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A hybrid AEGAN-PDO strategy for power quality enhancement in PV-based distributed generation with stacked multi-cell converter

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ABSTRACT

Conventional power plants pose a threat to the environment because of their substantial carbon emissions. Photovoltaic (PV) systems are becoming more and more popular as a sustainable alternative for clean electricity generation. However, because weather and environmental factors vary, partial shadowing affects PV output. The stacked multi-cell converter (SMC) provides a practical way to improve power extraction under these circumstances. This paper suggests a hybrid control approach for a photovoltaic (PV)-based distributed system (DS) using an SMC that is based on the attentive evolutionary generative adversarial network (AEGAN) and prairie dog optimization (PDO) algorithm. The AEGAN forecasts load requirements, while the PDO maximizes converter control to improve reliability, efficiency, and power quality (PQ). Under various load and irradiation circumstances, the system is modelled and verified in MATLAB/Simulink. Results from simulations show that the AEGAN-PDO approach performs better in both dynamic and steady-state situations. Transient disturbances on the load side are rapidly reduced with minimal overshoot. In contrast to traditional particle swarm optimization (PSO), ant lion optimizer (ALO), and archerfish hunting optimizer (AHO) controllers, AEGAN-PDO maintains the lowest THD (1.1%), least power loss (0.24 MW), and best efficiency (98.59%). These results validate the AEGAN-PDO approach as a reliable and effective way to operate renewable-integrated power systems in real-time, promoting improved PQ and grid dependability.

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1. INTRODUCTION

The European Commission's current energy and climate plan places a strong emphasis on integrating photovoltaic panels into the electrical grid in order to fully decarbonize the European electricity supply by 2050. The rising demand for electrical energy worldwide necessitates the use of renewable energies over traditional sources to lessen their detrimental effects on the environment. Therefore, the use of distributed energy resources (DERs) such as renewable energy sources (RESs), particularly solar photovoltaics in low-voltage distributed systems (LVDSs) is increasing regularly. Globally, the adoption of different DERs is rapidly growing, which affects contemporary power networks in a number of ways. In order to prevent the power quality of active distribution networks (ADNs) from declining, regulation is therefore necessary [1], [2]. Conventional passive, homogeneous radiative systems are giving way to functioning, bidirectional, interconnected structures in an essential shift in the distribution network (DN) structure. Additionally, the operational orientation is changing from being one entity providing power distribution services to becoming a successful framework for integrating the modes of origin, grid, load, and storage. The DN serves as an example of the power electronics technology pattern in the framework of "Double Carbon." The spread of contamination is decentralized and network-wide, and power quality issues such as voltage variation and distortions are brought on by a combination of power gadgets [3], [4].

Experts now have severe concerns about power quality issues linked to voltage and current caused by a sudden spike in the usage of non-linear loads in the distributed system (DS). Current disturbances in the DS are mostly caused by devices based on sophisticated semiconductor devices. Furthermore, when voltage variations are present, these nonlinear loads exhibit aberrant behavior. As a result, power converters or other devices that improve power quality have drawn a lot of interest for power quality improvement usage [5]. The photovoltaic (PV) system, which has uses in both grid integration and future generations, is regarded as the most significant RES in the world. Nonetheless, the primary concerns with solar power plants are grid stability, consistent power quality, grid integration, and performance. Several investigations have looked into ways to lower installation expenses and increase PV system efficiency [6]. The integration of sophisticated control techniques and compensation mechanisms may successfully enhance power quality in PV systems linked to the grid and distribution networks. PV-based systems benefit from improved voltage regulation and distortion abatement when a distribution static compensator (DSTATCOM) is managed by a fuzzy logic controller [7]. An adaptive neuro-fuzzy control approach provides dynamic power quality enhancement in multi-microgrid clusters by intelligently adapting to grid disruptions based on information [8]. Furthermore, effective reactive power compensation and better voltage stability in distribution networks are achieved by combining a multilevel STATCOM with an enhanced one-cycle control system [9]. Multilevel converters (MLCs) have drawn a lot of interest for stationary usage such as utility-grid connections for renewable energy sources, commercial motors, and static compensators. Even though MLCs have a lower switching frequency than two-level voltage-source inverters (VSI), they nonetheless produce high-quality alternating current (AC) voltage with less harmonic distortion [10], [11].

This section presents a discussion of existing works on distributed systems with an inverter or converter mechanism for improving power quality. Gada *et al.* [12] use a finite set model predictive control (FS-MPC) approach to demonstrate the effectiveness of two setups for incorporating solar power into the electricity grid: a neutral-point-clamped (NPC) inverter system and the voltage source inverter (VSI) system. With regard to expense and simplicity in modelling and control, the VSI inverter is still appealing, particularly when solar irradiation levels surpass 400 W/m^2. An input-paralleled and output-isolated (IPOI) DC-DC converter, decentralized energy storage units (ESUs), and an arm multiplexing multiport inverter (AM-MI) comprise the innovative converter architecture described by Wang *et al.* [13]. The medium-frequency DC/DC converter filters and boosts the voltage in this suggested structure, the ESU balances the structure's electric power, and the AM-MI increases sub-module consumption from 50% to 66.7%. An adaptive sliding mode controller (ASMC) designed specifically for solar energy systems with maximum power point tracking (MPPT) capabilities is described by Anssari *et al.* [14] in order to solve the common issues of chatter occurrences and high-frequency vibrations. The optimal gains for the stacked multi-cell converter (SMC) approach, particularly for managing the variable step of the typical perturb and observe (P&O) process, are found using the particle swarm optimization (PSO) approach. Mohanty *et al.* [15] describe techniques to minimize harmonics from the output voltage pattern of a lowered switch multilevel inverter (MLI) using black widow optimization (BWO), an effective bioinspired metaheuristic approach. In comparison with alternative nature-based strategies that take into account a vast exploring region, the suggested BWO method reduces the total harmonic distortion (THD) of the final voltage with minimal operating time. The autonomous power reserve control (PRC) approach, which requires little inter-module connection and makes construction easier, is described by Haghighat *et al.* [16] and is intended for cascaded H-bridge (CHB)-based PV systems. The effectiveness of the suggested method is validated by computational and empirical results, which demonstrate precise PV power calculation, smooth operating mode transitions, quick dynamic reaction, and dc-link voltage management under a range of circumstances.

