Enhancing Grid-Integrated Solar Systems Efficiency and Stability Through Advanced Control Algorithms

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Abstract: *Solar energy conversion through photovoltaic (PV) technology offers a promising avenue for sustainable electricity generation. This paper delves into the optimization of grid-integrated solar systems (GI_SS) using innovative control algorithms for DC-DC converters. The study investigates three systems: one employing Perturb and Observe (P&O) algorithm, another utilizing Grey Wolf Power Tracking Algorithm (GWPTA), and the third integrating a hybrid approach with both P&O and GWPTA. Through MATLAB/SIMULINK simulations, the research evaluates the impact of these algorithms on system efficiency, stability, and power quality. Analysis extends from the DC generation phase to the AC distribution phase, focusing on performance metrics such as voltage regulation, power transfer efficiency, and total harmonic distortion (THD) in voltage and current waveforms. Results highlight the effectiveness of the hybrid approach in minimizing distortion levels and improving power quality, thus offering insights for enhancing the reliability and robustness of grid-connected solar energy systems.*

Keywords: *Grid-integrated solar systems, photovoltaic technology, DC-DC converters, control algorithms, maximum power point tracking, Grey Wolf Optimization Algorithm.*

I. INTRODUCTION

Solar energy conversion into electricity through photovoltaic (PV) technology [1] involves using solar panels to harness the sun's power. These panels, often referred to as PV panels, are organized into arrays within a PV system, which can be set up either as connected to the grid or as independent, off-grid systems. Essential elements of these systems include solar panels, combiner boxes, inverters, optimizers, and disconnect switches. Systems connected to the grid might also incorporate meters, batteries, charge controllers, and switches for battery disconnection. Solar PV energy production presents various pros and cons.

Generally, photovoltaic (PV) systems are designed to be grid-connected due to the simplicity and cost-effectiveness of this configuration, as opposed to off-grid options that rely on battery storage. Grid-tied PV systems enable households to reduce their grid electricity usage and feed surplus electricity back into the grid. The specific use case of the system influences both its configuration and scale. For instance, residential systems connected to the grid usually have a capacity of under 20 kW. In contrast, commercial setups range from 20 kW to 1 MW, and systems designed for utility-scale energy storage exceed 1 MW.

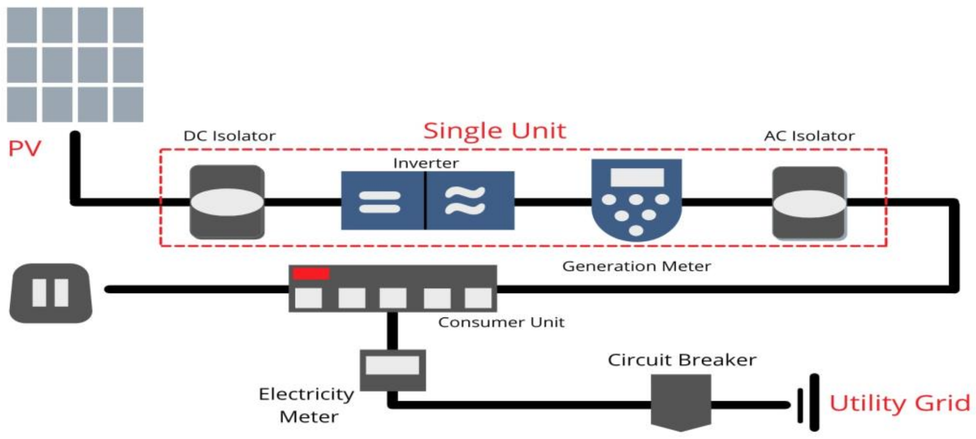

Figure 1. A typical setup for a PV system involves a grid-tied configuration without the inclusion of battery backup

A. Grid Connected Systems

In grid-connected setups, power is directly supplied to the grid, with key components being photovoltaic modules and inverters. This setup reduces overall costs and minimizes maintenance requirements compared to off-grid systems, as batteries, the most maintenance-in tensive elements, are excluded.

Grid-connected PV inverters differ in topology and operation from off-grid counterparts. They must generate high-quality sine wave outputs with low ripples (low THD), matching the grid's frequency and voltage for synchronization. Additionally, they employ Maximum Power Point Tracking (MPPT) algorithms for extracting maximum power from PV modules based on the I–V curve.

PV systems come in various sizes, spanning from small-scale DC modules to extensive PV power plants. PV power converters are classified into module, string, multistring, and central converters. In solar PV power installations, three-phase systems such as central converters and multistring converters are frequently employed in power plants, while single-phase systems like module and string converters are prevalent in residential applications [3]. Despite differences in their designs, these converters share common objectives. These include optimizing power generation from photovoltaic (PV) systems, converting direct current (DC) to alternating current (AC), aligning with grid synchronization requirements, complying with grid code regulations, managing reactive power, detecting islanding events, and implementing protective measures. Sophisticated control algorithms are indispensable for executing these functions, while the incorporation of advanced monitoring, forecasting, and communication technologies bolsters PV system integration to cater to specific demands.

Demands for Grid-Connected Photovoltaic Systems

Grid-connected PV systems are undergoing rapid development and are poised to play a significant role in electricity generation in certain regions. Simultaneously, the performance standards for photovoltaic (PV) systems, depicted in Fig. 1.2, are becoming stricter. Though the current power capacity of a PV system may not match that of an individual wind turbine system, PV system specifications are aligning with those traditionally linked to wind turbine systems. This trend is driven by the growing deployment of large-scale PV systems, or solar power plants, in ongoing development.

