

Design and Technical Analysis of Grid-Connected Solar System (GI-SS) Control Strategies for Dual-Stage DC-DC Converter Management at Load Points

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Abstract:

Solar based energy systems contribute to the broader goal of environmental sustainability by promoting the use of clean and renewable energy sources. Solar power significantly reduces greenhouse gas emissions and minimizes the environmental impact associated with conventional energy sources. Investigating control systems for GI_SS contributes to the improvement of efficiency and stability in power generation. This is crucial for maintaining reliable energy output and minimizing system downtime. This work on the solar photovoltaic (PV) system has focused on the creation of control algorithms for DC-DC converter systems. The Grid-Integrated Solar System (GI_SS) architecture includes a solar system supplying power to non-linear loads at the AC terminals, integrated with the grid. Three algorithms—P&O, AI-based Grey Wolf Power Tracking Algorithm (GWPTA), and a hybrid approach combining P&O and Wolf Power Tracking Algorithm (P&O_WPTA)—are employed to drive the DC-DC converters. In the evaluation, the hybrid P&O_WPTA algorithm displayed the highest stability in DC power output, with the least stabilization time for output voltage. Comparing two algorithms with a hybrid approach for driving the DC-DC converter further decreased current distortion levels to 1.77%, indicating improved performance. This concludes the effectiveness of the hybrid approach in driving the DC-DC converters that resulted in most effective functioning of GI_SS.

Keywords: *Model Predictive Control, Deep Reinforcement Learning, Eco-Driving, Battery Electric Vehicles, Energy Management, Sustainable.*

I. INTRODUCTION

The rise in global energy demand and the acute environmental issues created by fossil fuel consumption have put renewable energy technologies at the forefront of sustainable development. Among all the renewable sources, solar photovoltaic (PV) systems are considered best owing to their scalability, modularity, and falling capital costs [1]. With more installations worldwide, solar power has risen from a secondary form of energy into a chief source contributing to energy networks. If those systems are meant to fully harness their potential, grid integration should be employed. Solar PV systems integrated with grids enhance power quality and provide a reliable supply of energy as well as act as a stand against conventional power plants [2].

The highly complex arrangement of power electronics with DC-DC converters and inverters in a GI-SS has the requirements to be power, perhaps solar, by unstable output to convert into stable electricity for grid injection [3]. Hence, this is the chief function of this process of a dual-stage DC-DC converter architecture. The first stage usually consists of a boost converter with maximum power point tracking (MPPT) to ensure that the maximum energy is harvested from the PV array [4]. The second stage, usually a buck or buck-boost, regulates the DC link voltage to ensure stable input to the inverter and that power delivery to the grid is efficient [5]. This two-stage topology offers merits like faster dynamic response, less stress on semiconductor devices, and better efficiency under conditions of irradiance and load fluctuations [6]. In spite of their benefits, grid integration is still challenging because of solar energy's nonlinear and intermittent nature. Sharp changes in irradiance and temperature cause fluctuations of voltage and current at the DC link, whereas modern-day loads, variable frequency drives, and electronic devices contribute to harmonics and distortions on the AC side [7]. These problems decrease the overall efficiency, degrade grid stability, and sometimes may just violate international power quality specifications [8]. Solutions to these problems involve the intelligent and adaptive control of converters to ensure their operation is stable and grid-code compliant, with delivery of supply into loads in a reliable manner. Plenty of classical control methods such as PI, PID, and hysteresis controls are used to control converters connected to GI-SS [9]. While simple and computationally efficient, these methods possess limited adaptability in nonlinear and dynamic situations. PI controllers are hampered by harmonic distortions, PID controllers need to be accurately tuned, and hysteresis control causes switching frequencies that vary, contributing to a higher stress level on semiconductor devices [10]. These drawbacks render them inefficient in a modern-day, complex, and fast-changing environment of grid [11].

These AI-based methods present very promising opportunities given their highly adaptable nature, real-time optimization, and prediction. Among these methods, fuzzy logic controllers and neural networks or reinforcement learning allow for the handling of nonlinearities and uncertainties in solar power systems [12]. For instance, MPPTs backed by AI can react to irradiance changes and partial shading scenarios, harvesting more energy than their conventional counterparts [13]. Neural networks integrated with predictive control would bring converters into the fold to learn from past experiences and optimize decision-making in settings of load and grid variations [14]. Reinforcement learning, on the other hand, realizes adaptive control policies evolving in real time to address issues posed by unpredictability and long-term stability of systems [15]. Additional advantages are enabled by combining AI techniques with advanced converter topologies. Hybrid and bidirectional converter designs, when intelligent control strategies are applied, promote multi-direction power flow, voltage regulation, and fault tolerance [16]. Besides this, AI-based control can be put into predictive maintenance by diagnosing anomalies before a system failure actually occurs, thus reducing downtime and improving reliability [17]. These developments underscore the revolutionary potential AI holds in improving methods of energy extraction and stabilization, as well as the solar-grid resiliency in smart grid environments [18].

However, challenges exist in the practical adoption of AI-based converter control. Almost all algorithms proposed have been tested through simulations or at a very small scale. One wonders about the scalability, computational burden, and the ability to implement these methods in real time [19]. Also, the fact that we have no standardized metrics to evaluate the AI-based methods makes the task of comparing these methods in different systems and under different conditions infeasible. It is these limitations that must be tackled in order to go from proof-of-concept to deployment in the real world [20]. The present research focuses on the utilization of AI technology/conversion control approach for GI-SS to overcome the limitations of conventional methods and address dynamic challenges presented by renewable energy integration. Intending to show how intelligent converter control contributes to improving efficiency, stability, and power quality at load points through an analysis of advanced control techniques, hybrid MPPT algorithms, and their effects on DC line parameters and AC line parameters, the study explores these topics. The research anticipates results toward comprising resilient, adaptable, and sustainable solar PV systems that interface with future smart grids and support the worldwide transformation into carbon-free energy networks [1], [2].