According to Garcia *et al.* [17], the primary focus of MPC studies for MLIs is to develop a technique that can lessen the amount of computing required to run the control. A brief overview of these control methods is suggested in the research. Two novel pulse width modulation (PWM) techniques, enhanced level shifted PWM (ELS-PWM) and enhanced phase shifted PWM (EPS-PWM), are presented by Chamarthi *et al.* [18] to address the problems of decreased effectiveness and dependability. An encouraging approach for high-voltage use is provided by the results, which show notable gains in efficiency (up to around 97.8%) and total harmonic distortion (down to about 2.3%). Employing the analytic hierarchy process (AHP), Chen *et al.* [19] outline a methodology for assessing the total PQ of newly installed energypenetrated distribution systems (DSs). In DNs, this technique is essential for preserving power system equilibrium, safeguarding electrical devices, and improving general electrical security. A research study, preliminary details on distribution loss reduction, and an extensive evaluation of the primary approaches are provided by Sadiq and Antar [20] in order to investigate the most effective ways to reduce power losses. The switched capacitor MLI (SCMLI) structure, which can produce a 9-level final voltage with twin voltage gain, is described by Iqbal *et al.* [21]. It consists of only one capacitor, two DC voltage sources, and nine power semiconductor gates. At the maximum power rating of 0.9 kW, an effectiveness of 96.3% is attained, demonstrating the opportunity for outstanding durability and renewable energy transformation. Amini and Noroozian [22] describe methods to operate and regulate a low-voltage DC (LVDC) segregated distribution network that supplies imbalanced AC loads using distributed generation (DG) from a variable-speed wind turbine induction generator (WTIG). Symmetric AC voltages are efficiently delivered, with imbalanced values falling below 2%. A unique single-phase rectifier design and control system described by Ashraf *et al.* [23] may guarantee sinusoidal input current features with a double polarity-controlled final voltage. Regarding any orientation of the resultant DC voltage, it thereby enhances the THD and power factor (PF). A workable experimental circuit is constructed to verify the outcomes of the computing simulation and analysis. An inverter control and artificial neural network (ICANN) technique-based power management strategy (PMS) is presented by Zulu *et al.* [24] for controlling DC–AC microgrids with PV-wind hybrid systems. Improving PQ is the goal of the suggested IVANN approach. For PV-FC combination microgrids, Kumar *et al.* [25] propose a fuzzy logic (FL)-based current-controlled voltage source inverter (CC-VSI) as a solution to these problems and an improvement in PQ. The FL controller continually regulates the inverter current to preserve constant voltage and frequency ranges under IEEE 1547 rules. A method for evaluating the dependability of DS that integrates PV and electric vehicles (EVs) is presented by Xiao *et al.* [26], taking into account reliable predictions for both solar power plants and EV battery networks. Additionally, it establishes new metrics to examine the sufficiency and dependability of EV charging solutions from the perspective of the client. In order to improve the performance of DNs with a significant amount of DG, Ribeiro *et al.* [27] provide a multi-objective optimization technique. Integrated management of irregular and accessible supplies enhances voltage profiles, lowers network losses, and considerably lessens voltage imbalance, according to studies conducted using the IEEE 123-bus technology.

Salehi *et al.* [28] examined a grid-connected solar system with an emphasis on harmonic impacts caused by fluctuations in temperature and UV radiation. They validated their findings using simulation and compared harmonic distortion with IEEE STD 519-1992 norms. With a straightforward, reliable, and adaptable architecture, Hasanzadeh *et al.* [29] suggested an improved one-cycle controller to boost system reliability under voltage sag, swell, fluctuations, harmonics, and interruptions. In order to optimize profit, Haji-Aghajani *et al.* [30] presented a probabilistic model for the best long-term planning, positioning, and scheduling of EV parking spaces. Golnazari *et al.* [31] created a planning framework that combines smart inverter and soft open point (SOP) operation with optimal PV deployment in order to minimize losses, enhance voltage profiles, and lower operating costs in unpredictable situations using a genetic algorithm. Additionally, Golnazari *et al.* [32] suggested a functioning planning model that integrates optimal active and reactive power control with static VAr compensators (SVCs) and flexible loads to increase the capacity of PV hosting in distribution systems. Bijan *et al.* [33] examined optimization strategies for managing renewable energy, examining environmental, cost, and effectiveness goals using techniques like GA and PSO and emphasizing the financial advantages of combining biomass, solar, wind, and hydrogen sources of power.

The paper's main contributions are as follows: attentive evolutionary generative adversarial network (AEGAN) and prairie dog optimization (PDO) are combined in the study to improve the power quality of distributed systems with SMC. By increasing reliability, reducing losses, and improving voltage output, the study suggests reducing power quality issues brought on by imbalance when irradiance fluctuates. In order to maintain control and supply the grid with high-quality power injection, the main objective of the suggested approach is to lessen imbalances for a grid-connected converter. The PDO method is used to operate the converter after AEGAN predicts the load demand. In order to forecast and optimize the distributed system with SMC, this study is important for creating a hybrid approach that blends AEGAN and PDO. The manuscript's remaining sections are organized as follows: i) The proposed method of PV-based DS with SMC using the AEGAN-PDO method is explained in section 2; ii) The results and discussion, including the simulation and performance comparison, are explained in section 3; and iii) The paper is concluded in section 4.

