82	0.52
SWOA	0.948	0.06	0.85	0.49
DS-SWOA	**0.999**	**0.04**	**0.90**	**0.44**

4.2 Comparative Analysis

Tables 4 and 5 provides a performance analysis of existing methods. In table 4, the constant variable for 2s-3s and 3s-5s is 0.9 whereas 5s-7s and 7s-8s is 0.83. When compared to existing methods like MPPT-TOSMC, the proposed DS-SWOA obtains a less THD of 0.44% by effectively tuning power system controllers. It increases reactive power management and voltage regulation which minimize power losses and enhance efficiency. DS-SWOA adaptive nature allows rapid response to load variations which ensures robust performance in power quality enhancement.

Table 4. Performance analysis of Grid current in THD (%)

Methods	**Interval of Time**					
			2s-3s	**3s-5s**	**5s-7s**	**7s-8s**
FCS-MPC [21]	Irradiance	Constant variable	1.63	1.71	2.23	5.56
Proposed DS-SWOA			**1.45**	**1.67**	**2.09**	**4.19**

Table 5. Performance analysis of existing methods

Method	**PV Power Efficiency**	**Response Time (s)**	**Boost Converter Efficiency**	**THD (%)**
MPPT-TOSMC [22]	0.998	0.08	0.83	0.53
Proposed DS-SWOA	**0.999**	**0.04**	**0.90**	**0.44**

4.3 Discussion

The advantage of proposed DS-SWOA and limitation of existing methods are explained in this sub-section in detail. The limitation of existing methods like SOSF-PI [19] minimized dynamic response and sensitivity to parameter variations due to SOSF introduce phase delay which affect transient performance whereas PI struggles with harmonic distortion. SC-PLL [20] suffer from increased THD under rapid load changes due to dynamic adaptation introduce oscillations which degrade harmonic performance. FCS-MPC [21] suffer from high computational complexity which lead to slow response in practical applications. TOSMC [22] struggled with sensitivity to parameter variations and uncertainties which impact the performance of power tracking. The proposed DS-SWOA overcomes these existing method limitations by effectively reducing harmonics, imbalances in electrical systems, and voltage fluctuations. It employs dual strategies which helps to balance exploration and exploitation for optimal solutions which enhance speed of determining optimal parameters in power quality controllers. Its strong convergence ability minimizes response time in correcting power disturbance effectively. Moreover, it improves power factor correction and enhance voltage stability which results in overall system efficiency. These features make the proposed DS-SWOA a highly effective method for improving power quality in contemporary power systems.

Conclusion

This research proposes DS-SWOA for power quality enhancement in PV system. By incorporating circle map and dynamic adaptive boundary adjustment, the proposed DS-SWOA effectively balances exploration and exploitation which enhance convergence and solves local optima. DS-SWOA effectively reduces harmonic distortions and voltage fluctuations which ensure stable and effective power delivery. Moreover, the proposed DS-SWOA optimizes power extraction and voltage fluctuations due to the combination of boost DC-DC converter and 3-level NPC inverter. Boost converter based on PWM increase power extraction from PV source and simulation outcomes represents that DS-SWOA obtains better performance compared to existing methods like MPPT-TOSMC. The proposed DS-SWOA achieves a less THD of 0.44% using 3-level NPC inverter under varying load conditions. These results contribute that proposed DS-SWOA is robust and an efficient optimization technique for improving power quality in grid-connected PV systems. In the future, hybrid optimization or Deep Learning (DL) will be considered to minimize THD and enhance power efficiency in PV system.

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