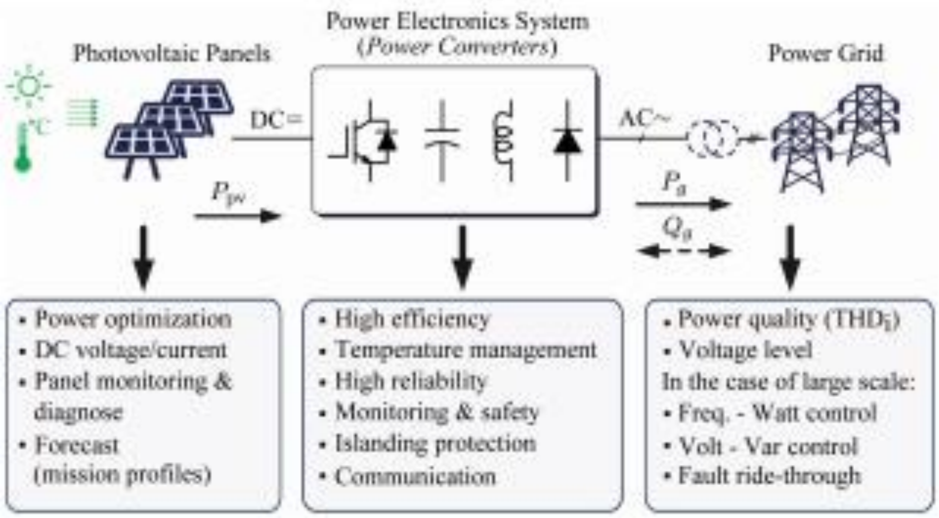

Figure 1 Demands (challenges) for a grid-connected PV system based on power electronics

However, the requirements for PV systems can be delineated across various facets. On the PV side, emphasis is placed on maximizing the output power of PV panels/strings, often achieved through the use of a DCDC converter in a double-stage PV system, known as Maximum Power Point Tracking (MPPT). In this scenario, maintaining the DC voltage (DC-link voltage) at an optimal level for the inverter is crucial. Additionally, safety measures, such as enhanced monitoring and diagnosis at the PV side (e.g., for fire prevention), need to be implemented [4]. On the grid side, the norm is to achieve a desirable Total Harmonic Distortion (THD) of the output current, typically aiming for values below 5%.

B. Maximum Power Point Tracking (MPPT)

The performance of Solar PV systems is negatively impacted by the discrepancy between the power produced and the demand of the connected load. To improve system efficiency, techniques like Maximum Power Point Tracking (MPPT) are utilized to ensure optimal power output is achieved. Due to the non-linear voltage-current (V-I) characteristics of Solar PV systems, boost converters are implemented alongside the panels to adjust the power output to match the requirements of the load. The harmonization of power generation with load demand is achieved by modulating the duty cycle of the converter in accordance with the Maximum Power Point (MPP). Understanding the configuration of the PV system is crucial in planning the control system. Different configurations are possible, ranging from a basic setup where PV systems supply power directly to an inverter connected to the grid to more complex arrangements. Another configuration involves diverting a portion of the power to be stored in a battery bank, while a third configuration stores the entire generated power in the battery bank. The latter approach offers the advantage of centralized connections, utilizing a single micro-inverter for improved efficiency, up to 20%.

MPPT systems are linked to conversion devices in the system capable of modulating current or voltage from the PV panel supply. These power electronic devices are responsible for converting the supply according to the load demand. The MPPT section operates in conjunction with the converter section, identifying the Maximum Power Point (MPP) characterized by specific values of current I_{mpp} and voltageV_{mpp}. The product of these two values yields the maximum power output [6].

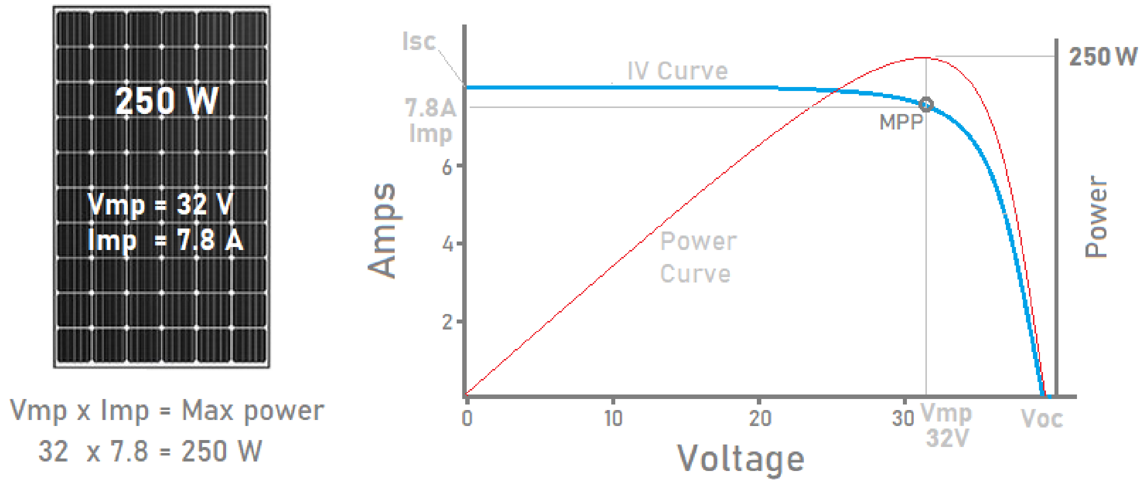

Figure 2 Maximum Power Point Tracking

Batteries undergo charging solely when the solar panel's output voltage surpasses that of the batteries, facilitating a unidirectional current flow from the panel to the battery. The panel's output voltage is contingent upon diverse factors, notably weather conditions such as irradiance. Optimal charging occurs on sunny days when the output voltage exceeds the rated value, while on cloudy days, the output voltage is typically suboptimal. Traditional controllers lack the adaptability to harness elevated output voltages for enhanced power delivery. In contrast, Maximum Power Point Tracking (MPPT) charge controller's exhibit proficiency in voltage adjustment, allowing for an increased current flow during periods of peak demand and delivering a charge to the battery that exceeds the rated capacity by optimizing the voltage-to-current ratio.

MPPT methodologies can be categorized into classical and advanced (soft computing) paradigms. Classical MPPT techniques, established in earlier research phases, are acknowledged for their simplicity and straightforward deployment, yet they are restricted to the identification of a singular Maximum Power Point (MPP) under homogenous solar irradiance. In contrast, contemporary MPPT strategies, which incorporate soft computing frameworks, bio-inspired algorithms, and artificial intelligence mechanisms, are characterized by their intricate algorithmic structures but afford superior efficacy in MPP detection across varying irradiance conditions, outperforming classical methods in tracking precision and operational efficiency.

II. LITERATURE REVIEW

Ishaq and Dincer et al. study investigates three distinct setups for hydrogen production using renewable energy sources: solar PV, geothermal power generation, and biomass gasification. Through parametric analyses, it evaluates their efficiencies. Biomass gasification achieves energetic and exergetic efficiencies at 53.6% and 49.8%, respectively, while geothermal and solar PV-based systems exhibit lower efficiencies.