2. METHOD

A photovoltaic (PV) system-based distributed system (DS) with a stacked multi-cell converter (SMC) improves PQ. The system architecture consists of several components and control techniques to provide reliable and efficient power delivery. The PV system uses photovoltaic panels to convert solar energy into electrical energy. It generates PV voltage (V) and current (I), which are subsequently supplied to the SMC. The PV system is connected to the remaining components of the electrical network via an electrical converter called the SMC. An inverter receives the AC power coming from the SMC. The SMC's electrical power is transformed by the inverter into a format that may be used for distribution and further computation. In order to comply with grid regulations, the inverter may additionally offer voltage and frequency control. The prairie dog optimization (PDO) method regulates the converter, whereas the attentive evolutionary generative adversarial network (AEGAN) method forecasts demand for loading. The system is controlled by the suggested AEGAN-PDO method to increase grid reliability, PQ, and system efficiency. Figure 1 shows the suggested way of PV-based DS with SMC utilizing the AEGAN-PDO technique. The present research used a hybrid strategy called the AEGAN-PDO method, which combines the usage of PDO and AEGAN. The main objective of the suggested method is to improve the voltage output while lowering losses, boost dependability, and reduce power quality issues caused by disturbances when irradiance fluctuates.

Sunlight is used by solar panels to generate electricity. A PV module is an interconnected set of solar cells, usually powered by solar energy. PV modules make up the PV array, which generates and distributes solar power in homes as well as businesses. While grid-connected activities, the distribution grid keeps the DS's power supply balance stable. The SMC is a new kind of hybrid MLC. A variant structure called SMC stacks a large number of flying capacitor (FC) converters. This arrangement has obvious advantages. First of all, SMC shares several advantages with FC converters, such as the ease of development and modularization, which eliminates the need for numerous segregated DC sources and safety measures. It also has the advantage of operating in four quadrants and providing sufficient alternative switching components to increase system control adaptability. Additionally, compared to traditional FC converters, SMC significantly reduces the quantity and dimensions of flying capacitors since they retain less electricity. Because of this, this configuration is a high-power density arrangement that offers several benefits, including reduced system component expenses, increased capacity size, and improved system resilience. Figure 2 illustrates the architecture of the 2×3 cell-7-level SMC. Reactive power (RP) and active power (AP) types, or PV types, can be used to represent DSs to determine the evaluation of load flow. The DS is an instance of a PQ type. In this type of modelling, DS is represented as a renewable resource with uniform AP and RP results. The power factor (PF) and AP of the DS are included in this type of modelling. The difference between the input and output power is known as the power loss.

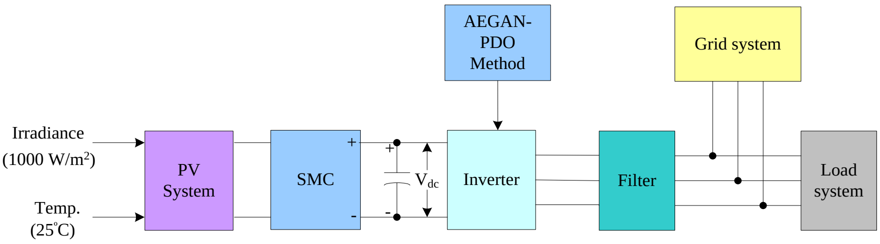


Figure 1. Proposed approach of PV-based DS with SMC using the AEGAN-PDO method

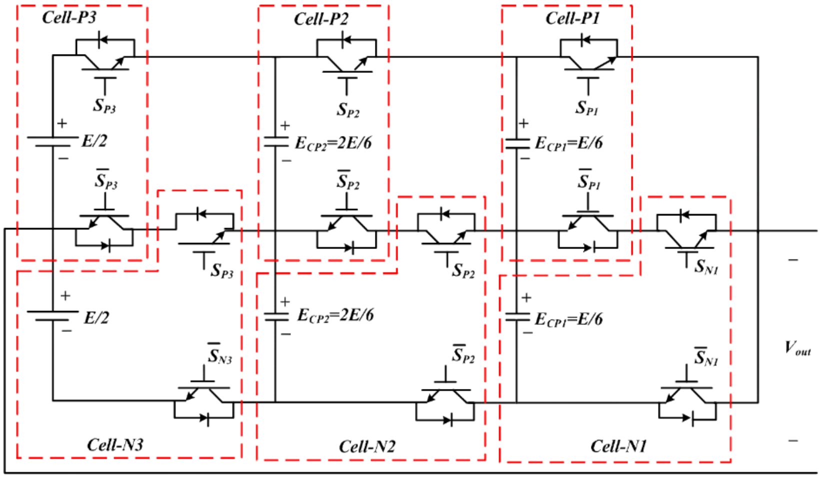


Figure 2. Structure of 2×3 cell-7-level SMC [34]

2.1. AEGAN method for load demand prediction

When combining a DS with an SMC to improve PQ, the load demand is predicted using the AEGAN method. The scaled self-attention (SA) process and the improved evolutionary method are both incorporated into the AEGAN. First, the generators adapt to the dynamic surroundings by using a modified evolutionary method inside the AEGAN. The scaled SA process is applied to the generator band discriminator to determine the relationship between operators and related regions. The discriminator is progressively adjusted by the evolutionary generators, indicating that it can learn the data allocation and produce increasingly accurate results. To improve correlated calculations, the scaled SA process is attached to the AEGAN's discriminator and generator. By normalizing the attribute vectors of the SA process, larger-scale data is introduced while fewer computations are required.

