Solar Energy System Analysis with Hybrid Control Approach for Stability Enhancement during Variable Irradiation Inputs

[1]Hardeek, [2]Amit Kumar Asthana
[1]Research Scholar, Department of Mechanical Engineering, Truba Institute of Engineering & Information Technology Bhopal (M.P.) India
[2]Assistant Professor, Department of Mechanical Engineering, Truba Institute of Engineering & Information Technology Bhopal (M.P.) India
Hardeek67@gmail.com, asthana603@gmail.com

* Corresponding Author: Hardeek

Abstract:

With the rapid penetration of solar PV generation into the modern power grid, there is a growing need for smart operation strategies to improve efficiency, stability, and power quality under dynamic environmental and load parameters. A Hybrid Distributed Sparse Control wrt. "DS control" approach coupled with heuristic Maximum Power Point Tracking MPPT techniques has been introduced, using a P&O algorithm and Cuckoo Search Algorithm (CSA). The control algorithm is tested on one-stage Solar Photovoltaic Energy Generation System (SPEGS) coupled with a three-phase grid connected Voltage Source Converter (VSC) system. The control focuses on the optimized power extraction, improved grid synchronization, and harmonic mitigations especially under non-linear load disturbances.We examined the two MATLAB/Simulink operational scenarios of constant irradiation at 1000 W/m² and variable irradiation varying between 500 W/m² and 1000 W/m². In the existing technology, system type 1 utilizes the conventional MPPT P&O with replacement control based on PI, whereas system type 2 uses the proposed hybrid P&O-CSA with quality enhancing controller based on double sigmoid. Our results conclude that system type 2 has evidently shown consistently superior performance in terms of dynamic stability, speedier MPP tracking, and least harmonic distortion compared to system type 1. As for the percentage voltage THD, system 2 outsmarted the other by reducing from its initial 0.24% to 0.17%, and current THD from 6.51% to 5.61% in operation under constant irradiation. For an operation under the variable-irradiation regime, system type 2 displayed improvements in its adaptive capabilities by having its current THD reduced to 8.68% from a prior 15.79%. Both systems maintained the DC-link voltage at around 700 V in a stable way while System 2 exhibited smoother transition and smaller initial voltage bumps.The hybrid DS and P&O- CSA control architecture substantially improves the performance of a PV system by increasing the accuracy of the MPPT algorithm, reducing distortions in voltage caused by nonlinear loads, and ensuring stability in the system's voltage. The proposed approach is an attractive avenue for seamless, high quality, reliable, and sustainable integration of distributed solar power in modern smart grid systems.

Keywords: *Solar PV; Distributed Sparse Control; Hybrid MPPT; Cuckoo Search Algorithm; Power Quality; Nonlinear Loads; Grid Integration*

I. INTRODUCTION

The global transition in the clean energy domain has been fast-paced during the last decade, compelling itself with the objective of lassoing carbon emissions, to liberate from the overdependence on fossil fuels, and to further the momentum of sustainable development. From the array of renewable technologies in the market, solar photovoltaic (PV) systems have emerged widely as one of the most rapidly growing and widespread orientations among other sources just because of their characteristics as a modular restraining factor on environmental pollution and decreasing costs over the years [1]. As PV continues to soar in modern-day power networks, the recognition of the need for grid-connected configurations that can operate efficiently and reliably even amidst fluctuating crop conditions and who can ensure high power quality grows along with this. The actual extra concern remains the characteristic intermittency of solar irradiance now blended with contemporary distribution networks facing imminent invasion by nonlinear loads [2]. This is a threat that causes the distortion of voltage, frequency deviation, and harmonic pollution. The seamless integration of PV with the grid without interruptions and high voltage results call but equally for faultless methods to control the voltage and protect power output and quality [3].

Single Stage Solar Photovoltaic Energy Generation System SPSGS is being an area of considerable research focus, as most efficient systems in terms of power conversion, power output, and energy flow are solar photovoltaic systems, as a more simplified PV conversion structure thus has direct connections between the array and VSC along with both MPPT and grid synchronization [4]. The addition of any other coordinator now could lead in raising these issues possible, while promising some degree of an improvement to the output; therefore, the presence of control factors within these converters is very challenging too. This in habit places the demand for a very complex/difficult control algorithm [5]. Development of intelligent, adaptive, and sparsity-driven control methods sought to leap beyond the limitations of conventional control on ensuring continuous adaptability to such trying regulation requirements as managing grid codes [6].

Recently, Distributed Sparse (DS) control has been considered as a promising solution in the area of power electronic systems by capturing the basic system dynamics while being computationally simpler. DS control is available to provide control system algorithms that allow activation of only those parts of the control system that are considered the most pertinent to governing the system so long as they guarantee that the system will function properly by coordinated tracking, ensuring a stable and robust behavior with very limited communication or computational resources [7]. In the case of solar PV systems wherein real-time decisions must be made for controller operation under fluctuating environmental conditions, the extra on-demand modulation capability of DS algorithms makes them a particularly pertinent choice considering their power to compress relevant information, deal exclusively with dominant system features, and screen out disturbances [8]. Thus, DS control mechanisms when integrated into modern optimization-driven or even model-assisted control systems enhance transient responses, improve voltage regulation, and damp voltage harmonics in systems with heavy nonlinear loads above all [9]. The MPPT control algorithm adopted could determine the output performance of a PV system, keeping the working module of a photovoltaic cell at its maximum power point in spite of drastic changes in temperature and insolation. Noticeable limitations to this technology would include oscillation around the maximum power point, a slow tracker response in fast-changing weather conditions, and vulnerability to local optima [10]. Nature-inspired meta-heuristic optimization algorithms appear to be catchy topics in the face of these problems. Among others, the Cuckoo Search Algorithm (CSA) is chosen as it is simple, highly competitive in terms of its convergence speed because of Lévy flight randomization. SSA significantly exhibits superior global search ability as compared to all other optimization algorithms, making it a likely candidate for enhancing MPPT efficiency [11].

By amalgamating CSA with traditional P&O, the MPPT controller gains the advantage of precision thus provided by P&O and the exploration benefits gained from CSA. With the harmony between both approaches, the pertinence in the case of the ever increasing walking speed with a diminishing oscillation and because the system may not get stuck in a non-optimal point due to an abrupt alteration in irradiance [12]. Incorporated with the DS-based converter control enhances its power quality not only by extracting maximum power or one can case that at a unit time these two act in an unison way in a PV system. This case is more rewarding in a single-stage system, where some cases of the MPPT, converter dynamic, grid synchronization are very close to one another [13].