Muhammad Shahzad Javed et al. The paper extensively examines hybrid solar-wind power systems with pumped hydro storage (PHS). It highlights PHS technology's viability, enhanced efficiency, and its integration with alternative storage solutions for improved reliability, especially in off-grid scenarios. The review categorizes studies based on economic, environmental, and technical aspects, offering valuable insights for researchers.

Amjad Ali et al. (Maximum Power Point Tracking Techniques for PV Systems) This comprehensive review addresses the challenges of selecting suitable maximum power point tracking (MPPT) techniques for photovoltaic (PV) systems. It categorizes online, offline, and hybrid optimization MPPT algorithms under various irradiance conditions, offering insights for researchers and energy engineers.

Rabindra Nath Shaw et al. (IoT Integration in PV Systems):Focusing on maximizing power production in photovoltaic systems, this study introduces IoT integration under partial shading conditions. It explores MPPT techniques to enhance efficiency, crucial for optimizing energy production and overall system efficiency.

Kangante Vishal et al. (Grid-Connected PV System with SRF Control): This study presents a grid-connected PV system utilizing Synchronous Reference Frame (SRF) theory for advanced control. It addresses challenges such as maintaining stable AC-side voltage, compensating for harmonic currents, and detecting islanding events for reliable operation.

Tabbi Wilberforce et al. (CSP and EGE Technologies):The review provides an overview of Concentrated Solar Photovoltaics (CSP) and Enhanced Geothermal Energy (EGE) technologies, emphasizing their potential as alternatives to traditional fossil fuels. It discusses primary types, challenges hindering commercialization, and future prospects.

F.A. Khan et al. (Hybrid Renewable Energy Systems): Focusing on economic feasibility and optimization of hybrid energy systems, this paper explores the combination of solar PV and wind resources. It discusses sizing strategies, advancements, and development of effective storage systems.

C. Dondariya et al. (Grid-Connected Rooftop Solar PV Systems):Investigating the viability of grid-connected rooftop solar PV systems in Ujjain, India, this study employs various simulation tools for performance analysis. It offers insights into energy generation, performance ratio, and solar fraction crucial for system deployment.

Amresh Kumar Singh et al. (Distributed Sparse Control for PV Systems): This research introduces a Distributed Sparse (DS) control method for a single-stage Solar Photovoltaic (PV) energy generation system integrated into a three-phase grid. It addresses varying solar irradiance levels and nonlinear loads, demonstrating adaptability and performance.

Shubhra et al. (Neural Filter-Based Control for PV-Battery Microgrid): Proposing a novel control methodology, this study enhances the performance and reliability of grid-connected solar PV-battery energy storage microgrid systems. It employs neural filter-based control and dynamic charge-discharge operations to optimize power extraction and ensure uninterrupted power supply.

Amit Kumar Gupta et al. (Transformerless Topology for Grid-Connected Applications): Introducing an innovative transformerless topology for 3-phase grid-connected applications, this study merges benefits from DC and AC bypass circuit configurations. It employs sinusoidal Pulse Width Modulation (PWM) and specialized logic functions to minimize common mode voltage variation and achieve low Total Harmonic Distortion (THD).

III. OBJECTIVE

This research is aimed to achieve following key objectives:

1. Develop a Grid-Integrated Solar Systems (GI_SS) in MATLAB/SIMULINK environment driving non linear loads on the AC side.
2. 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
3. Analyse the impact of controllers designed at the DC line parameters as well as AC line parameters for quality and stability
4. Reduce the current and voltage distortion levels and improving the power quality delivered at the loading points.\

IV. METHODOLOGY

A. Software selection for analysis

The model has been created in climate of MATLAB/SIMULINK. It functions as a high-level matrix/array language equipped with data structures, functions, control flow statements, and input/output capabilities, along with features for object-oriented programming. Key characteristics of these features are outlined below:

- Offering royalty-free deployment options, they provide alternatives for sharing MATLAB programs with end clients.
- Featuring add-on tool compartments catering to a diverse array of engineering and scientific applications.
- Providing a desktop environment finely tuned for design, iterative exploration, and effective problem-solving.
- They provide Royalty-free deployment alternatives for sharing of the MATLAB programs with end clients.
- They have Add-on tool compartments for a wide range of engineering and scientific applications.
- They include Desktop environment tuned for design, iterative exploration and problem solving.
- They prefer of the scientific and engineering computing for High-level language.
- They have tools for custom user interfaces with building applications.
- They have apps for data classification, signal analysis, curve fitting, control system tuning, and other numerous assignments.

- They also provide graphics for visualizing data and tools for making custom plots.

The primary aim of this thesis is to examine and break down the power tracking strategies most applicable to photovoltaic applications. It seeks to assess their implementation and advantages through the utilization of artificial intelligence-based optimization algorithms, such as the Gray Wolf strategy optimization. The current study involves performing two power tracking calculations on grid connected PV modules driving non linear AC loads on the system

B. Photovoltaic Modeling

Solar cells are p-n semiconductor junction also addressed as a diode circuit displayed below in Figure 4.1 which includes series resistance (Rs), parallel resistance (Rsh) and photocurrent (Iph) of the PV cell. Series cells and parallel cells are connected to form the PV which is used in building solar panel. The mathematical formation of PV panel is mentioned below:

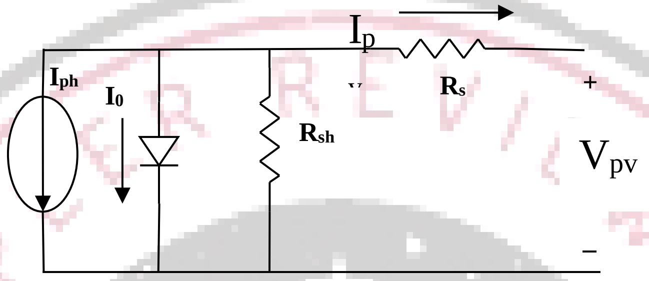

Figure 4. Solar cell circuit

Table 4.1 Parameters selected for PV modeling in MATLAB		
Parameters	**Symbols**	**Values**
Shortcircuit current	Isc	6.14 A
Irradiation	R	1000 W/m^2
Open circuit voltage	Voc	64.6 V
Maximum current	Imp	5.76 A
Temperature	K	35 K
Maximum Power	Pmax	315.072 W
Maximum voltage	Vmp	54.7 V
Series	N_s	5
Parallel	N_p	64