On the one hand, $x \in R^{C\,X\,N}$, represents the deep features, and on the other hand, it represents the number of networks (C) and feature assignments (N), respectively, and it is represented by (1) and x originally transformed into $f(x)$ and $g(x)$. The AEGAN trains the weight matrices $W_g \in R^{\bar{C}\,X\,C}$ and $W_f \in R^{\bar{C}\,X\,C}$. The network performance is reduced to improve storage effectiveness when m is set to 2. The vector of features is normalized in the system's direction as $norm(x) = x/\|x\|$. The dimension of the model at the ith moment when creating the jth region is indicated by the self-attention $Map\ \beta_{ji}$. In (2) represents the self-attention $Map\ \beta_{ji}$ description. In (3), the normalized SA stage is used to determine $O = O_1, O_2, \ldots., O_j, \ldots.., O_N) \in R^{C\,X\,N}$ result. The formula $y_i = \mu A_i + x$, is used to determine the outcome. Here, μ stands for a scale variable, A_i for the outcome of the attention layer, and x for the input data. A system can improve power quality in the DS connected with the SMC by utilizing the AEGAN method's capacity to make alterations based on anticipated load demand numbers.

$$f(x) = W_f W_f x \ and \ g(x) = W_g x \tag{1}$$

$$\beta_{ji} = \frac{\exp\left(norm\left(f^T(x)\right).norm\left(g^T(x)\right)\right)}{\sum_{i=1}^{N} exp\left(norm\left(f^T(x)\right).norm\left(g^T(x)\right)\right)} \tag{2}$$

$$O_j = v\left(\sum_{i=1}^{N} \beta_{ji}\, m(x_i)\right); \ and \ m(x_i) = W_m X_i \tag{3}$$

2.2. SMC control mechanism using PDO algorithm

The SMC mechanism is managed by the PDO algorithm. The movements of four prairie dogs are modelled by the PDO method. The study aims to clarify the field of interest by examining the consuming and burrowing behaviors of the PDs. A plentiful food supply is essential to the PD tunnels. When the current food supply runs low, they either search the entire colony or create space for fresh food supplies and alternatives. New tunnels are constructed around each fresh food supply they discover. PDs have developed adaptive features, including short, robust limbs and enormous toes to endure in their environment. For brief runs, they can run up to 35 mph and build tunnels to escape hunters and return to their nests. Natural disasters such as flooding, drought, hailstorms, grassland fires, and snowstorms pose danger to the habitat of prairie dogs.

2.2.1. Steps 1 to 3: Initialization, random generation, and fitness function calculation

Configure the input variables, such as power, voltage, and current, to their starting settings. The (4) is used to express the arbitrary vectors that produce the input variables at random points after initialization. In the jth dimension of a coterie, $PD_{i,j}$ stands for the ith Prairie Dog. The (5) is used for determining the fitness function, which depends on the objective function.

2.2.2. Step 4: Searching phase

An organizational ward or its equivalent has been allocated to each coterie in the query search space. Each ward has at least ten burrow gaps, and during nesting, there might be as many as 100. A large supply of food serves as the foundation for the PD tunnel. When the food supply goes out, they look for other options or remedies throughout the entire region. They create a new tunnel with each new food supply they encounter. Burrows are crucial for defence from the surroundings and predators. PDO may have had to decide whether to look for and take advantage of new chances. A certain number of iterations is permitted in four distinct groups: maintenance, exploration, and exploitation. Whereas the two exploration strategies rely on (6), and the two exploitation strategies rely on (7).

$$PD = \begin{bmatrix} PD_{1,1} & PD_{1,2} & \dots & PD_{1,d-1} & PD_{1,d} \\ PD_{2,1} & PD_{2,1} & \dots & PD_{2,d-1} & PD_{1,d} \\ \vdots & \vdots & PD_{i,j} & \vdots & \vdots \\ PD_{n,1} & PD_{n,2} & \dots & PD_{n,d-1} & PD_{n,d} \end{bmatrix} \tag{4}$$

$$FF = min\,[P_{loss}, THD_v] \tag{5}$$

$$iter < \frac{Max_{iter}}{4}\ and\ \frac{Max_{iter}}{4} \leq iter < \frac{Max_{iter}}{2} \tag{6}$$

$$\frac{Max_{iter}}{2} \leq iter \leq 3\,\frac{Max_{iter}}{4}\ and\ 3\frac{Max_{iter}}{4} \leq iter \leq Max_{iter} \tag{7}$$

2.2.3. Step 5: Exploration phase

Finding healthy food options in the ward is the coterie's first strategy during the inquiry stage. The Levy flying movement best depicts the PDs' hunting actions. The (8) and (9) give updates on foraging positions. $Gbest_{i,j}$ stands for the best response on the market right now. The effects of the best successful treatment currently accessible globally by $eCbest_{i,j}$ in (10), and randomized cumulative influence of the entire population of prairie dogs in the colony is represented by $CPD_{i,j}$ in (11). The exact location of an arbitrary response is represented by the rPD, and r is a tailored food supply alert operating at 0.1 kHz. $Levy(n)$ promotes more effective and successful exploration of challenging search spaces. The (12) illustrates the distinctions between PD and r using the DS, a tiny integer. To validate explorations, r displays unanticipated possessions, which can take the value -1 or 1, depending on the iteration. The current iteration is represented by $iter$, while Max_{iter} is the ideal number of iterations.