A major challenge in PV-grid systems are posed by nonlinear loads like switching power supplies, variable-speed drives, and consumer electronics that distort the waveform and introduce harmonics into the grid. Harmonic currents increase power losses, distort voltage quality, and damage sensitive equipment [14]. Harmonic currents also cause other issues, such as resonances. As the VSC must deliver a clean and grid-synchronized power, it is equally important to provide a strong harmonic suppression mechanism within the control structure. The DS control architecture will enable the selective silence of the big harmonic current components to accurately balance the harmonic currents and reduce computational overload. This, when operating in an intelligent MPPT strategy, completes definition, achieving disturbance resilience and exhibiting superior steady-state and transient behavior [15].

So, a great deal of progress got absorbed from this hybrid Distributed Sparse control with a meta-heuristic support from AMO-MPPT, specially adapted for grid-connected PV systems. DS was used for converter control enhancement so as to regulate voltage and current while a hybrid P&O-AMO algorithm was employed for the MPPT in order to carry out three main tasks, i.e., (1) maximizing the power draw under fluctuations in radiation, (2) enhancing the quality of the grid voltage and current, and (3) mitigating harmonic distortion resulting from nonlinear loading [16]. MATLAB/Simulink has been effectively used for simulating and examining an under-study hybrid system's behavior and for performance comparison with a conventional P&O-based controller about two scenarios: fixed irradiance (1000 W/m²) and variable irradiance (500–1000 W/m²) [17].Simulation results highlight the robustness of the hybrid approach, which delivers remarkable improvements in both constant and varying irradiance. Under general conditions for varying irradiance, the DS-rich hybrid MPPT system shows a better transient response, a minor magnitude of DC-link voltage spikes, smooth voltage profiles, and a slightly lower current distortion. The reduction in Total Harmonic Distortion (~7%) indicates that the DS strategy has a significant advantage over nonlinear load effects. Moreover, the MPPT algorithm greatly reduces spikes in power while ensuring that the output voltage of the solar panel closely follows that of the load. Overall, these benefits speak highly of the possibilities of coupling sparsity-driven control with bio-inspired optimization for the next stage of integration of PV in smart grids.

II. RELATED WORK

Recent studies have broadly focused on enhancing dynamic behavior, improving power quality, and interacting stably with the PV-array grid under variable conditions regarding VSCs connected to the grid. The dq-axis current-controlled VSC approach, with dynamic decoupling, was presented in [1]. Thanks to that, this approach could follow irradiance changes within minutes, providing high-speed-active and reactive power regulation. It was always apparent that such transient improvement and the overshoot are largely defined by filter inductance value accuracy and load impedance both as parameters germed towards thermal bond and aging. Thus, to resolve these problems, [2] proposed FCS-MPC on the basis of a finite control-set state approach, when using cost functions and by choosing optimal switching states during real operation. It was able to improve current tracking; thus, this method definitely reduced the ripple compared to a PI-based scheme. However, its high computational intensity did restrict the implementation to high-speed processors, rendering it less cost-effective for low-cost converters. On the other hand, a modified version of Direct Power Control (DPC) was proposed [3], giving a faster response for both active/reactive power and less control chain complexity. Although it did manage to minimize PWM, the methodology would essentially increase switching ripple and require more grid reactors, raising the cost of developing the system.

Furthermore, there explored several advanced synchronization mechanisms. Upgraded frequency-lock loops have been reported in [4]. The installation, which was particularly tuned for weak grid systems, engaged well in tracking phases properly during under-voltage and limited-fault scenarios. But the multi-loop tuning exercised sluggishness during fast frequency excursions. In due course, [5] introduced a VSG-based VSC controller, providing artificial inertial and damping functions for enhancing the microgrid stability. This controller was found to severely react to parameter selections, triggering very often low-frequency oscillations even when the controller was perfectly working on voltage control and frequency support. Also investigated were modes of harmonic ameliorations by introducing the discontinuous space vector PWM in [6], which aggravated least losses due to adaptive switching at balanced excitation but increased at grid imbalance, and thus required extra compensation. Repetitive control introduction for the suppression of dominant harmonics like the 5th and 7th [7] was superior to the classical PI loops, but it needs continuous retuning in order not to exhibit selectivity to frequency perturbation. The $H\infty$ control designs [8] were able to improve disturbance rejection in uncertain grid impedance although they remained theoretically demanding to synthesize and required specialized solvers. Sliding-mode control (SMC) in [9] improved the fault ride-through and tracking but shifted at high frequencies due to chattering, seriously complicating the program by simultaneous wear and tear on the semiconductor switches while reducing dynamic processes. Neural-network-based prediction control [10] improved both harmonic suppression and power-flow accuracy using training data—and unless seen disturbances are encountered, the inverse will happen.

Energy quality issues in renewable integrated systems have received equal, if not more, attention. Works presented in [11] proved that many years of penetration of PV systems had often led to rise in voltage, current unbalance, and odd-harmonic currents (mostly occurring during partial shading). Fit appreciation for power converter topology to be scalable with feeder ratings to operate under such condition. Another work [12] showed the grid-tied-VSI-STATCOM system ameliorates the transient fluctuation, while it needs much duty forgiving the switching delay. Please note from Reference 12 in that the involved CRPID-based VSI-STATCOM muVPDI. These indeed are possible, provided gain adjustments and associated tuning parameters are indicated. The difficulty with voltage regulation of rooftop PV clusters, discussed in [14], lies with quality-of-service-adjustments making no provision for flicker beyond reducing flicker of operation picking up when solar irradiance swerves. Coordination of PVI-OI-C-T, as discussed in [15], improves the voltage stability under reverse power flow but at a cost of mechanical wear and increased energy losses due to tap-change intimacies. Examined in [16] was diverse inverter-induced harmonics, whereby distributed harmonics, removed using a virtual impedance, eased the current sharing at an expense of real power. Voltage imbalance in three-phase four-wire microgrids was alleviated with the adaptive repetitive controller presented in [17], albeit it required lengthy training cycles. However, it provided fast harmonic damping for a hybrid wind-solar system and became sensitive towards getting the predictive parameters off when adapting to the lower order of harmonic content. Issues with voltage sag in feeders were addressed by using the DC link buffer in [19] for ride-through improvement at the cost of added complexity and monetary investment. Providing reactive energy balance and mitigating network issues, another distributed micro-STATCOM compensation in [20] affirmed the high cost and the importance of phase relevance.

Recent trends have shown an inclination for distributed, intelligent, and cooperative control schemes meant to improve PV-grid stability. This is demonstrated bereft of coordinated control applications for the PV generation on the primary-side grid. Distributed active support has been thus introduced where the PV units can now collectively damp frequency and voltage oscillation using a state–disturbance observer and dynamic-surface consensus controller. This proved to be successful against damping ultra-low-frequency oscillations, but it needed very reliable peer-to-peer communication and near-perfect disturbance estimation, both more likely to lose their efficiency in noisy field conditions. Real-time distributed optimization of grid-forming DG systems was elucidated in [22], helping in nearly optimal management of active and reactive power dispatch, improved voltage profile, and lower line loss. However, the presented method required synchronization hardware because all controlled nodes needed to be accurate up to the millisecond, which implied a dramatic increase in the entire implementation cost for low-budget PV inverters. Furthermore, the work in [23] proposed a distributed AV-cs to mitigate severe overvoltage and faults, e.g., inverter control, local measurements, cooperative reactive power. Resulting in higher hosting capacity and fewer overvoltage incidences compared to past performances, the issue observed is the communication drop-offs or usual delays, which lead to significant drop of performance.