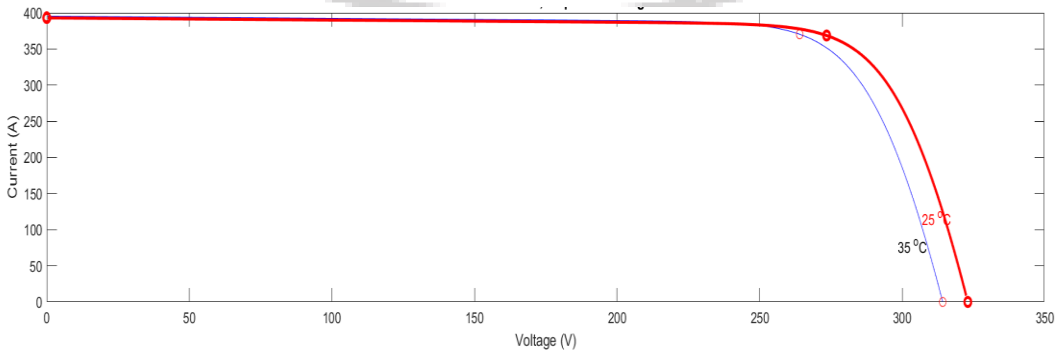

Figure 5 Current-voltage curve of panel for irradiations 1000 Wb/m^2

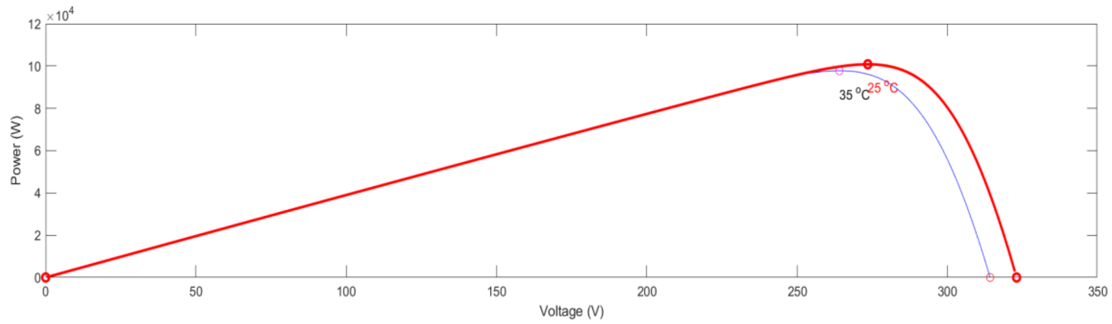

Figure 6 PV curve of panel for irradiations 1000 Wb/m^2

C. Power Tracking using DC-DC converter Concept

Overall four control plans are cultivated for network-associated single-stage PV framework viz current control, maximum power point tracking control, grid synchronization, and voltage control. Climatic temperature and sunlight-based lights are factors in which PV power depends which changes with time. Also, due to the non-linear loads and power attributes of the PV module to improve the utilization of the PV module, power tracking control becomes a major part of the PV system. Now it is important to develop a productive calculation for maximum power that relentlessly checks the terminal voltage and current and aligns them with the MPP values. A DC-DC converter has been brought to use for this purpose which is being controlled by three major algorithms: Perturb and Observe (P&O), Grey Wolf Power Tracking Algorithm (GWPTA) and an hybrid approach comprising of P&O and wolf power tracking algorithm (P&O_WPTA).

Boost converter is utilized when the increased of DC O/P voltage is obtained from low DC I/P voltage. The Input current should be more than the O/P current to conserve the power. As shown below in figure 4.4, it contains Diodes (D), a semiconductor switch and an energy of storing elements (L-C).

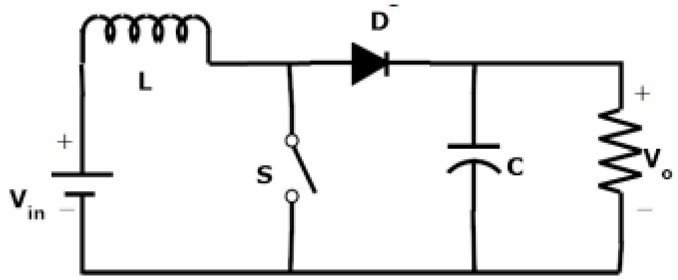

Figure 7 Boost converter circuit diagram

Duty ratio is denoted by D in which o/p voltage of the boost converter relies on. By overseeing the obligation proportion the yield voltage can be gotten. The ideal yield voltage can be dictated by the formula:

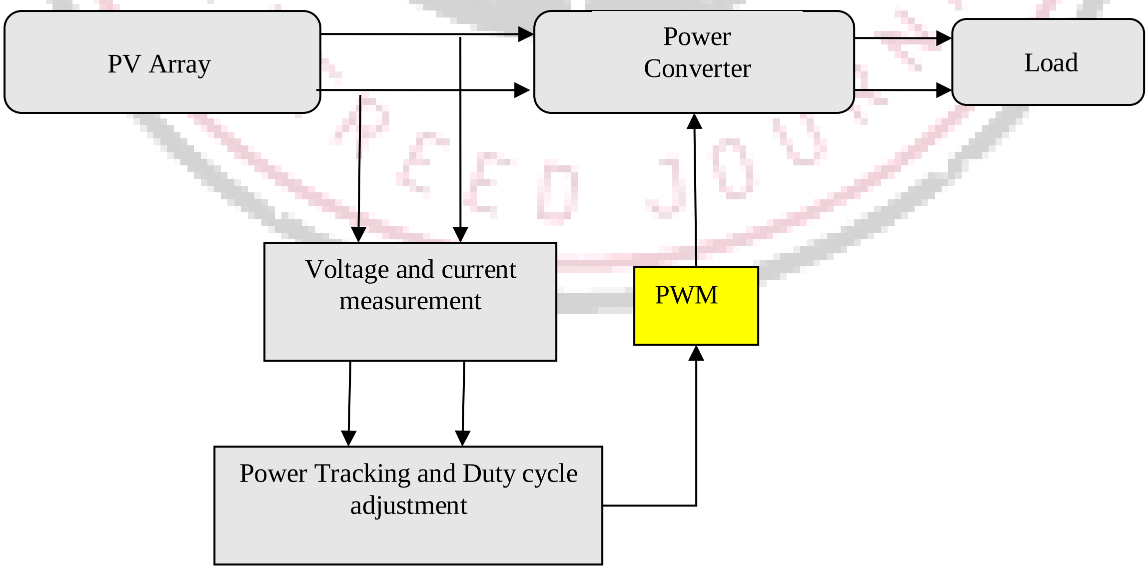

Figure 8 Principle of tracing maximum power from the solar system

D. Designing of Grey Wolf Power Tracking Algorithm (GWPTA)

In this investigation, the GWPTA (Gray Wolf Particle Swarm Optimization with Teaching-Learning-Based Optimization Algorithm) control technique is employed to govern the DC-DC converter within a solar panel system. The real-time monitoring of the solar panel's current and voltage parameters is utilized to dynamically ascertain the duty ratio for the switching signal. The adjustment of the Pulse Width Modulation (PWM) signal and converter operations is contingent upon the instantaneous performance of the solar panel system. The GWPTA system continuously assesses the current and voltage parameters of the solar panel, subsequently deriving the alpha power value and duty ratio crucial for achieving optimal power extraction from the system. By initializing predefined values for the solar panel system within the software, a validity function is constructed, delineating the system's power as the product of current and voltage.

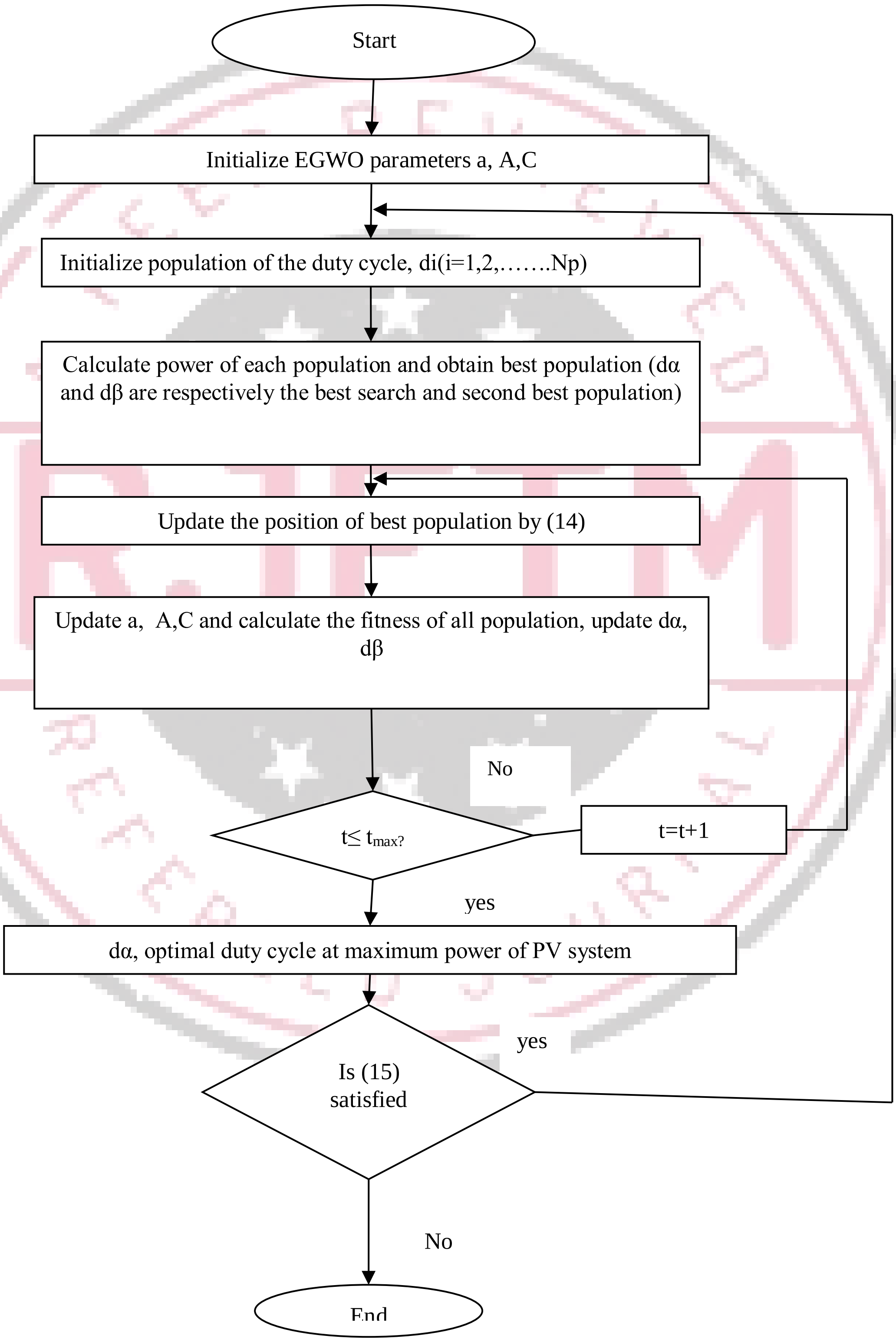

Figure 9 Flow chart for GWO MPPT Algorithm for power optimization

E. DC-DC converter control system with hybrid approach having P&O_WPTA approach

We integrate the Grey Wolf Optimizer algorithm with the Perturb and Observe (P&O) method through a low-level co-evolutionary mixed hybridization approach. This hybridization is considered low level due to the combination of functionalities from both variants. It is co-evolutionary, operating in parallel rather than sequentially, and mixed as it involves two distinct variants to generate final solutions for the given problems. With this modification, we enhance the exploitation capability of P&O by incorporating the exploration ability of the Grey Wolf Optimizer, leveraging the strengths of both variants.

In the hybrid algorithm, the positions of the first three agents in the search space are updated using the proposed mathematical equations (16-18). Rather than employing conventional equations, we utilize an inertia constant to regulate the exploration and exploitation of the grey wolf within the search space.