II. RELATED WORK

A dual-controlled bidirectional converter with two interleaved stages is added here as an engineering-efficient interface for hybrid AC/DC grids that would facilitate a smooth power exchange between the two networks. However, even if the concept met with good simulation results, scarcely any experimental validation was undertaken to check on its practical feasibility [21]. Another development introduced a high-performance two-stage DC/DC converter that combined the two-phase interleaved buck converter with the three-phase LLC resonant converter. This high hybrid efficiency ensures focal power density, also some being control-wise and implementation-wise truly complex to handle [22].

Due to ongoing efforts for higher efficiency, the other development was a double-stage high-gain converter with double inputs and an interleaved structure. This development could curb input current ripples and improve efficiency; however, the increase in the number of components within the interleaved design raised concerns on the system's overall complexity [23]. Another approach dwelled on control methods to develop a robust two-stage tracking controller for a bidirectional full-bridge Buck inverter-DC motor system. Although it improved the dynamic behavior and stability, the method was tailored mainly for motor control applications, making its use in other renewable energy systems rather limited [24].

Thermal management evolved into another key innovative area. Two-stage thermal control procedures were provided that used the switching frequency and MPPT operation changes to regulate temperatures for enhancing the lifetime of the converter. However, the procedure may not be generalized for all converter topologies [25]. Voltage regulation enhancements were demonstrated by means of an observability-based control strategy under consideration for renewable energy systems, microgrids, and electric vehicles; however, practically implementing it is difficult due to the necessity of very accurate system modeling [26].

A two-stage, bidirectional DC–DC converter with multiple operation modes was designed in aerospace applications to fulfill evolving, electrically powered aircraft requirements, hence offering versatility, but there are very few applications directly in renewable energy systems [27]. Another proposed system is an ultra-high voltage gain DC/DC converter based on the coupled inductor, quadratic boost, and voltage multiplier cell. Therefore, it allowed achieving ultra-high conversion ratio but it actually increased the stress on the components affecting the reliability in the long run [28].

In conjunction with these technical-level approaches, reviews spanning broad topics have apprised control schemes for enhancing the dynamic response, MPPT performance, and stability of the system. While such studies offer excellent reviews, they often remain at a very high level setting and do not offer concrete algorithms [29]. Lastly, classification attempts have given topologies for DC–DC converters according to microgrids and renewable systems, constituting a nice reference point—these latter classifications might not be capturing the latest hybrid or sophisticated designs [30].

Recently, an array of studies have been published to highlight different power quality issues and corresponding mitigation measures in grid-connected solar systems. One of these investigated sub-cycle overvoltage in solar and wind farms, especially in Type-4 wind turbines and PV systems, with suggested solutions to enable low-voltage ride-through (LVRT) in order to prevent the instantaneous disconnection of the renewable sources. Nevertheless, the application of such solutions in practice remains a challenge [41]. Another study compared several transformerless inverter topologies in PV systems,

concluding the H5 topology has an effective tradeoff between low leakage current, THD, and efficiency, although its long-term reliability under different environmental conditions was not fully addressed [42].

Similarly, further developments aimed at providing reactive power-management analytical models for PV systems through curve fitting intended to support grid stability. While wonderful in the preliminary tests, this approach requires further study for applicability in high renewable scenarios [43]. Another method studied the use of MBBs for managing power quality in grid-microgrid networks supplying sensitive loads. Good results were yielded in simulations, but questions remain about their scalability and field implementation [44]. The broader resilience studies looked at threats, vulnerabilities, and approaches for microgrids but did not tackle power quality issues in grid-tied solar systems directly [45].

Prior energy management schemes that incorporated a storage-aware model of battery degradation would inherently improve resilience while still meeting power demand. This area, however, still demands further investigation when directly applied to power quality mitigation of PV systems [46]. The repeated analyses of different transformerless inverter topologies and MBBs reaffirmed earlier conclusions but also showed the short- and long-term reliability constraints, as well as the large-scale applicability of such schemes [47],[48]. Lastly, strategies that aim for enhanced resilience of microgrids with storage proved to increase capabilities but still do not provide a solution to power quality mitigation in grid-connected PV systems [49],[50]. Together, these studies clearly expose the continuing challenges faced by power quality management for solar integration and highlight the desperate need for scalable, trustworthy, and self-adaptive solutions.

Table 1: Based on AI-Based Converter Control for Grid-Integrated Solar PV Systems

Ref	Technique Used	Key Findings	Results	Limitations
[21]	Fully-controlled bidirectional dual-stage interleaved converter	Efficient interface for hybrid AC/DC grids, enabling power exchange between AC and DC networks	Improved power flow management in simulation	Mostly simulation-based; limited experimental validation
[22]	Hybrid topology: two-phase interleaved buck + three-phase LLC resonant converter	High efficiency and power density in two-stage DC/DC conversion	Achieved high-performance operation for renewable systems	Hybrid design increases control and implementation complexity
[23]	Dual-stage high-gain converter with dual inputs and interleaved structure	Reduced input current ripple and improved efficiency	Demonstrated in prototype systems	Interleaved structure adds components, increasing system complexity
[24]	Robust two-stage tracking controller for bidirectional full-bridge Buck inverter–DC motor	Improved dynamic performance and stability	Better transient response in DC motor applications	Control strategy focused on DC motor systems; limited general applicability
[25]	Two-stage thermal control with switching frequency and MPPT regulation	Temperature regulation and extended converter lifetime	Optimized thermal management for renewable systems	May not be suitable for all converter topologies
[26]	Observability-based voltage control for two-stage DC–DC converters	Efficient voltage regulation in microgrids, EVs, and renewable systems	Stable voltage output achieved	Requires accurate system modeling, difficult in practical setups
[27]	Two-stage bidirectional DC–DC converter with multiple operation modes	Adaptable converter operation for more-electric aircraft	Enhanced versatility in aircraft energy systems	Limited direct applicability to other renewable energy systems
[28]	Ultra-high voltage gain DC/DC converter: coupled inductor + quadratic boost + voltage multiplier	High voltage gain for renewable energy applications	Achieved high voltage conversion	High voltage gain increases component stress, impacting reliability
[29]	Review of control schemes for dynamic response, MPPT, stability	Summarized approaches for renewable energy system control	Provided high-level overview	Did not detail specific control algorithms