$$PD_{i+1,j+1} = Gbest_{i,j} - eCbest_{i,j} * \rho - CPD_{i,j} * Levy(n) \tag{8}$$

$$PD_{i+1,j+1} = Gbest_{i,j} - rPD * \rho DS * Levy(n) \tag{9}$$

$$eCbest_{i,j} = Gbest_{i,j} * \Delta + \frac{PD_{i,j} * mean(PD_{n,m})}{Gbest_{i,j} * (UB_j - LB_j) + \Delta} \tag{10}$$

$$CPD_{i,j} = \frac{Gbest_{i,j} - rPD_{i,j}}{Gbest_{i,j} * \Delta} \tag{11}$$

$$DS = 1.5 * r * \left(1 - \frac{iter}{Max_{iter}}\right)^{\left(2\frac{iter}{Max_{iter}}\right)} \tag{12}$$

2.2.4. Step 6: Exploitation phase

The (13) and (14) are used to illustrate the objective of PDO's utilization methods, which are to thoroughly examine the possible zones discovered throughout the exploration step. ECB examines the effects of the newly discovered optimal approach, whereas $Gbest_{i,j}$ is the most efficient solution on the globe to date. PE expresses the predator impact, the random number between 0 and 1 is expressed by $rand$. The small value shows the available food supply ε, and the overall effect of all the PDs in the colony is expressed by $CPD_{i,j}$. In this case, PE stands for the predator impact that (15) represents.

$$PD_{i+1,j+1} = Gbest_{i,j} - eCbest_{i,j} * \varepsilon - CPD_{i,j} * rand \tag{13}$$

$$PD_{i+1,j+1} = Gbest_{i,j} * PE * rand \tag{14}$$

$$PE = 1.5 * \left(1 - \frac{iter}{Max_{iter}}\right)^{\left(2\frac{iter}{Max_{iter}}\right)} \tag{15}$$

2.2.5. Steps 7 to 8: Update best solution and termination criteria

For the above minimization problem with a small fitness value, the procedure that follows is thought to be the best solution to date. The parameters for the fitness function are contained in a sorted array. The (16) compares the following three to determine which is the greatest alternative for building protected burrows that will help them evade predators. If the termination characteristics are met, the best solution has been found; if not, proceed to step 3. The converter control procedure can be adjusted to successfully meet the intended power quality improvement goals by utilizing the adaptive character of the optimization method inspired by the prairie dog.

$$PD_{i+1,j+1} = Gbest_{i,j} * PE * rand \tag{16}$$

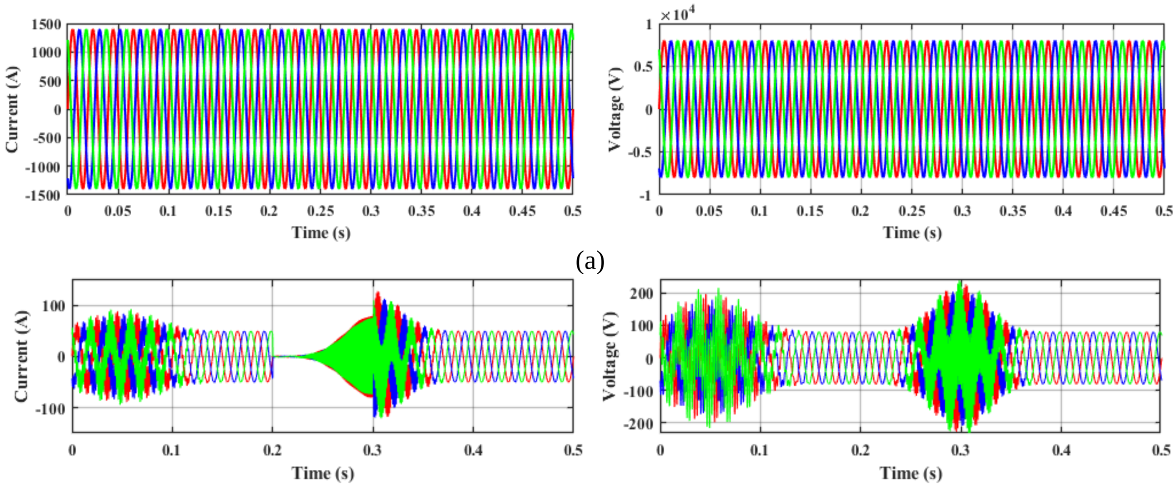
3. RESULTS AND DISCUSSION

The results of the AEGAN-PDO approach for PV-based DS with SMC are covered in this section. This approach's performance and simulation outcomes were compared to the current methods and validated using the MATLAB Simulink platform. A simulation time of 0.5 seconds was chosen to get the functional findings. This section discusses the simulation findings of the active and reactive grid and load-side voltage and current. This section also examines the proposed work's grid reactive power comparison, THD analysis, and power losses in comparison to current methods. The detailed simulation parameters used for evaluating the proposed AEGAN-PDO-controlled PV-based DS with SMC are summarized in Table 1.

Figure 3 shows the voltage and current simulation results for the grid and load system. Figure 3(a) shows the grid-side current and voltage, whereas Figure 3(b) shows the load-side current and voltage. This method performs better in both dynamic and steady-state scenarios. Stable voltages ($\pm 1.5\times10^5$ V) and balanced three-phase sinusoidal currents (±1000 A) on the grid side attest to smooth power injection and efficient synchronization. Within 0.1 seconds, switching and disturbance-induced early transients (±100 A, ±150 V) on the load side are quickly controlled. Smooth sinusoidal waveforms are maintained by the controller, demonstrating low harmonic distortion and high-power factor performance. These findings demonstrate the way AEGAN-PDO performs in waveform control, transient reduction, and improving grid reliability and power quality in renewable-integrated systems.