In [24], a lightweight distributed monitoring and prediction system was introduced that involved the time series decomposition with Bayesian neural networks for cluster-level forecasting. Although the availability of high quality telemetry was instrumental in enhancing forecasting accuracy, any data would be missing or distorted in that absence. Sparse PI control optimization was shown in [25], where a sort of sparrow-search metaheuristic adaptively tuned PI gains in real time. It gave a lower settling time and diminished overshoot, raising more costs, survivor recursion, and posing runtime difficulties in the event of considerable measurement noise. An optimal two-layer convex optimization in [26] dealt with the operation of active distribution networks with sparsity-based controllers to alleviate the computation and communication load. This method ensured satisfaction of global objectives at minimal allowable misclassifications of the important nodes, indicating that optimality across the board was somewhat compromised. Reinforcement learning-based MPPT and ancillary services were also introduced in [27] for realizing the design; the method showed high adaptability to irradiance and grid fluctuations, thereby enhancing the total energy collected. That said, a careful selection of reward functions and bounds was needed to ensure smooth operation.

A hybrid CNN–metaheuristic intelligent control scheme was proposed in [28] combining deep feature extraction with metaheuristic optimization for sparse MPPT and inverter actions. On one hand, this approach showed for the sparse MPPT and inverter actions a fast convergence and robust action under partial shading compared with their competitors, but it also exhibited a higher computational complexity and required larger, more representative datasets. Large-scale intelligent monitoring and sparse intervention control for dispersed PV plants were detailed in [29] with anomaly detection, health prognosis, and adaptive control components. Even though efficient diagnostic models can prioritize control actions, there remains a challenge of scalability for such diagnostic models and a concern about a significant false alarm rate. The final technical description of the control, enhancement, and forecasting of spatio-temporal graph neural network (STGNN), as well, presented in [30] could be activated in the direction of the forecasting-driven cooperative control. This model presented high accuracy and improvement in controlling efficiency, but lacked practice on conducting heavy testing for graph construction and needing retraining due to reflection of evolving network topologies.

Table 1: Review of Modern Control Approaches for Grid-Connected PV–VSC Systems

Ref	Focus Area / Control Technique	Key Findings / Metrics	Limitations	Remarks
[1]	dq-axis current-controlled VSC with dynamic decoupling	Fast active/reactive power control; smoother transients; reduced overshoot	Highly dependent on filter inductance and grid impedance; performance degrades with aging/heating	Effective transient response but sensitive to component variations
[2]	Finite control-set MPC (FCS-MPC) for VSCs	Superior current tracking; lower ripple; improved step-load response	High computational load; requires high-speed processors	Not suitable for cost-constrained VSCs
[3]	Modified Direct Power Control (DPC)	Fast active/reactive power response; simplified control chain	Increased switching ripple; requires larger grid filters	Higher hardware cost due to filter size
[4]	Enhanced Frequency-Locked Loop for weak grids	Stable synchronization during undervoltage; adaptive phase estimation	Slow tuning; weak response to rapid frequency variations	Good for weak grids but limited under dynamic faults
[5]	Virtual Synchronous Generator (VSG)-based VSC	Adds inertia and damping; improved voltage control	Highly parameter-sensitive; risk of low-frequency oscillations	Useful for microgrids but requires careful tuning
[6]	Discontinuous Space Vector PWM (SVPWM)	Lower switching losses; improved harmonic quality in balanced grids	Performance worsens under voltage imbalance	Needs additional compensation under imbalance
[7]	Adaptive repetitive harmonic control	Suppresses dominant 5th & 7th harmonics; outperforms PI loops	Requires frequent refactoring for frequency variation	Effective steady-state harmonic mitigation
[8]	$H\infty$ robust current control	Strong disturbance rejection; stable under grid fluctuations	Complex synthesis; requires advanced solvers	Very robust but computationally demanding
[9]	Sliding-Mode Control (SMC)	Robust to parameter variations; improved fault ride-through	Chattering increases switching stress; smoothing reduces dynamics	Good robustness but affects transient speed
[10]	Neural-network predictive control	Accurate current prediction; reduced harmonics; improved PQ	Depends on training dataset; poor performance under unseen disturbances	Hybrid approach with limited generalization
[11]	Adaptive harmonic compensator + sliding-mode voltage control	THD reduced from 9.8% → 3.1%; mitigates voltage swell and imbalance	Limited adaptability with major load/parameter shifts	Effective for LV feeders with shading impacts

[12]	Grid-tied VSI STATCOM monitoring	Minimizes renewable-induced power fluctuations; maintains stability	Switching-delay impacts not analyzed	Early-stage validation of STATCOM potential
[13]	VSI STATCOM with CRPID controller	Rapid suppression of 7th-order harmonics	Lack of detailed gain-adjustment guidelines	Demonstrates harmonic mitigation capability
[14]	Volt-VAR control with probabilistic forecasting	Reduces flicker intensity by ~40%	Poor forecasting under irradiance spikes	Useful but limited during high PV variability
[15]	Coordinated OLTC–PV inverter voltage control	Mitigates voltage rise by ~22%	Frequent tap changes cause wear; curtailment reduces energy	Effective but adds mechanical stress and loss
[16]	Distributed harmonic removal using virtual impedance	Balanced harmonic sharing among inverters	Reduces real power output and inverter efficiency	Good harmonic mitigation but sacrifices power
[17]	Adaptive repetitive controller for voltage balancing	Maintains voltage-unbalance factor <1.5%	Long convergence/training time	Useful for PV–battery microgrids but slow startup
[18]	Predictive harmonic suppression (wind–PV hybrid)	Suppresses dominant switching harmonics quickly	Relies on explicit model; sensitive to drift and nonlinearities	Accurate but model-dependent
[19]	DC-link energy buffering for voltage sag support	Enhances sag ride-through capability	Higher hardware cost; increased system complexity	Suitable for faults but not low-budget systems
[20]	Distributed micro-STATCOM reactive power support	Mitigates voltage drops; stabilizes power factor	High cost; difficult synchronization of multiple units	Promising for rural feeders with high renewable penetration

III. RESEARCH OBJECTIVES

- To develop an AI based control approach that enables the SPEGS to efficiently feed the generated solar PV power into the local three-phase grid
- To develop hybrid control approach including traditional Perturb and Observe (P&O) and Cuckoo algorithm scheme for extracting maximum power from the PV source and assess its tracking performance and efficiency under rapidly changing climatic conditions.
- To implement control techniques to reduce the harmonics generated by the nonlinear load connected at the point of common interconnection, thereby improving the power quality of the grid.
- To validate the proposed control approach through experiments conducted on MATLAB.