[30]	Classification of DC–DC converter topologies	Organized topologies and applications in DC microgrids and renewable systems	Useful reference for converter selection	Classification may not include all new hybrid/topologies
[41]	Low-voltage ride-through (LVRT) solutions for Type-4 wind turbines and PV systems	Prevents instantaneous disconnection of renewable sources during sub-cycle overvoltage	Enhanced stability under grid faults	Implementation is difficult in practice
[42]	Transformerless inverter topologies (H5) for PV systems	Balanced leakage current, THD, and efficiency	Demonstrated effective trade-off in operation	Long-term reliability under environmental variation not fully studied
[43]	Reactive power management model using curve fitting	Supports grid stability with PV integration	Effective in analytical studies	Needs validation under high renewable penetration
[44]	Modular balancing blocks (MBBs) in grid–microgrid networks	Mitigates power quality issues for sensitive loads	Worked well in simulations	Large-scale applicability uncertain
[45]	Resilience strategies for microgrids	Identified threats, vulnerabilities, and resilience methods	Enhanced understanding of microgrid resilience	Did not focus on power quality in grid-tied PV systems
[46]	Storage-aware energy management strategy (battery degradation considered)	Improved resilience while meeting demand	Demonstrated efficient management of storage	Not directly evaluated for PV power quality mitigation
[47]	Re-analysis of transformerless inverters	Confirmed prior results on efficiency and leakage reduction	Reinforced suitability of H5 topology	Reliability over long term remains a concern
[48]	Re-analysis of MBBs in PV–microgrid systems	Reaffirmed ability to improve power quality	Validated prior simulation outcomes	Scalability and deployment limitations noted
[49]	Resilience-oriented strategies for microgrids with storage	Strengthened grid reliability and flexibility	Enhanced resilience with storage integration	Power quality issues in PV systems left unaddressed
[50]	Storage-based strategies for grid-connected PV systems	Highlighted resilience benefits of storage	Showed potential for stability improvement	Did not solve open issues of PV-related power quality

III. RESEARCH OBJECTIVES

- Develop a Grid-Integrated Solar Systems (GI_SS) in MATLAB/SIMULINK environment driving non linear loads on the AC side.
- Design and implement innovative control algorithms for DC-DC converters in GI_SS inspired by artificial intelligence (AI) focusing on improving efficiency and stability at the loading points
- Analyse the impact of controllers designed at the DC line parameters as well as AC line parameters for quality and stability
- Reduce the current and voltage distortion levels and improving the power quality delivered at the loading points.

IV. PROPOSED METHODOLOGY

a. Photovoltaic Modeling

Solar cells are also called p-n semiconductor junction or diode. The circuit shown has a series resistance (R_s) and a parallel resistance (R_{sh}) along with the photocurrent (I_{ph}) of the PV cell. Two or more series cells, together with two or more parallel cells, make up the PV which, in turn, is used to construct the solar panel. The mathematical formation of PV panel is given below:

Shunt Current I_{sh} Module

$$I_{sh} = (V + IR_s)/R_{sh} \quad \dots (1)$$

Temperature module from degrees to Kelvin

$$T_{kelvin} = 273 + T_{degree} \quad \dots (2)$$

Photo Current I_{ph}

$$I_{ph} = [I_{sc} + K_i(T - 298)]G/1000 \quad \text{.....(3)}$$

Reverse Saturation Current Module Irs

$$I_{rs} = I_{sc} / [\exp(\frac{qV_{oc}}{N_s k n T}) - 1] \quad \text{.....(4)}$$

Saturation Current I_o Module

$$I_o = I_{rs}(T/T_n)^3 \exp[qE_{go}(\frac{1}{T_n} - \frac{1}{T})/nK] \quad \text{.....(5)}$$

The current output of PV module IPV

$$I_{pv} = N_p \times I_{ph} - N_p \times I_o \left\{ \exp\left[\frac{q(V+I R_s)}{K n T}\right] - 1 \right\} - I_{sh} \quad \text{.....(6)}$$

b. Power Tracking using DC-DC converter Concept

In general, four control schemes are proposed for a network-connected single-stage PV system: control of current, MPPT control, synchronization to the grid, and voltage control. The output power of the PV system varies with environmental conditions, i.e., ambient temperature and solar irradiance, which change with time. Moreover, the MPPT control ensures that the PV system is fully beneficial, as the following factors prevent this: non-linear characteristics of the PV module and the load-cum-dynamic influence. Therefore, it is very important to have an efficient MPPT algorithm that continuously monitors the terminal voltage and current and tracks or adjusts them to the MPP values. This is basically achieved through a DC-DC converter, the control of which is based on the three algorithms: P&O, GWPTA, and P&O_GWPTA. The boost converter increases the DC output voltage from a lower DC input voltage, ensuring that input current is more than the output current for power conservation. Figure 1: Flow chart for Perturb and Observe (P&O) scheme.