Table 1. Simulation parameters of the proposed PV-based DS

Parameters	Values
PV rated power (P_{PV}), PV open-circuit voltage (V_{oc}), short-circuit current (I_{sc})	20 kW, 220 V/module, 8.2 A per module
No. of series modules, No. of parallel strings	15, 4
DC-link voltage (V_{dc}), switching frequency, and inverter rated output	800 V, 10 kHz, 15 kW
Grid nominal voltage (V_{grid})	415 V (L–L, 50 Hz, 3-phase)
Load resistance (R_L), and inductance (L_L)	30 Ω, 25 mH
Load switching events	0.125 s and 0.25 s
Reactive power compensation range (Q)	±10% of rated power
Total simulation duration	0.5 s



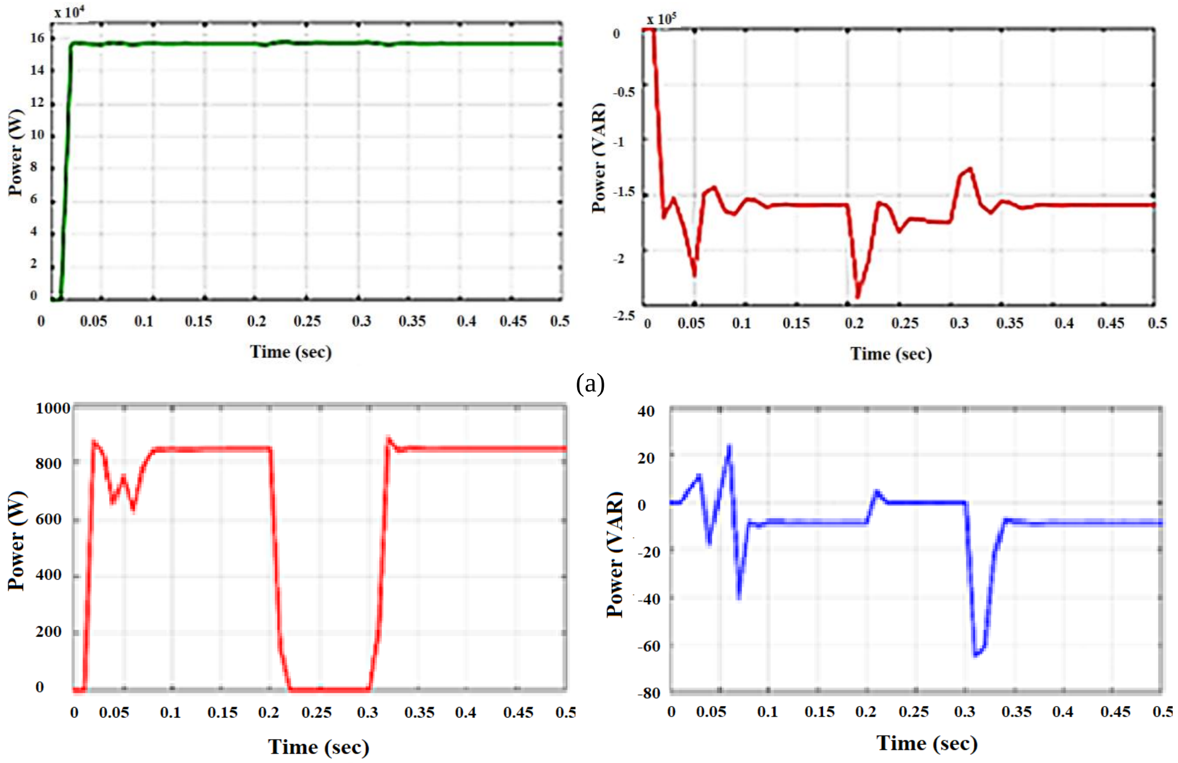
(a)

(b)

Figure 3. Simulation results: (a) grid current & voltage, and (b) load current & voltage

The simulation results of the grid and load system's active and reactive powers are illustrated in Figure 4. The grid-side active and reactive powers are illustrated in Figure 4(a), and the load-side active and reactive powers are illustrated in Figure 4(b). Active power quickly stabilizes at about 15 kW on the grid side in 0.02 seconds, demonstrating strong MPPT performance, quick transient response, and effective PV energy use. Near-unity power factor functioning in steady state is confirmed by reactive power's initial transients, which peak at $\pm 2.5\times10^3$ VAR before convergently approaching zero.

Active power experiences sudden changes on the load side, increasing to about 900 W and decreasing to 0 W, which correspond to load switching activities at 0.125 and 0.25 seconds. The controller guarantees minimum overshoot and quick adaptation. After every switching event, reactive power temporarily drops to -60 VAR before steadily returning to a range of ±10 VAR, indicating that voltage and reactive power disturbances are effectively suppressed. These outcomes demonstrate the extent to which the AEGAN-PDO-SMC framework works in real-time, grid-connected PV systems to guarantee steady active power transfer, low reactive power deviation, and strong power quality control.



(a)

(b)

Figure 4. Simulation results: (a) grid-side active and reactive power and (b) load-side active and reactive power

The grid-side reactive power response of a PV-integrated system under different metaheuristic-based controllers is depicted in Figure 5 as: PSO [35] (magenta), ALO [36] (green), AHO [37] (red), and the suggested AEGAN-PDO (blue). The algorithms PSO, ALO, and AHO were chosen for comparison because they are examples of popular metaheuristic optimization methods that are commonly used to solve power quality management and renewable energy issues.