Table 4.2 Input parameters for GWO MPPT in simulation

Parameters	Symbols	Values
Duty cycle (Maximum limit)	d_{max}	0.5
Duty cycle (Minimum limit)	d_{min}	0.1
number of search agents used in the flock	f	10
Number of iterations	i	100

V. RESULT ANALTSIS

The solar based renewable energy systems have been recent focus area for all the researches to enhance the output power from the PV systems and reduce the dependency on the grid. A grid-integrated solar energy system encompasses the amalgamation of solar photovoltaic (PV) panels with the electrical grid infrastructure. The energy generated by the PV panels undergoes conversion from direct current (DC) to alternating current (AC) through inverters, facilitating its integration into the electrical grid. The optimization of power transfer from the solar panels to the inverters relies significantly on the functionality of DC-DC converters. Analyzing the DC-DC converter entails a meticulous examination of its core characteristics and performance metrics, critical for the efficient operation of the overall system. MATLAB, a widely utilized tool, finds application in simulating and analyzing power electronic systems, offering valuable insights into the intricacies of grid-integrated solar energy systems.

The DC-DC converter plays a pivotal role in enhancing the performance and efficiency of the overall system. One of its primary functions is to regulate and optimize the direct current (DC) voltage generated by the solar panels. By doing so, the DC-DC converter ensures that the output voltage remains stable and well-suited for further processing within the system. Additionally, the converter acts as a crucial intermediary, matching the output voltage of the solar panels to the specific input voltage requirements of the inverter. This voltage matching process is essential for seamless integration, allowing the inverter to efficiently convert the DC power into alternating current (AC) suitable for the electrical grid. Importantly, the DC-DC converter goes beyond voltage regulation; it is designed to maximize power transfer efficiency.

The solar PV system analysis has been focused designing the control algorithms for DC-DC converter systems The Grid integrated solar system (GI_SS) architecture comprises of a solar system driving non-linear loads at the AC terminals which is further integrated with the grid.

System 1: GI_SS having DC-DC converter driven by P&O algorithm

System 2: GI_SS having DC-DC converter driven by AI based grey wolf power tracking algorithm (GWPTA)

System 3: GI_SS having DC-DC converter driven by hybrid approach with P&O and wolf power tracking algorithm (P&O_WPTA)

The overarching goal of this research is for providing insights into the performance and robustness of the solar-based energy system, addressing both the DC generation phase and the subsequent AC distribution phase. By specifically focusing on the impact of nonlinear loads on the AC side, the research aims to propose mitigation strategies and solutions for enhancing the overall quality and reliability of the energy delivered to the grid or end-users.

A. Analysis on the DC outputs of the GI_SS

The research conducted focuses on a comprehensive analysis of a solar-based energy system, with a particular emphasis on the direct current (DC) output generated by the solar panels. This initial phase of the investigation involves scrutinizing the characteristics and performance metrics of the DC power produced by the solar panels. Researchers aim to understand variations in voltage, current, and power levels

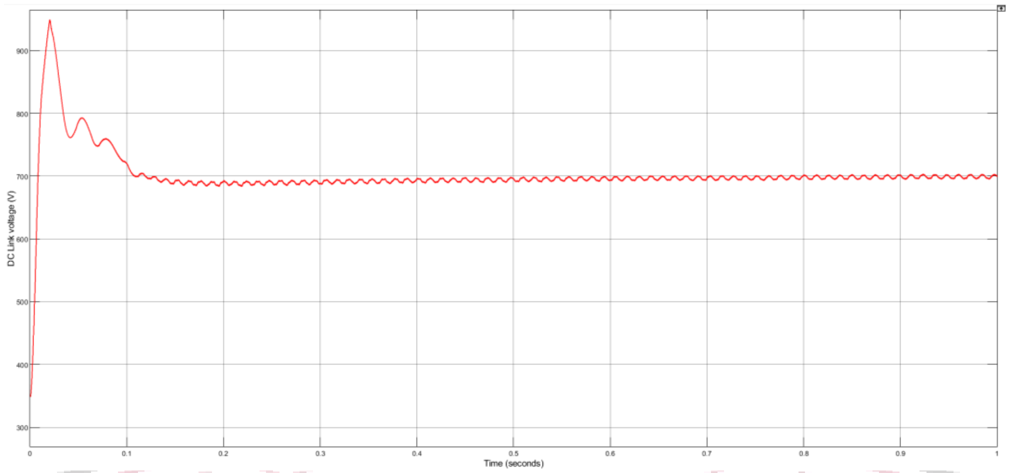

Figure 10: DC output voltage in system 1

Figure 10 represents the DC voltage output waveform of solar energy system where the DC-DC converter is being driven by the P & O control algorithm, as it can be seen that the voltage is highly variable in nature in the starting points. The mention of voltage variability in the starting points suggests that the system experiences fluctuations in its output voltage during the initial phases, possibly due to dynamic environmental conditions impacting solar panel efficiency.

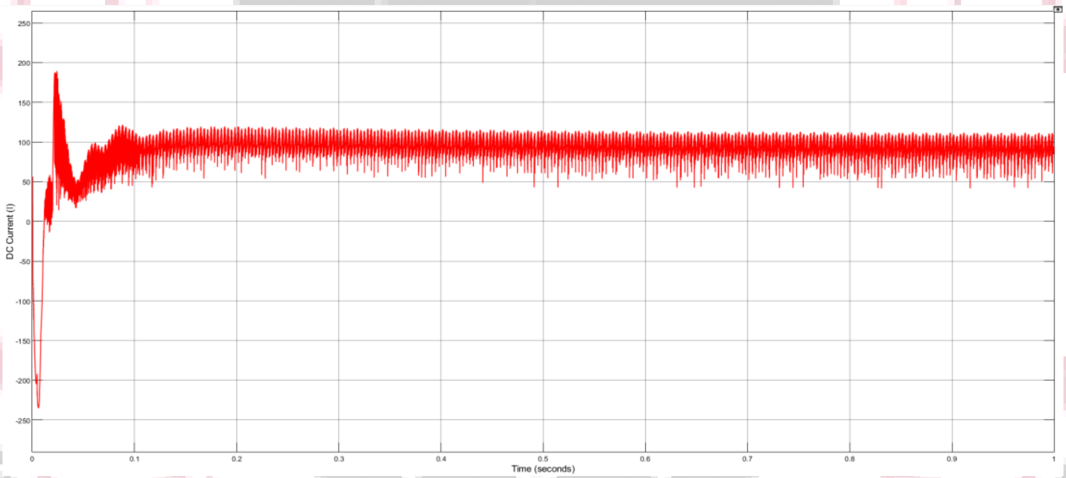

Figure 11 DC output current in system 1

The DC output current in the solar energy system where the DC-DC converter is being driven by the P & O control algorithm is represented by the figure 11. The inference drawn from the graph is that the nature of current is highly unstable under this control.