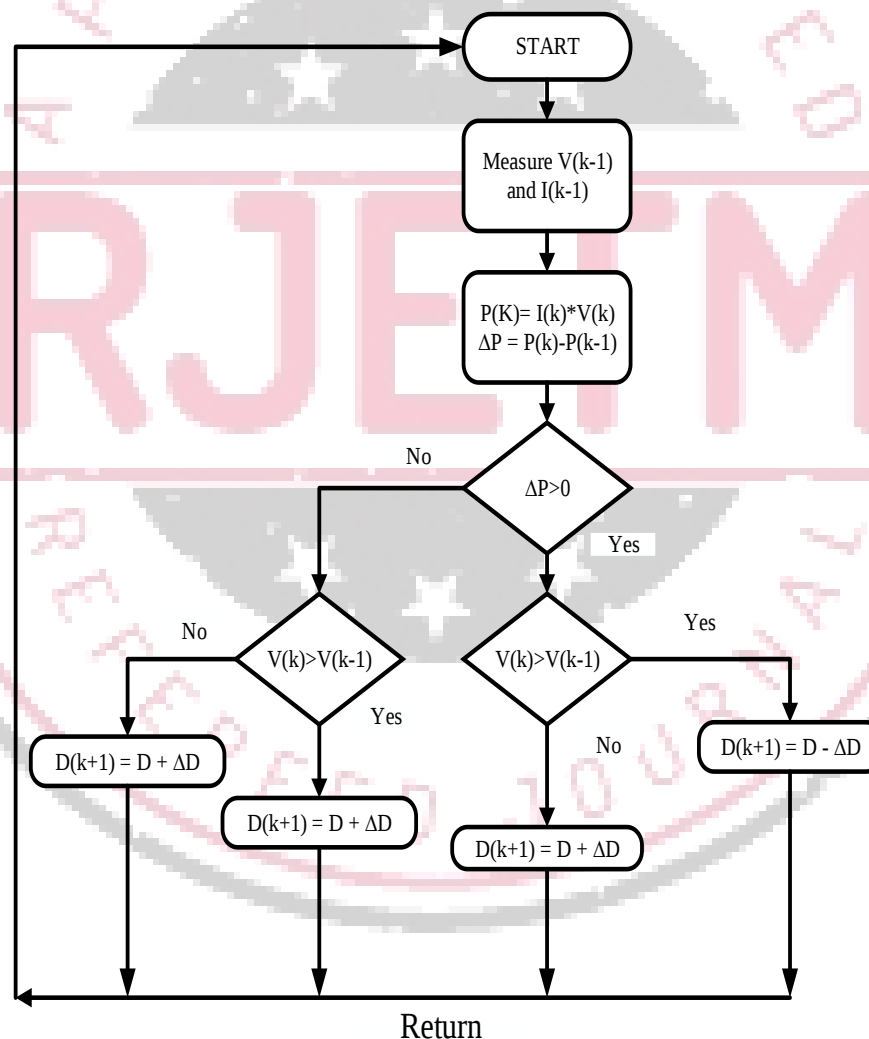


Figure 1: Flow chart for Perturb and Observe (P&O) scheme.

The P&O technique works perfectly fine in so many situations but one thing it cannot do is lock on and oscillate around the MPP, especially when conditions are changing rapidly. Furthermore, in the presence of noise and even partial shading, the method can undergo performance degradation.

c. Evaluate the position of the prey

Calculate fitness values i.e., PV power of the population. Assign $d\alpha$ and $d\beta$ as first and second best population with highest PV power.

Updating the positions of search agents

The positions of the population d_i are updated according to positions of $d\alpha$ and $d\beta$.

$$\vec{D}_\alpha = |\vec{C}_1 \cdot \vec{d}_\alpha - \vec{d}_1| \quad \dots(10)$$

$$\vec{D}_\beta = |\vec{C}_2 \cdot \vec{d}_\beta - \vec{d}_1| \quad \dots(11)$$

$$\vec{d}_1 = \vec{d}_\alpha - \vec{A}_1(\vec{D}_\alpha) \quad \dots(12)$$

$$\vec{d}_2 = \vec{d}_\beta - \vec{A}_2(\vec{D}_\beta) \quad \dots(13)$$

$$\vec{d}_i(t+1) = \frac{\vec{d}_1 + \vec{d}_2}{2} \quad \dots(14)$$

where $D\alpha$ and $D\beta$ are distance of $d\alpha$ and $d\beta$ from maximum power.

The PV powers are calculated for updated positions of population and finish hunt when prey stops moving i.e., when maximum PV power is obtained.

Termination criterion

The algorithm terminates when it reaches maximum number of iterations and outputs $d\alpha$ as the optimal duty ratio to operate at maximum power.

Reinitialize

The algorithm reinitializes search for a change in solar irradiation using

$$\frac{|P_{pv} - P_{pv,old}|}{P_{pv,old}} \geq \Delta P \quad \dots(15)$$

where $P_{pv,old}$ is power at MPP of last operating point, ΔP is set to 10% Figure 2: Flow chart for GWO MPPT Algorithm for power optimization.