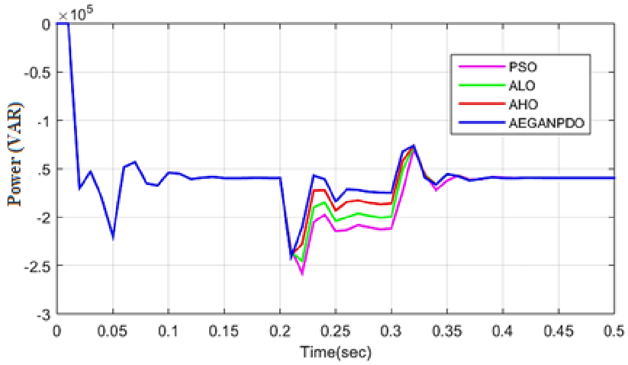


Figure 5. Grid reactive power comparison of the proposed work with existing approaches

Although PSO is renowned for its quick convergence, it frequently experiences premature stagnation; ALO and AHO have better global search capabilities, but at the expense of increased computational complexity. In optimization-based controller tuning, these techniques are considered benchmarks. The suggested AEGAN-PDO method, on the other hand, combines dynamic particle-based search with adaptive learning. It offers better harmonic suppression, lower power loss, and faster convergence with less computational overhead, which makes it more appropriate for distributed systems based on real-time PVs.

The same dynamic load conditions are used to evaluate each controller, and switching events are added at 0.125 and 0.25 seconds. When compared to other methods, the AEGAN-PDO controller shows the least amount of power fluctuation and the best transient stability. Although grid-side reactive power decreases significantly at the switching instants for all approaches, AEGAN-PDO recovers more quickly and has less oscillations. AEGAN-PDO's peak negative power disturbance stays below -2.5×10^5 VAR, while PSO and ALO show deeper sags that reach -3.0×10^5 VAR. Furthermore, AEGAN-PDO has a noticeably shorter settling period, which suggests that it is more effective in reducing oscillations after switching events. According to this comparative analysis, AEGAN-PDO performs better than traditional PSO, ALO, and AHO in terms of transient response, steady-state accuracy, and disturbance rejection. This improves overall grid reliability in PV-assisted systems and guarantees stable grid-side functioning during load disturbances.

A performance comparison in terms of THD (%), power loss, and power efficiency for four metaheuristic optimization-based control strategies, PSO [35], ALO [36], AHO [37], and the suggested AEGAN-PDO, is shown in Table 2. By attaining the lowest THD value of 1.1%, the AEGAN-PDO technique shows exceptional performance and a great ability to sustain high-quality sinusoidal waveforms with little harmonic interference. The THD values obtained by the ALO and AHO methods are 1.5% and 1.3%, respectively, while the PSO approach produces the greatest THD at 1.7%. The standard approaches' relatively limited ability to mitigate harmonics is reflected in these results. AEGAN-PDO performs better than its competitors in terms of power loss, recording a minimum loss of 0.24 MW. In terms of energy management efficiency, this is a significant improvement above PSO (0.85 MW), ALO (0.66 MW), and AHO (0.48 MW).

The AEGAN-PDO 98.59%, AHO 97.18%, ALO 96.12%, and PSO 95.00%. AEGAN-PDO reduces harmonic distortion and increases energy conversion efficiency, as these data demonstrate. Thus, it can be concluded that the suggested AEGAN-PDO framework is a very successful control method for grid-integrated renewable energy systems. It is suitable for optimal power management in smart grids enabled by DG since it can simultaneously minimize power losses and reduce THD.

Table 2. Performance analysis comparison of the proposed approach with the existing approaches

Methods	THD (%)	Power loss (MW)	Efficiency (%)
AHO	1.3	0.48	97.18
ALO	1.5	0.66	96.12
PSO	1.7	0.85	95
AEGAN-PDO	1.1	0.24	98.59

3.1. Performance comparison

A comparison of different design approaches for power system optimization is shown in Table 3 [37]–[40], with particular attention paid to THD, efficiency, adaptability, and forecasting features. PDO with fractional order proportional integral derivative (FOPID), third-order SMC (TOSMC), PDO, and predictive direct power control-space vector modulation (PDPC-SVM) are among the various optimization techniques used in the work. The suggested approach maintains a high efficiency of 98.59% while drastically lowering THD to 1.1%, the lowest of all compared approaches. Additionally, the AEGAN-PDO technique is the only one with full forecasting capabilities, allowing it to foresee system dynamics and proactively modify control measures. It also shows very high adaptivity. These improvements highlight the way the suggested model performs in dynamic and unpredictable grid conditions, making it a very successful approach to intelligent energy utilization and power quality enhancement.

Table 3. Performance comparison of the proposed approach with the existing methods

Ref	Year	Design approach	THD (%)	Efficiency (%)	Adaptivity	Forecasting
[37]	2024	PDO+FOPID	2.3	98.1	Moderate	No
[38]	2024	TOSMC	1.68	98	High	No
[39]	2024	PDO	1.4	98.3	Moderate	No
[40]	2025	PDPC-SVM	1.62	99.1	High	Partial
Proposed		AEGAN-PDO	1.1	98.59	Very high	Yes

The comparative analysis of hybrid controllers for PV-based DS is tabulated in Table 4. The advantages of the suggested AEGAN–PDO hybrid controller over current methods like PDO [41], GAN–PSO [42], and GAN–GA [42] are demonstrated in the comparative analysis Table 4. The AEGAN–PDO delivers balanced and optimum performance, while GAN-based hybrids enhance learning but have slower convergence or higher computing load, and classic PDO offers simplicity but restricted adaptability. It provides the fastest transient response (0.02 s), lowest THD (1.1%), and best efficiency (98.6%), guaranteeing steady reactive power performance even in the face of grid variations. Its dynamic PDO optimization allows for quick fault recovery and effective real-time operation, while its adaptive attention-driven generative model improves prediction accuracy. Furthermore, it is ideally suited for real-world grid-integrated PV applications because of its moderate computing requirement and FPGA/DSP practicality in the future, which combines hardware implementability and precision.