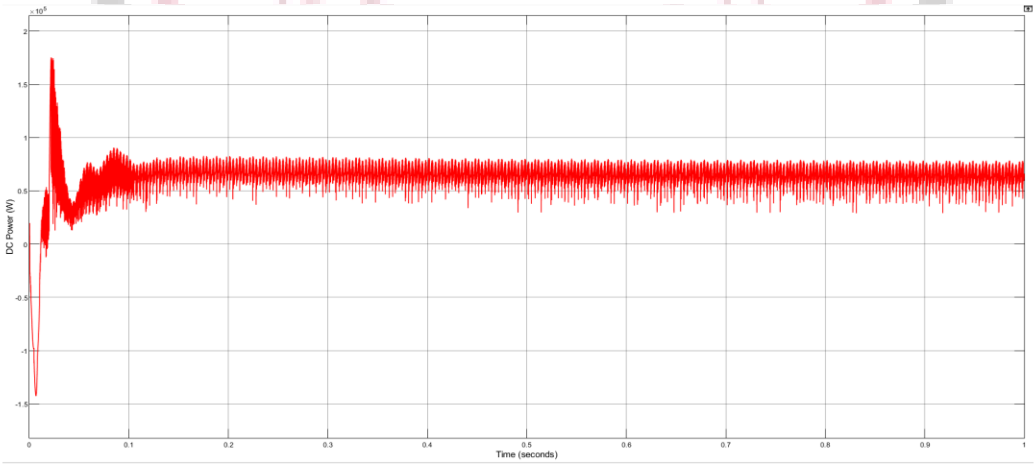

Figure 12 DC Power Output in system 1

The DC output power from the solar energy system where the DC-DC converter is being driven by the P & O control algorithm is represented by the figure 12. The inference drawn from the graph is that the nature of power unstable due to unstable nature of current.

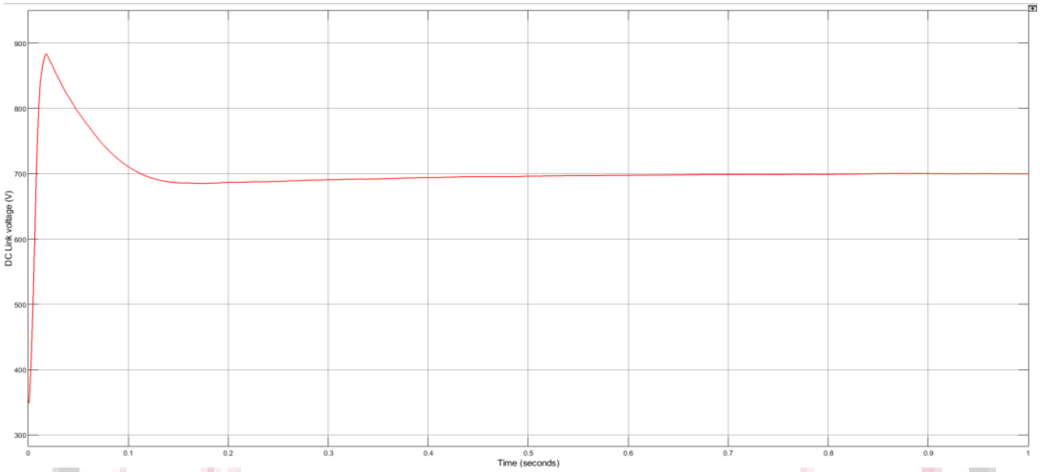

Figure 13: DC output voltage in system 2

Figure 13 represents the DC voltage output waveform of solar energy system where the DC-DC converter is being driven by the grey wolf power tracking algorithm (GWPTA), as it can be seen that the voltage is slightly stabilized at the starting points.

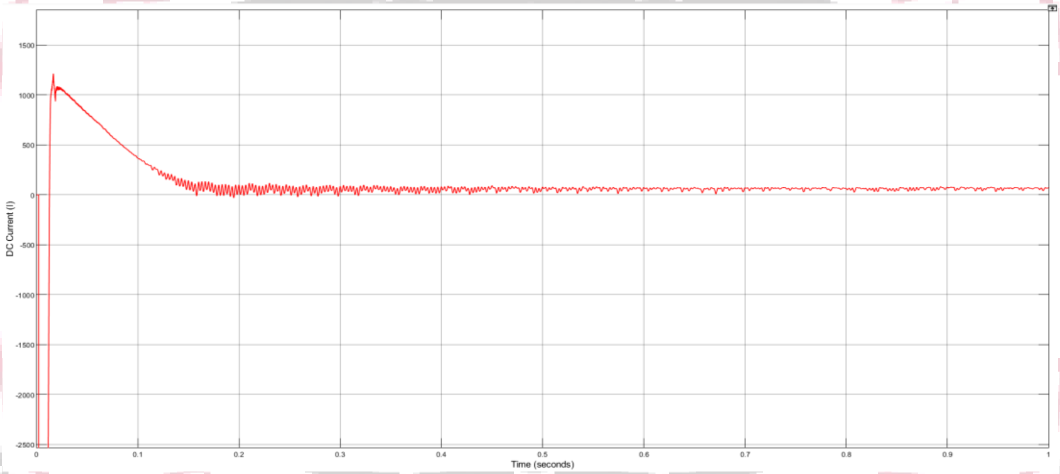

Figure 14 DC output current in system 2

The DC output current in the solar energy system where the DC-DC converter is being driven by the grey wolf power tracking algorithm (GWPTA) which is represented by figure 14.