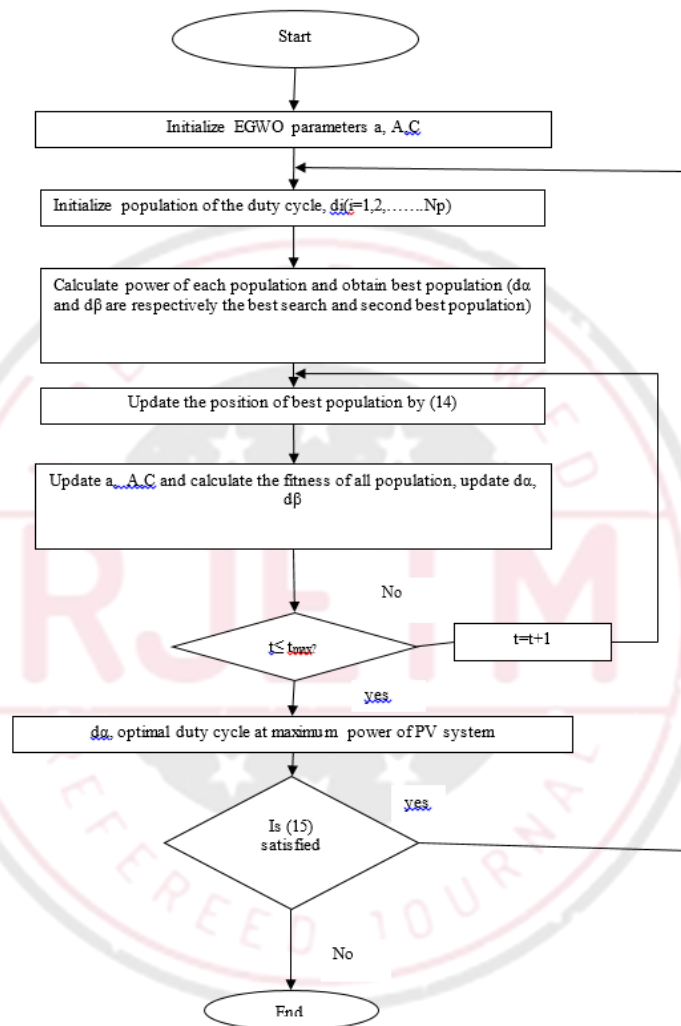


Figure 2: Flow chart for GWO MPPT Algorithm for power optimization

V. RESULT AND DISCUSSION

This section focuses on evaluating the DC output of PV-based solar energy systems, analyzing voltage, current, and power yield under varying irradiation and temperature conditions. The DC-DC converter plays a key role by regulating voltage and ensuring operation at the maximum power point (MPP). Classical methods like Perturb and Observe are simple but prone to oscillations, while AI-based approaches, such as the Grey Wolf Power Tracking Algorithm, offer faster and more adaptive convergence. Hybrid strategies like P&O-WPTA further enhance stability under dynamic conditions. Understanding DC behavior and control strategies is essential for optimizing energy harvest and improving AC power

a. Analysis on the DC outputs of the GI_SS

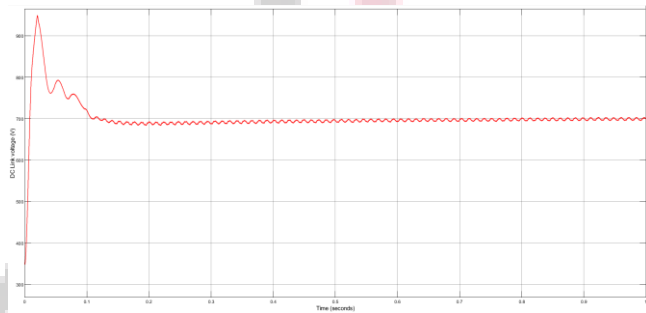


Figure 3: DC output voltage in system 1

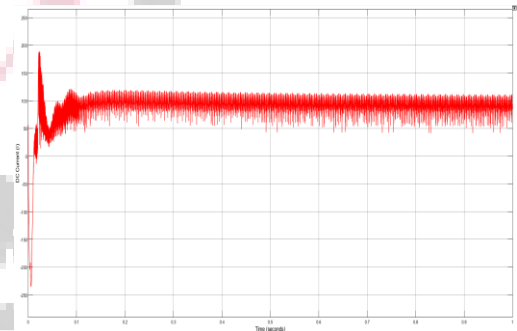


Figure 4: DC output current in system 1

As Figure 3 depicts, the DC voltage output presents high variability at the initial stages for the solar system under P&O control, whereas Figure 4 depicts the DC output current yielding high fluctuations under the same method of control.

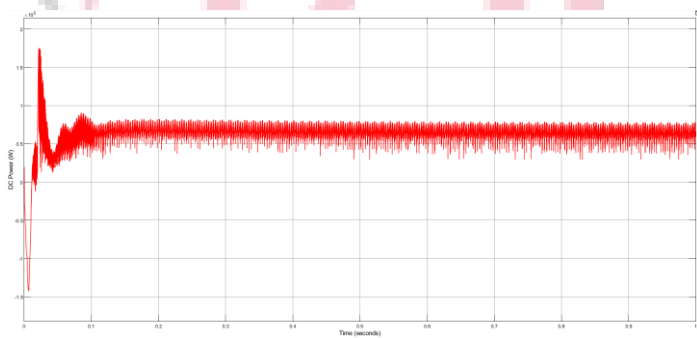


Figure 5: DC Power Output in system 1

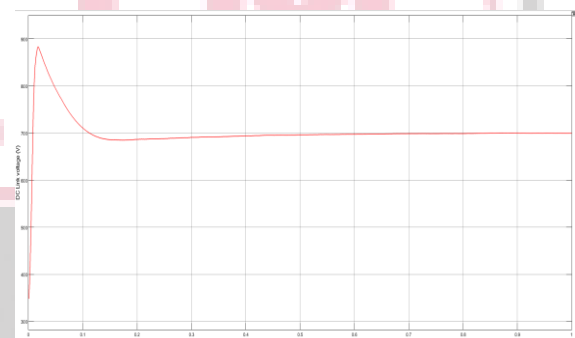


Figure 6: DC output voltage in system 2

In Figure 5, we see the solar system's DC output power being unstable under the P&O technique due to the unstable current, whereas Figure 6 depicts the DC voltage output with GWPTA, which begins with a slight instability behavior but tends to settle up thereafter.