Table 4. Comparative analysis of hybrid controllers for PV-based DS

Criterion	PDO [41]	GAN–PSO [42]	GAN–GA [43]	Proposed AEGAN–PDO
Control nature	Optimization-based (single)	Generative + swarm hybrid	Generative + Evolutionary hybrid	Attentive generative + dynamic optimization hybrid
Convergence speed	Moderate (linear)	Fast (PSO accelerates GAN learning)	Slow (GA iteration-heavy)	Very fast (AEGAN attention + adaptive PDO search)
Prediction/forecasting ability	None	Moderate (GAN learns trend patterns)	Moderate	High (AEGAN learns dynamic irradiance/load patterns)
THD (%)	2.96	1.4	1.7	1.1 (lowest harmonic distortion)
Transient response time (s)	0.08	0.05	0.08	0.02 (Fastest settling)
Reactive power stability (VAR)	$\pm 3\times10^{3}$	$\pm 2.8\times10^{3}$	$\pm 2.7\times10^{3}$	$\pm 2.5\times10^{3}$ (Stable and consistent)
Efficiency (%)	95.0	96.3	96.8	98.6 (Highest)
Computational Complexity	Low	Moderate	High (GA population operations)	Moderate (offline AEGAN training, fast PDO runtime)
Adaptability to grid faults/load swings	Limited	Moderate	Moderate	High (adaptive control, fast re-synchronization)
Real-time implementation feasibility	Easy	Moderate	Difficult	Feasible with FPGA/DSP (low-latency PDO)

3.2. Standards compliance strategy

The proposed AEGAN-PDO-controlled PV-based distributed system is guaranteed to operate dependably and legally because it has been developed to comply with important international grid connectivity and power quality requirements. The system maintains steady voltage, frequency, and reactive power support at the point of common coupling (PCC), in accordance with IEEE 1547 criteria for connecting dispersed energy resources. Reactive power compensation requirements are met in both steady-state and transient scenarios by the inverter's control system, which guarantees dynamic voltage regulation and power factor close to unity. The summary of the standards compliance of the proposed AEGAN-PDO-Controlled PV-based DS is tabulated in Table 5.

The system's performance meets the IEC 61000-3-2 standards for current harmonics in low-voltage grid-connected equipment, specifically regarding harmonic control. The obtained THD of 1.1% shows outstanding waveform quality and is much below the IEEE 519 suggested limit of 5%. Reactive power support capable of ±10% of the rated capacity was integrated for transient stability, and design margins for voltage sag tolerance up to 15% were preserved to improve grid resilience.

Additionally, the controller supports fault ride-through, seamless synchronization, and power quality protection during switching or load disturbances, owing to its quick dynamic response and low distortion levels, which ensure compliance with national grid interconnection rules. All things considered, the suggested approach not only satisfies but also surpasses common PQ standards, offering a strong basis for practical implementation in smart grid and renewable-integrated settings.

Table 5. Summary of the standards compliance of the proposed AEGAN-PDO-controlled PV-based DS

Parameter	Standard/guideline	Permissible limit	Achieved in the proposed work	Compliance status
THD	IEEE 519 / IEC 61000-3-2	≤5%	1.1%	✓ Compliant
Power factor (PF)	IEEE 1547	≥0.95 (unity preferred)	≈ 0.99	✓ Compliant
Voltage sag tolerance	IEEE 1547 / IEC 61000-4-11	≤15% deviation	12%	✓ Compliant
Reactive power support	IEEE 1547	±10% of rated capacity	±8–10%	✓ Compliant
Voltage stability at PCC	National grid code (India)	±5% of nominal	±3.5%	✓ Compliant
Response time to transients	Industry benchmark	≤0.1 s	0.02 s	✓ Superior
Harmonic current injection	IEC 61000-3-2	Within class A limits	Within limit	✓ Compliant

4. CONCLUSION AND FUTURE WORK

This study presents AEGAN-PDO-SMC, an efficient hybrid control approach to enhancing grid-connected PV-based distributed systems' operational performance. With the help of optimal converter regulation (PDO) and intelligent load forecasting (AEGAN), the suggested approach shows exceptional ability to control dynamic load events and preserve power quality. The simulation results validate sustained high-quality voltage/current waveforms, efficient mitigation of reactive power fluctuations, and quick stabilization of active power. The AEGAN-PDO method performs better than conventional metaheuristic strategies (PSO, ALO, and AHO) in comparative evaluations in terms of energy efficiency, power loss minimization, and THD reduction. The AEGAN-PDO framework is a reliable real-time power control system with a THD of 1.1%, power loss of 0.24 MW, and efficiency of 98.59%. This makes it ideal for smart grid uses and the best possible integration of renewable energy sources. The framework's potential to guarantee dependable, effective, and disturbance-resistant energy delivery in contemporary PV-assisted distribution systems is highlighted in the study.

However, this study is limited to simulation-based validation of the proposed AEGAN-PDO-controlled SMC for PV-based distributed systems. Although the MATLAB/Simulink findings verify better power quality, lower THD, and increased efficiency, real-time testing and hardware-level validation are still required. Future developments should incorporate embedded deployment or FPGA/DSP implementation using platforms such as Xilinx Zynq or STM32 to evaluate practical feasibility for embedded smart-grid applications.

Sensitivity analysis under various load and irradiance conditions should be the focus of future study, which should also include robustness testing for partial shading, grid failures, and islanding scenarios. Control stability under dynamic grid settings will be strengthened by improving the AEGAN-PDO framework with adaptive convergence analysis and efficient parameter-tuning techniques. Furthermore, reliability assessment would be enhanced by expanding the model to include energy yield, fault ride-through, anti-islanding, and EMI behavior during switching transients. Long-term performance measures such as thermal stress, mean time between failures (MTBF), and power-loss distribution should also be investigated to strengthen the practical applicability of the proposed framework.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [BNS], upon reasonable request.

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