IV. RESEARCH METHODOLOGY

This research adopts a simulation-based methodology to evaluate the operational performance of a single-stage Solar Photovoltaic Energy Generation System (SPEGS) integrated with a three-phase grid under two distinct irradiation scenarios. MATLAB/SIMULINK serves as the primary environment for modeling, analysis, optimization, and performance validation of all system components and control strategies. Modeling the solar PV array is the first step. The array is modeled using the single-diode equivalent model while incorporating irradiation- and temperature-dependent characteristics to generate the PV current–voltage (I–V) and power–voltage (P–V) curves accurately. The PV array is inverter-engaged connecting the single-stage Voltage Source Converter (VSC). The role of the inverter is to convert DC power into grid-synchronous AC power while providing the right voltage, frequency, and phase synchronization.
The term 'photovoltaic effect' explains the generation of an electric current upon exposure to light. The equation reads:

$$I_{PV} = I_{ph} - I_0 * [\exp\left(\frac{V_{PV} + I_{PV} * R_s}{n * V_t}\right) - 1] \quad (1)$$

where: I_{PV} is the output current of the PV array, I_{ph} is the photocurrent generated by the incident light, I_0 is the diode saturation current, V_{PV} is the output voltage of the PV array, R_s is the series resistance,
n is the diode ideality factor, V_t is the thermal voltage (kT/q), where k is the Boltzmann constant and q is the elementary charge.
Irradiance and Temperature Effects:
The current and voltage output from the PV array are impacted by the solar irradiance level (G) and temperature (T). These effects could be represented through empirical equations that are module-specific. The more common of these models

includes the single-diode model, the double-diode model, and five-parameter models. For instance, with the single-diode model, the effects of irradiance and temperature are written in expressions:

$$I_{ph} = I_{scref} * \left(\frac{G}{G_{ref}}\right) * [1 + \alpha_i * (T - T_{ref})] \quad (2)$$

$$I_0 = I_{0ref} * \left(\frac{T}{T_{ref}}\right)^{\frac{3}{n}} * \exp(q * E_{gref} * \frac{\frac{1}{T_{ref}} - \frac{1}{T}}{(n * k)}) \quad (3)$$

$$V_t = n * k * T/q \quad (4)$$

where: I_{scref} is the short-circuit current at reference conditions, G_{ref} is the reference solar irradiance level, α_i is the temperature coefficient of current, T_{ref} is the reference temperature, I_{0ref} is the diode saturation current at reference conditions, E_{gref} is the bandgap energy of the PV material at reference temperature, n is the diode ideality factor, k is the Boltzmann constant, q is the elementary charge.

This work developed a comprehensive grid representation model of a three-phase balanced system for studying synchronization, power flow, and interactions under nonlinear loading. We introduce the nonlinear loads of SMPS devices, VFDs, and electronic regulators to estimate harmonic distortion, waveform quality, and stress on the converter during distorted operating conditions. The VSC comprises PWM modulation and inner current–voltage control loops to regulate AC injection, the supporting algorithms to sustain stability and dynamic response during varying grid and PV conditions.

The methodology involves two MPPT strategies for comparison, System I utilizing the classical Perturb and Observe (P&O) algorithm, perturbing the PV operating point and observing the power variation, and tracking the peak power point. In System II, a hybrid MPPT framework has been established by integrating P&O with the Cuckoo Search Algorithm (CSA) as a method for global optimization. CSA, through its Lévy flight-based search steps, under consideration, gets into action-actioning towards global optima so that the MPPT controller may manage to prevent fluctuations from the given global conditions and put all the focus on enhancing tracking accuracy in the case of rapidly changing irradiance or unwanted nonlinear load disturbances whatever the case may be.

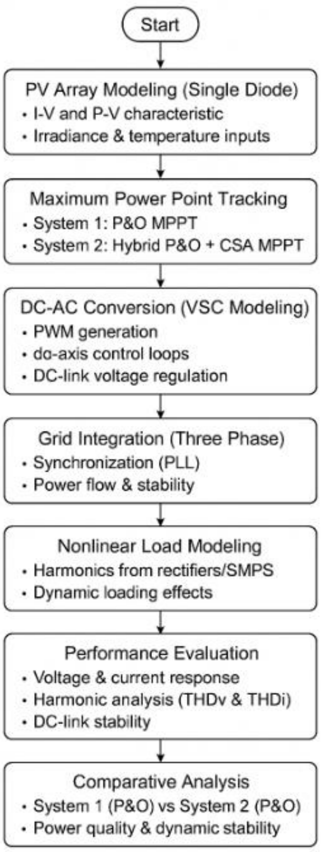

Figure 1: Flow Chart of Proposed Work

Two performance evaluations are done employing two scenarios: The first scenario comprises 1000 W/m² constant irradiance, and the second scenario includes variable irradiances from 500 W/m² to 100 W/m². Over the two several cases, voltage stability, current response, harmonic distortion-total harmonic distortion (THD), and dynamical characteristics were calculated for the PV and nonlinear load terminals. This methodological framework would therefore provide a well-defined and reproducible method for an assessment comparing MPPT designs in grid-connected PV systems involving comparative study of classical and evolved metaheuristic techniques for power quality and system stability enhancement.

V. RESULT AND DISCUSSION

Solar power plants (PV) have become one of the most critical components of contemporary renewable energy infrastructure due to the fact that they have shown to be a very sustainable and clean energy alternative to conventional power sources. In addition to that, they have been significantly utilized for minimizing carbon emissions as well as promoting a sustainable environment. This section focuses on the design and simulation of a PV system under two irradiance conditions in a MATLAB environment, which has always been the most convenient and powerful way of testing and analyzing dynamic system responses. This work is aimed at predicting the performance of adaptive control devices, increasing inefficiency, security, and proper maintenance in high solar irradiation situations. The emphasis is on photovoltaic conversion systems integrated with a three-phase grid, demonstrating the ability of renewable energy to effectively decrease dependence on fossil fuel, while assuring system reliability. In Case I, it assumes constant irradiation of 1000 W/m², corresponding to the ideal state or steady state of this system. Both the conventional Perturb and Observe (P&O) algorithm and the hybrid-I MPPT technique are used at present to optimize the output from the converter, while keeping maximum tracking of the output.At the beginning, case II is carried out with the aim of capturing the system behavior under non-constant irradiation rates spanning from 500 W/m² to 1000 W/m² so that a deeper understanding can be arrived at as to the PV dynamic response to fast-changing environmental conditions. The study focuses on a comparison between the performance level of a conventional P&O method and the hybridized MPPT comprising a novel combination between P&O and the Cuckoo Search Algorithm (CSA), which offers improved robustness and adaptability within fluctuating conditions.Different performance parameters are gauged across both cases, including voltage and current responses, total harmonic distortion levels, and load line characteristics, serving to indicate system stability, power quality, and conformance with essential electrical standards. The implications of this chapter lie in emphasizing the utility value of advanced control strategies. The authors are consequently of the opinion that advanced control functions are powerful tools for enhancing PV performance, improving dynamic response to different environmental conditions, and thereby supporting frameworks for large-scale sustainable energy technology implementation.