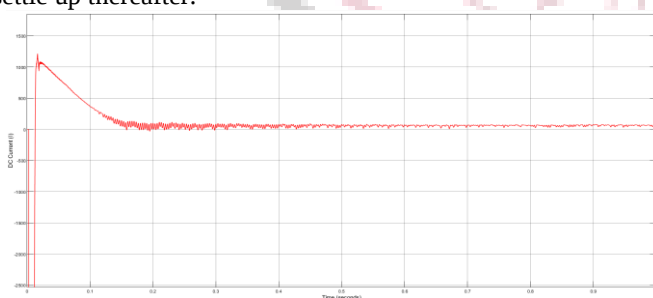


Figure 7: DC output current in system 2

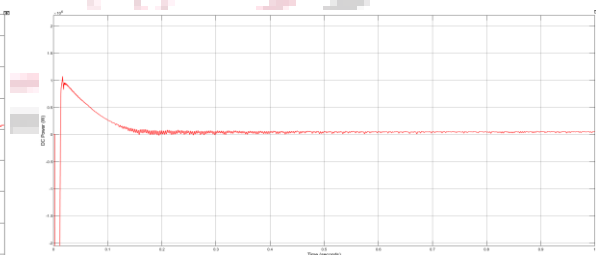


Figure 8: DC power output present in system 2

Figure 7 shows a smooth and stable output of current by the solar system under the GWPTA control, having reduced oscillations of current and tracking efficiency; and Figure 8 shows the profile of DC power, stable in nature, due to the nature of the current with enhanced stability.

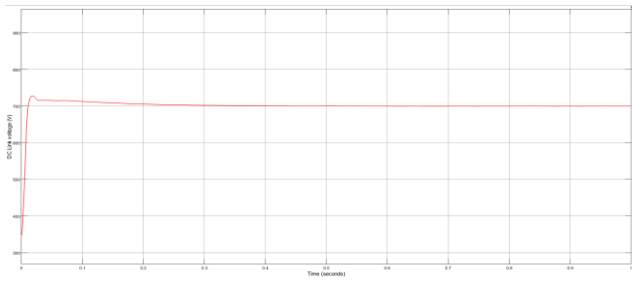


Figure 9: DC output voltage in system 3

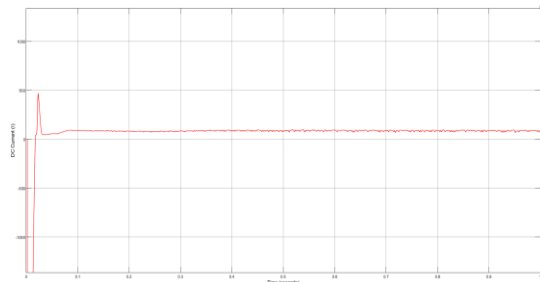


Figure 10: DC output current in system

In Figure 9, the DC output voltage waveform of the solar system with the DC-DC converter running via the hybrid technique with P&O and Wolf Power-Tracking (P&O_WPTA) is shown. It is observed that the voltage is more stable with this approach. Figure 10 represents the DC current in a solar energy system wherein the DC-DC converter is driven by the hybrid approach of P&O and the wolf power tracking algorithm (P&O_WPTA).

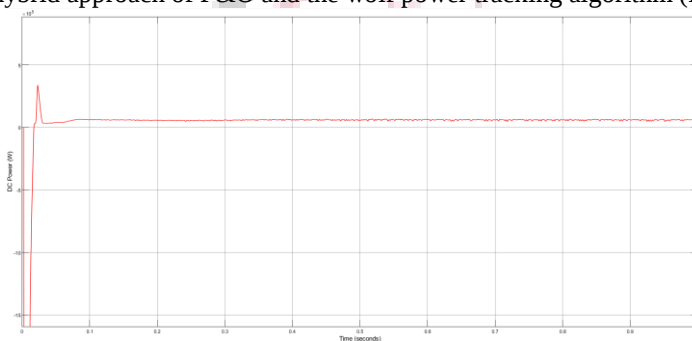


Figure 11: DC output power in system 3

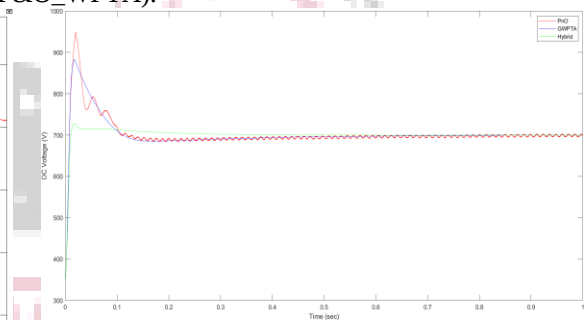


Figure 12: Comparative analysis of DC output voltage in GI_SS having different controllers for DC-DC converters

Figure 11 illustrates the stable DC output power of the solar system through the hybrid P&O_WPTA controller, while Figure 12 gives a comparison of GI_SS DC output voltage under three controllers, showing the higher stability of the hybrid technique.

b. Analysis of the control algorithms and its impact on the AC side of GI_SS

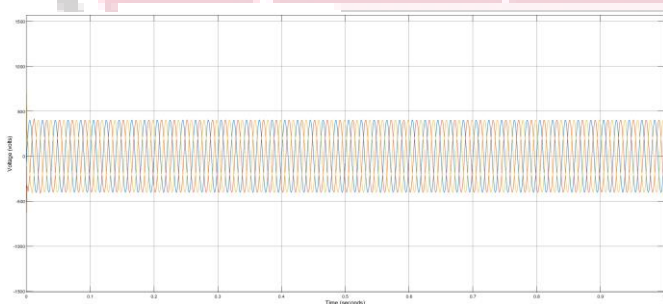


Figure 13: Nonlinear load terminal AC voltage present in system 1

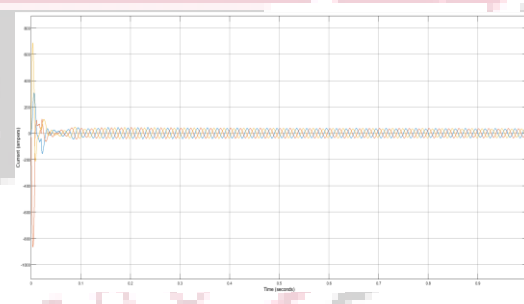


Figure 14: AC current drawn at the terminal in system 1

Figure 13 shows three-phase AC voltage waveforms at the load terminal, since the DC-DC converter is being driven by the P&O algorithm, while Figure 14 shows the three-phase AC current waveforms under the same control.

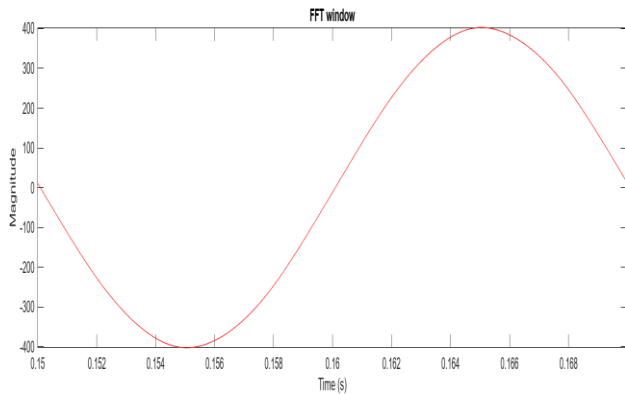


Figure 15:: FFT analysis of AC voltage present in system 1 in the MATLAB

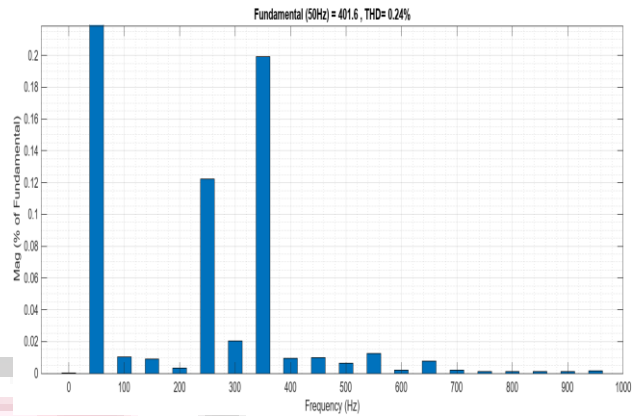


Figure 16: THD% evaluation of AC voltage present in system 1

In support, Figure 15 demonstrates the FFT analysis of the AC voltage in System 1 with the DC-DC converter under P&O control. Meanwhile, Figure 16 shows the THD% analysis, which gives a 0.24% value under P&O control.

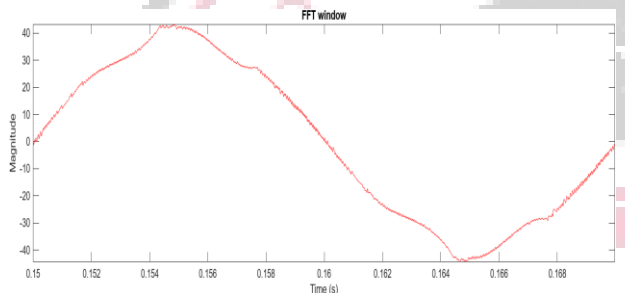


Figure 17: FFT analysis of AC current drawn at the loading terminals of system 1

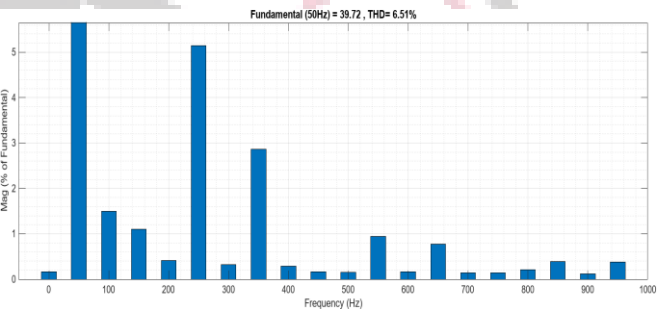


Figure 18: THD% evaluation of AC current drawn at the loading terminals of system 1

Depicted in Figure 17 of the AC current FFT analysis in System 1 with a P&O-controlled DC-DC converter, Figure 18 records the THD% that reached a peak value of 6.51% with the same control.