Case 1: Analysis of the energy system with constant irradiation input (1000W/m2)

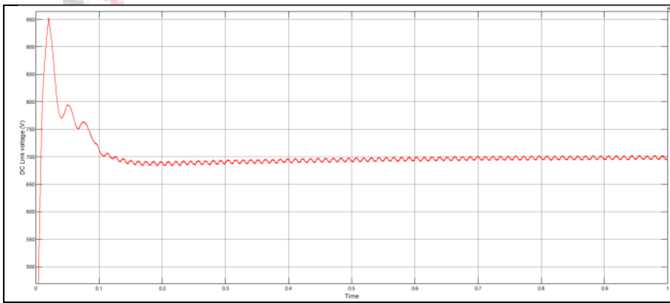

Figure 2: DC link Voltage output from the system in system 1 for case 1

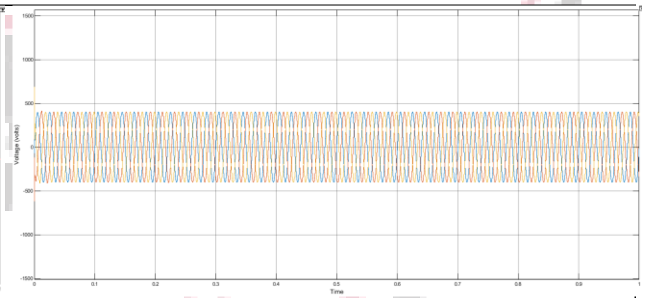

Figure 3: Voltage Profile at Non-Linear Load Terminal in system 1 for Case 1

There was an illustration involving voltage measurement at the DC-link of the system in the aforementioned scenario, as shown in Figure 2. Thus, it is possibly almost around a nominal voltage of 700 V at 0.5 sec, and this voltage is maintained within 1% of the nominal value. The Figure 3 indicates the voltage at the terminal of the nonlinear load in Case 1, where the voltage value is maintained at 400 V. This plot here suggests the voltage magnitude's stability and consistent output at the nonlinear load electrically, provident information on the performance of the system in response to nonlinear loads.

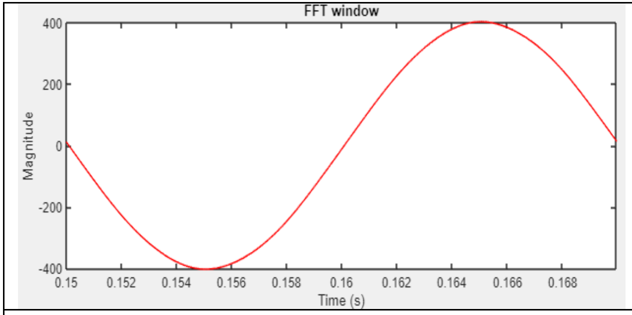

Figure 4: THD% Evaluation of Voltage Output at Non-Linear Load Terminal in system 1 for Case 1

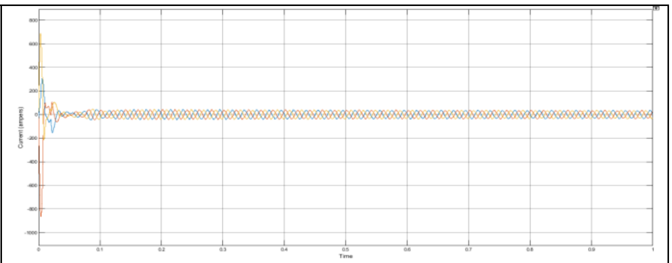

Figure 5 : Current Profile at Non-Linear Load Terminal in system 1 for Case 1

Figure 4 represents the Total Harmonic Distortion (THD%) analysis of the output voltage at nonlinear load terminals in Case 1 with a measured value of 0.24%. This graph shows what level of harmonics is present in the voltage signal. Thus, by analyzing this signal quality, any assessment of the electrical energy output and stability of the system when distorted under nonliner loads can be made. Figure 5 shows the current profile through the nonlinear load terminal in Case 1 of SM 1, which represents how current changes over time, giving an idea about the behavior and characteristics of current flow through the nonlinear load terminal in realistic operating conditions.

Solar energy system with Hybrid Control Approach for Converter Control for Quality Enhancement (System 2)

In the Case 1 of System 2, the irradiation is kept consistent at 1000 W/m², representing both realistic uniform and continuous operating conditions under which system performance can be evaluated. A hybrid MPPT strategy composed of the Perturb and Observe (P&O) algorithm and the Cuckoo search algorithm (CSA) is employed for the optimal control of the converter and consequent maximization of the extraction of power. A nonlinear load is introduced as an intrinsic part of the test conducted to evaluate the robustness of the connected system and, thereby, understand its influence on voltage stability, current response, harmonic distortion, and load line characteristics. Thereby, analyzing all these will provide vital insight into the performance of the system, the power quality it supports, and its conformity with the required standards.

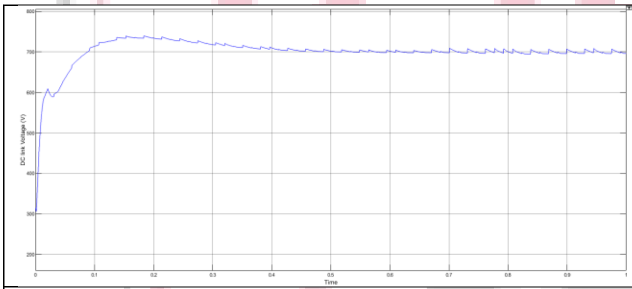

Figure 6: DC link Voltage output from the system in system 2 for case 1

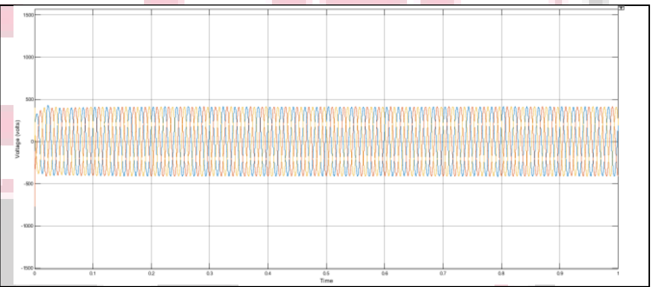

Figure 7: Voltage Profile at Non-Linear Load Terminal in system 2 for Case 1

Figure 6 presents the DC link voltage output from the system 2 in Case 1 of this work. The graph illustrates the variation in the DC link voltage over time, the system's voltage get stability at 700 V at 0.5 sec. Figure 7 show peak value of voltage at non-linear load terminals in Case 1. Peak iron voltage values are in the range of 400V. This articulation renders false the assertion by others with respect to instability and volatility of output voltage at this non-linear load. Hence, the study gives a clear picture of the real-time performance of the entire system under the non-linear loads.