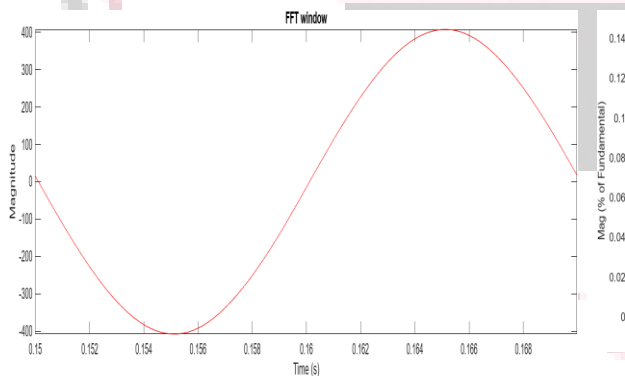


Figure 19: FFT analysis of AC voltage present in system 2 in the MATLAB

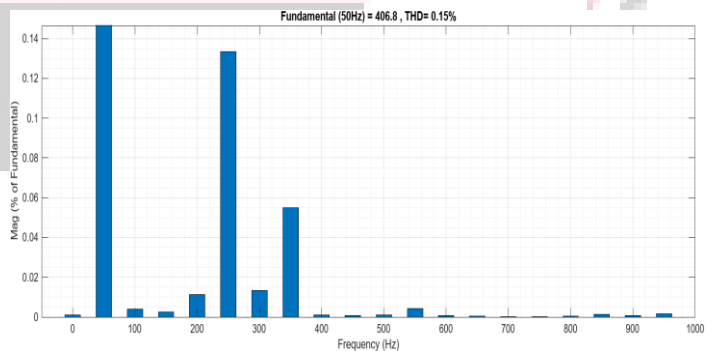


Figure 20: THD% evaluation of AC voltage present in system 2

Figure 19 shows the FFT analysis of the AC voltage in System 2 with the DC-DC converter controlled by GWPTA, while Figure 20 shows the percentage of THD, which is 0.15% with the same control.

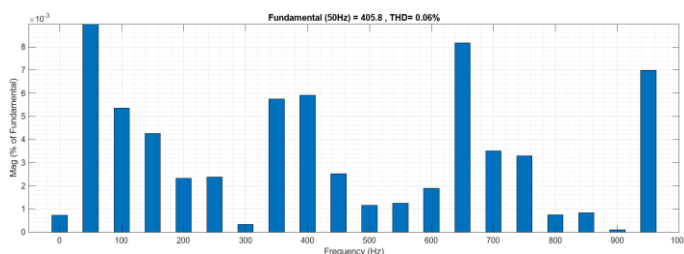


Figure 21:: THD% evaluation of AC voltage present in system 3

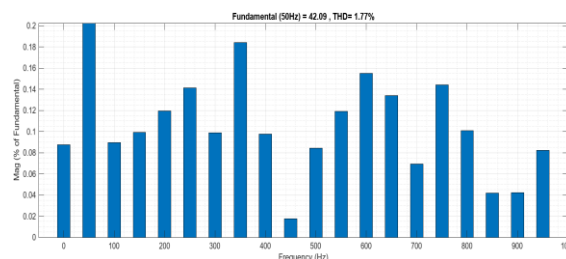


Figure 22:: THD% evaluation of AC current drawn at the loading terminals of system 3

Figure 21 illustrates the THD% of AC voltage in System 3 as 0.06%, while the THD% of AC current is specified as 1.77% in Figure 22. These measurements were taken when the DC-DC converter was under the control of the P&O_WPTA algorithm.

Table 2: Comparative analysis of quality at the AC terminal of the GI_SS

System	Parameters	Values
System 1 (DC-DC converter driven by P&O algorithm)	THD% voltage	0.24 %
	THD% current	6.51 %
System 2 (DC-DC converter driven by AI based grey wolf power tracking algorithm (GWPTA))	THD% voltage	0.15 %
	THD% current	4.19 %
System 3 (DC-DC converter driven by hybrid approach with P&O and wolf power tracking algorithm (P&O_WPTA))	THD% voltage	0.06 %
	THD% current	1.77 %

Table 2 shows the two THD percentages of the voltage and current waveforms under different controls in the GI_SS. For System 1 with P&O, the distortion is at its highest level, whereas on any other hand, System 2 with GWPTA almost eliminates it. Finally, System 3, which uses the hybrid P&O–GWPTA, causes the least distortion, resulting in better power quality.

VI. CONCLUSION AND FUTURE WORK

The study presents the designed and analyzed grid-interfaced solar systems (GI-SS) with dual-stage DC–DC converters while emphasizing the power of advanced control strategies to improve system performance. The considered research considers the three MPPT methods of conventional Perturb and Observe (P&O), Grey Wolf Power Tracking Algorithm (GWPTA), and combination thereof. The results showed that in P&O, simplicity and easy acceptance by users are attached; however, it is slow in response and suffers from oscillations. GWPTA leads to great improvements in dynamic allowing for reducing the total harmonic distortion from 6.51% to 4.19%. Using the hybrid P&O–WPTA method gives the best results with respect to DC-link stability, voltage settling time, and the quality of AC injection with THD being dropped to 1.77%. These results firmly confirm the fact that hybrid and AI-inspired algorithms do enhance robust and dependable solutions for GI-SS for efficient power extraction, minimal distortions, and improved stability toward next-generation grid systems.

Future research ought to proceed with extending the analysis to complex and real operating conditions. Intelligent algorithms should be tested for adaptability to dynamic variations in irradiance and temperature, grid disturbances, and partial shading scenarios. Advanced AI methods, including reinforcement learning or deep learning, could be employed to further enhance the optimization of MPPT and control. Also, integration of GI-SS with advanced energy storage systems such as lithium-ion batteries, flow batteries, or supercapacitors would add resilience against intermittency. Hybrid renewable installations combining PV with wind or fuel cells and carrying AI-based converter management could be another exciting path to explore. Lastly, an important topic for future research concerns grid resilience and compatibility with the smart grid such that intelligent converter controls promote not only efficiency and stability but also fault tolerance, demand response, and smooth integration with the next generation of energy networks.

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