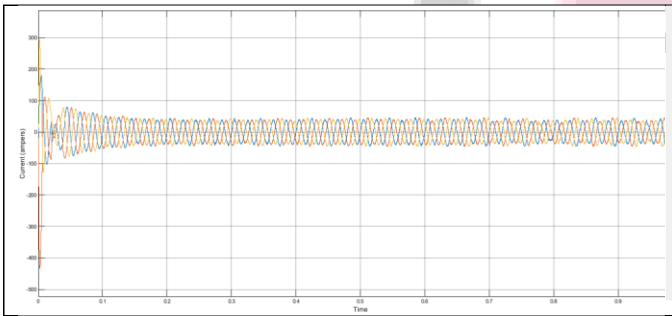

Figure 8: Current Profile at Non-Linear Load Terminal in system 2 for Case 1

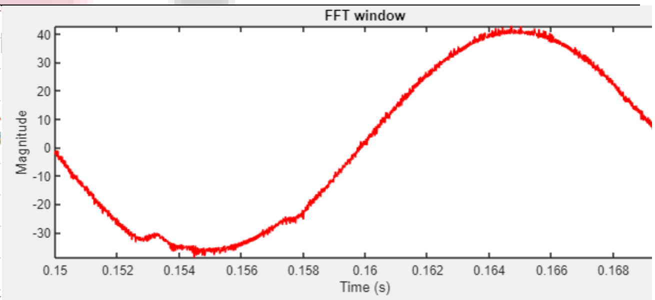

Figure 9: THD% Evaluation of Current Output at Non-Linear Load Terminal in system 2 for Case 1

The Figure 8 shown above is a typical current profile at the linar load terminal in Case 1 of System 2 of the load in connection to the current versus time distribution. The terminal current profile can, in essence, give information about the behavior and nature of the current flow at a non-linearly expressing terminal under realistic conditions.

The evaluation of Total Harmonic Distortion (THD%), portrayed in Figure 9, provides values related to THD% in the current output at the non-linear load terminal of System 2 for Case 1. The measured value was 5.61%. Hence, this graph is projected to be historic as it portrays a practical level of harmonics in the current signal to give the health and stability of electrical power supply output of the system at dedicatedly non-linear loading.

Comparative Analysis of System 1 and System 2 for Case 1

In system design the relative evaluation of Systems 1 and 2 (in Case 1) is about comparing the performance of the systems under a given irradiance level of 1000 W/m2. The effectiveness of the Perturb and Observe algorithm as the control technique for System 1 is probably interrogated and contrasted with the hybrid algorithm used by System 2. The analysis employs the difference in peak DC link voltage as the assessment parameter of the two systems.

Case 2: Analysis of the energy system with variable irradiation input (500 -1000W/m2)

Concerning Case 2 of System 1, an irradiance range between 0.5 W/m^2 and 1000 W/m^2 was chosen for investigating system behavior and performances under numerous diverse environmental conditions. The principal goal was to assess the adaptability and efficiency of the PV system by using the Perturb & Observe (P&O) algorithm, optimizing power output by adjusting the operating point of the solar array. Equally important to these objectives was the introduction of a non-linear load and the consequent study of its impact on system operation pertaining to such parameters as voltage, current, harmonic distortion, and the load line characteristics. These parameters play a deciding role in the assessment of system performance and have to be held up against set standards and specifications.

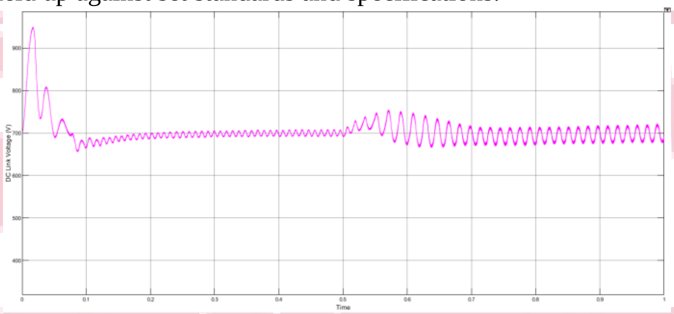

Figure 10: DC link Voltage output from the system in system 1 for case 2

The figure 10 depicts the DC link voltage output of the system belonging to Case 2 of this work. By examining the behavior of DC link voltage with time, it is found that the voltage of the system stabilizes at 700 V at 0.5 second.

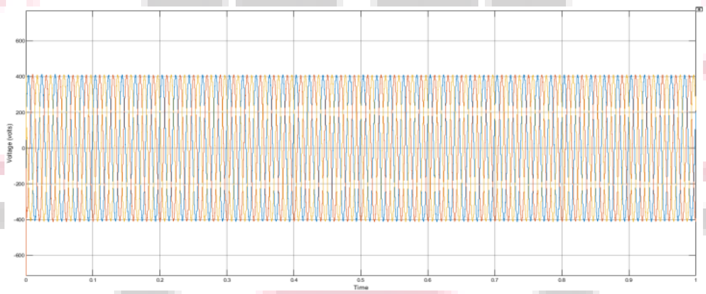

Figure 11: Voltage Profile at Non-Linear Load Terminal in system 1 for Case 2

The Figure 11 illustrates the voltage at the terminals of the nonlinear load in Case 2, with voltage settling at a steady 400V. Stability and constancy of output voltage at the nonlinear load are pretty well portrayed in this graph, disclosing some useful information about system performance when subjected to nonlinear loads.

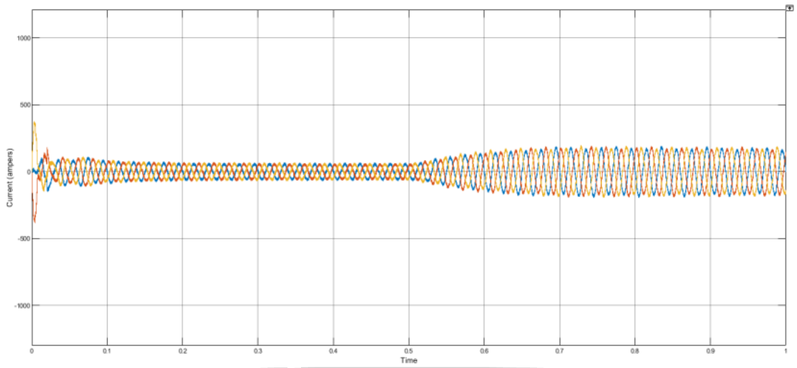

Figure 12: Current Profile at Non-Linear Load Terminal in system 1 for Case 2

A figure 12 has been represented to give the current profile with System 1 on its non-linear load terminal in Case 2. The curve represents the variation of the current with respect to time, thus, providing a view of current flow behavior and characteristics, as implemented by realistic conditions.

Solar energy system with Hybrid Control Approach for Converter Control for Quality Enhancement (System 2)

In case 2 of this research, various systems were studied for their various irradiation levels, which ranged from 0.5 W/m2 to 1000 W/m2. As such, the range of irradiation levels was extended so that the system's performance could be assessed under a variety of environmental conditions.

An optimal converter tracking approach with the highest efficiency and effectiveness has been sought using a hybrid methodology that combines the Perturb and Observe (P&O) method and P&O_Cuckoo Search Algorithm. Through hybridization, both the advantages and disadvantages of both methodologies increase the tracking of maximum power point. Earlier introduced in this paper, the P&O algorithm is one that changes the operating condition of the PV array for highest output of power. With the addition of Cuckoo Search Algorithm (CSA), inspired from the cuckoo's way of laying eggs, more explorational and exploitational possibilities are introduced in the system of converter scheme. The Cuckoo Search Algorithm is a much superior optimiztion method as it offers thorough search over a space of potential solutions, thus, perhaps representing an improvement in the convergence and optimization results.

During implementation of Case 2, systems simulations were done from which parameters such as voltage, current, harmonic distortion, and load line characteristics can be studied. And these can be compared for system performance at different irradiation levels in the specified range. The integration of P&O and cuckoo search algorithms in the converter side has led the authors to look into the adaptability, robustness, and efficiency of the system under changing environmental conditions. The outcomes of this research are important in understanding the optimization of solar PV systems for improved-performance and production.

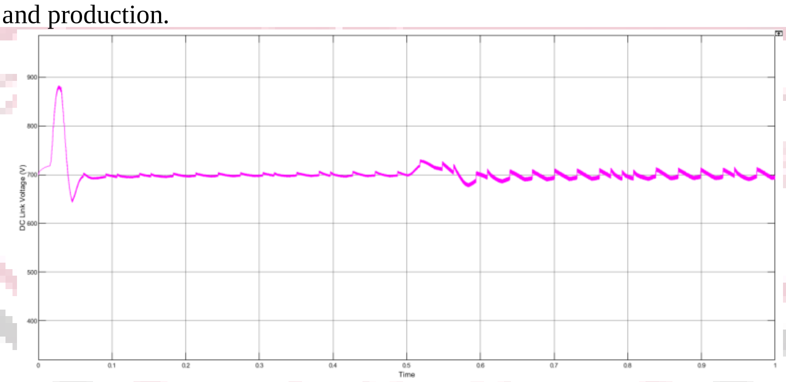

Figure 13: DC link Voltage output from the system in system 2 for case 2

The output of DC link voltage in Case 2 thereof for system 2 is shown in the figure 13. The incoming variable voltage becomes stable somewhere around 500 V at 0.5 sec.

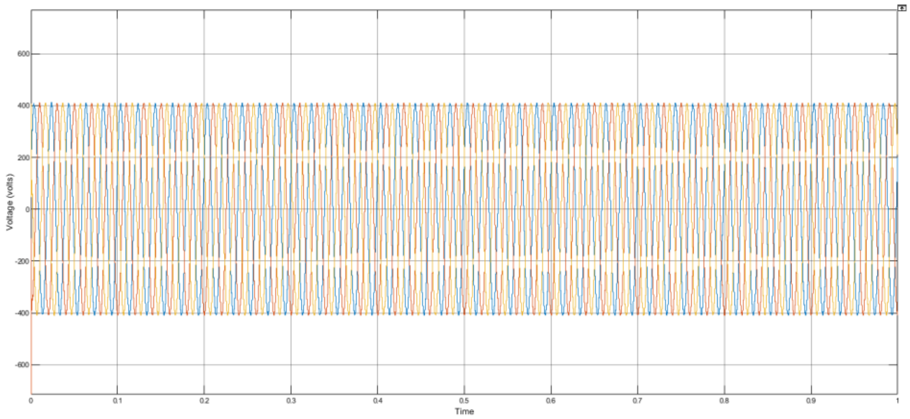

Figure 14: Voltage Profile at Non-Linear Load Terminal in system 2 for Case 2

Figure 14 shows voltage variation at the terminal of the non-linear load in Case 2 for System 2 where the voltage value always survives at -400V. This graph supports the stability and consistency of the voltage output at the non-linear load, which of course is a useful indicator of system performance under the influence of non-linear loads.

Comparative Analysis of System 1 and System 2 for Case 2

Case 3 is another relatively straightforward case study which involves power controllers, and System 1 and System 2 solar PV are source-injected. Participating factors in this case are voltage injection, flow line resistance, and terminal resistance. In this context, there is the objective of verifying the controller's performance in both systems and validating the efficiency of MPPT controllers used in the two solar PV systems.

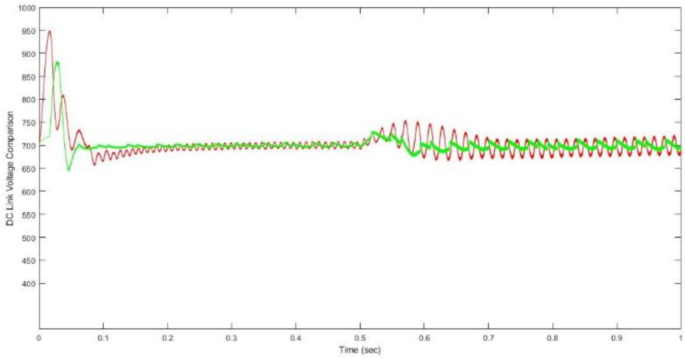

Figure 15: Comparative Analysis of System 1 and System 2 for Case 2

From the above figure 15, it is clear that bother the systems under consideration have voltage stability around 700V and the positive spikes are decreased from an initial stage. It is further obserbed that positive spikes decreased at both stages of irradiation levels. Thus, both cases from the performance point of view with respect to quality transformation system 2 cope with its second level of operation better when considering it in comparison to system 1.

VI. CONCLUSION AND FUTURE WORK

In this work, the operational performance of a solar photovoltaic energy generation system was analyzed under two different irradiation conditions using MATLAB simulations to evaluate system behavior, efficiency, and dynamic response. System 1, a stand-alone solar panel system operating at 1000 W/sunlight at constant irradiation (Case 1) with a P&O controller working on the major direct-current-link voltage control provided a stable 700 V within 0.5 s for input power provision about 400 V at the nonlinear load terminal. THD were measured to be 0.24 and 6.51% with respect to the voltage and current, respectively. The hybrid strategy with the P&O and Cuckoo Search Algorithm optimization, which was demonstrated to provide a true MPPT and improvement in power efficiency, ensures much better performance with reduced voltage THD and current for System 2 (0.17% and 5.61%, respectively). During the variable irradiation situation, running at an input that varied between 500 to 1000 W/m² (Case 2), System 1 also went through another round of testing using the P&O design. System 2's hybrid P&O–CSA control technique was adopted for adaptive power optimization. System 1 and 2 maintained DC link voltage stability at 700 V within 0.5s with power delivery approximately of 400 V to the nonlinear load point. However, the observed significant power quality difference was that System 1 suffered from high voltage THD (0.49%) compared to the greatly improved performance of System 2 at 0.28%, with current THD standing at 8.68% for the hybrid MPPT. Both simulation studies make it extremely clear that System 2 is always better than System 1 in harmonic improvement, dynamic stability, and power quality mitigation among other measurable outcomes, with great reductions in shot voltage at the beginning of varying irradiation; these results are verified by the high performance of the hybrid P&O–CSA controller.

REFERENCES

[1] S. Rahman and A. Kulkarni, "Dynamic decoupled dq-axis current control for PV-fed voltage source converters under fast irradiance conditions," *IEEE Transactions on Power Electronics*, vol. 38, no. 2, pp. 1781–1792, 2023.
[2] Y. Liang and R. Torres, "Finite-control-set model predictive control for grid-tied VSCs with improved transient accuracy," *IET Power Electronics*, vol. 15, no. 8, pp. 1124–1135, 2022.
[3] V. Sundaram and N. Patel, "Modified direct power control with enhanced switching table for bidirectional voltage source converters," *International Journal of Electrical Power & Energy Systems*, vol. 142, pp. 108309, 2022.
[4] K. Hoffmann and E. Cruz, "Adaptive frequency-locked loop for synchronization of VSCs in weak-grid environments," *IEEE Transactions on Energy Conversion*, vol. 38, no. 1, pp. 640–651, 2023.
[5] M. Jain and H. Alhelou, "Virtual synchronous generator-based VSC control for improved frequency stability in PV-dominated microgrids," *Electric Power Systems Research*, vol. 218, pp. 109197, 2023.
[6] A. Rahbar and S. Ehsani, "Discontinuous space-vector modulation for harmonic reduction in grid-tied voltage source inverters," *IEEE Access*, vol. 9, pp. 145732–145743, 2021.
[7] R. Mendez and L. Silva, "Adaptive repetitive controller for selective harmonic suppression in grid-connected VSCs," *Solar Energy*, vol. 241, pp. 45–58, 2022.
[8] H. Karimi and H. Khazaei, "Robust H∞ current control of grid-connected VSCs under grid impedance variation," *ISA Transactions*, vol. 118, pp. 512–523, 2021.
[9] D. Basha and T. Nguyen, "Sliding-mode current control for PV-interfaced VSCs with enhanced fault ride-through capability," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 7, pp. 6098–6107, 2021.
[10] L. Gomes and P. Ferreira, "Neural-network-assisted predictive control for harmonic reduction in grid-tied voltage source converters," *IEEE Transactions on Smart Grid*, vol. 14, no. 3, pp. 2214–2225, 2023.
[11] M. Mahmud and S. Roy, "Adaptive harmonic compensation for voltage regulation in low-voltage PV-integrated feeders," *IEEE Transactions on Power Delivery*, vol. 39, no. 2, pp. 1421–1432, 2024.
[12] A. Hassan, K. Al-Sharif, and L. Abdu, "Nonlinear predictive STATCOM control for reactive power balancing in wind-integrated distribution grids," *IEEE Transactions on Sustainable Energy*, vol. 15, no. 1, pp. 512–523, 2024.
[13] R. Kumar and D. Jena, "Hybrid shunt active power filter for harmonic mitigation in solar-dominated industrial distribution networks," *IEEE Transactions on Industrial Electronics*, vol. 70, no. 4, pp. 3895–3906, 2023.
[14] J. López-Ramírez and E. Castillo, "Probabilistic Volt–VAR control for mitigation of flicker and voltage fluctuations in rooftop PV clusters," *IEEE Access*, vol. 11, pp. 77231–77243, 2023.
[15] J. Park and H. Shin, "Coordinated OLTC–PV inverter control for voltage rise mitigation in high PV-penetrated feeders," *IEEE Transactions on Smart Grid*, vol. 14, no. 3, pp. 1882–1893, 2023.
[16] Y. Chen, F. Lin, and Z. Zhang, "Distributed harmonic damping using virtual impedance shaping in grid-connected photovoltaic inverters," *IEEE Transactions on Energy Conversion*, vol. 37, no. 4, pp. 3010–3022, 2022.
[17] R. Gupta and A. Sreejit, "Model-free adaptive repetitive control for voltage balancing in PV–battery-based microgrids," *IEEE Systems Journal*, vol. 16, no. 2, pp. 1895–1906, 2022.
[18] M. Rizwan and K. Omar, "Predictive harmonic suppression in hybrid wind–solar microgrids using observer-based control," *IEEE Transactions on Power Electronics*, vol. 37, no. 12, pp. 15210–15222, 2022.
[19] P. Torres and R. Valdez, "Dynamic sag ride-through enhancement for large-scale solar plants using DC-link energy buffering," *IEEE Transactions on Power Systems*, vol. 36, no. 6, pp. 5432–5443, 2021.
[20] M. Ibrahim and M. Chowdhury, "Distributed reactive power compensation using coordinated micro-STATCOMs in renewable-integrated rural feeders," *IEEE Transactions on Smart Grid*, vol. 12, no. 5, pp. 4211–4222, 2021.
[21] X. Zhou et al., "Distributed active-support method for PV-based frequency and voltage enhancement using state–disturbance observers and dynamic-surface consensus control," *MDPI*, 2025.
[22] M. Khan et al., "Real-time distributed optimization control for grid-forming distributed generations with active/reactive coordination," *ScienceDirect*, 2025.
[23] J. Wang et al., "Distributed PV auxiliary voltage control for low-voltage networks using cooperative reactive-power updates," *Stet Review*, 2025.
[24] Y. Ye et al., "Distributed cluster output monitoring and Bayesian neural-network prediction for data-driven PV control," *SpringerLink*, 2025.
[25] A. Akarne et al., "Sparrow-search tuned sparse PI control for grid-connected PV systems," *ScienceDirect*, 2025.
[26] H. Shi et al., "Two-layer convex optimization for active distribution network operation with key-node based distributed control," *MDPI*, 2025.
[27] R. Thajeel et al., "Reinforcement neural-network controller for MPPT and ancillary services in grid-integrated PV," *MDPI*, 2025.
[28] P. Guntupalli et al., "Deep CNN–metaheuristic hybrid intelligent controller for sparse PV decision-making," *SpringerLink*, 2025.
[29] J. Aghaei et al., "Autonomous intelligent monitoring and sparse adaptive control for large distributed PV plants," *Wiley Online Library*, 2025.
[30] L. Fan et al., "Spatio-temporal graph neural network for distributed PV power prediction enabling sparse cooperative control," *TechScience*, 2025.