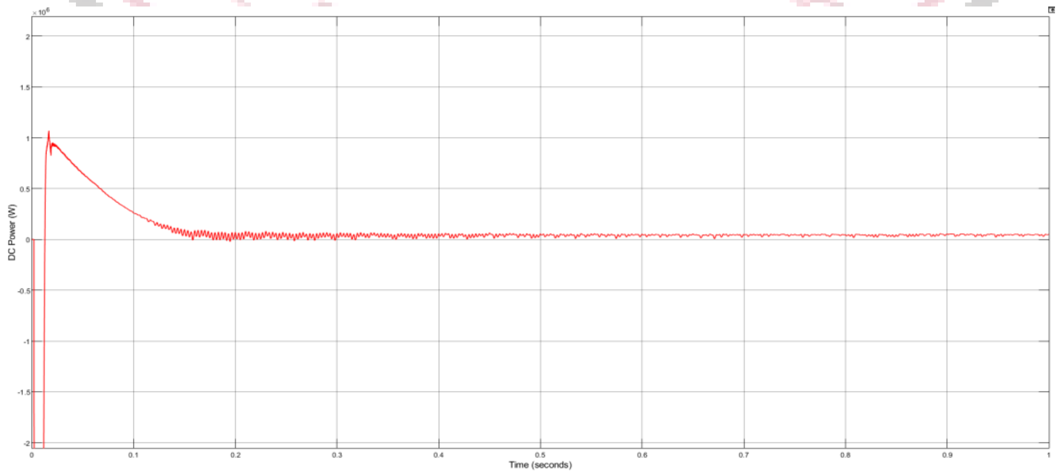

Figure 15: DC power output present in system 2

The DC output power from the solar energy system where the DC-DC converter is being driven the grey wolf power tracking algorithm (GWPTA) which is represented by the figure 15. The inference drawn from the graph is that the nature of power is stable due better stability of current.

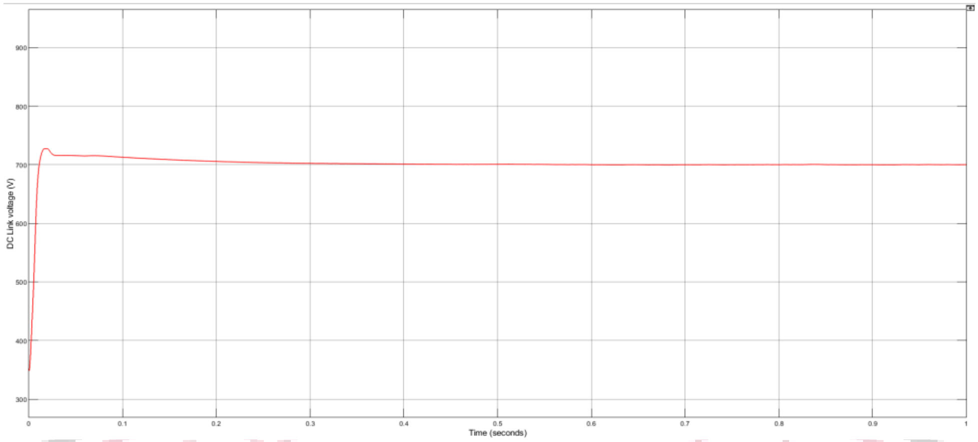

Figure 16: DC output voltage in system 3

Figure 16 represents the DC voltage output waveform of solar energy system where the DC-DC converter is being driven by hybrid approach with P&O and wolf power tracking algorithm (P&O_WPTA), it can be seen that the voltage more stable using this approach.

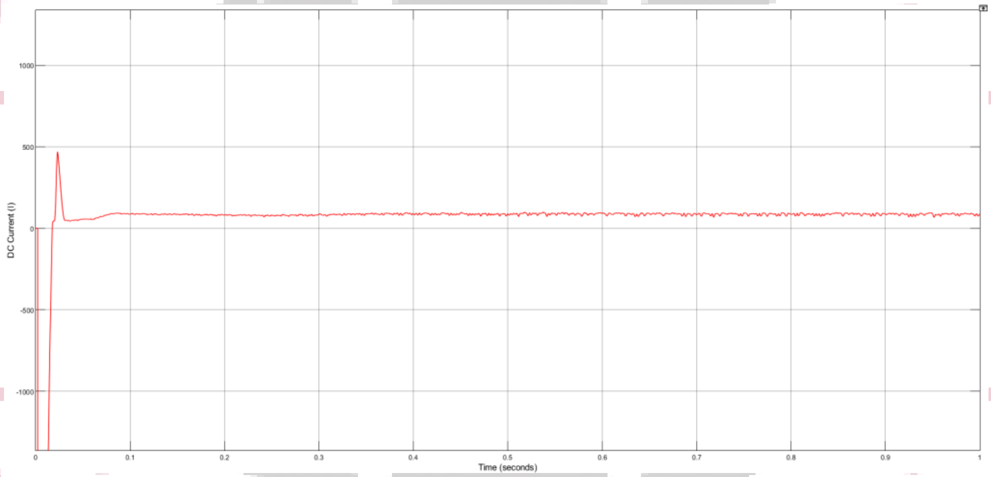

Figure 17: DC output current in system 3

The DC output current in the solar energy system where the DC-DC converter is being driven by hybrid approach with P&O and wolf power tracking algorithm (P&O_WPTA) which is represented by figure 17.

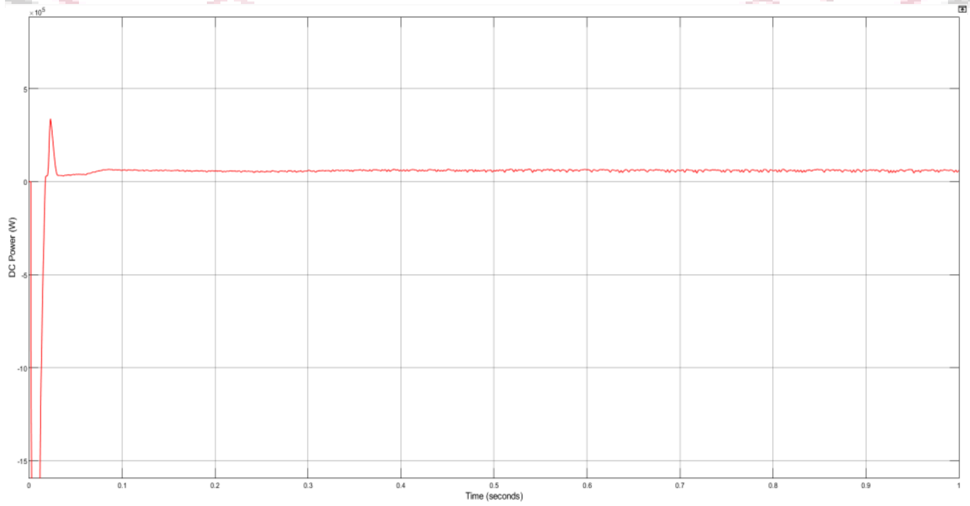

Figure 18: DC output power in system 3

The DC output power from the solar energy system where the DC-DC converter is being driven by hybrid approach with P&O and wolf power tracking algorithm (P&O_WPTA) which is represented by the figure 18. The inference drawn from the graph is that the nature of power is stable.

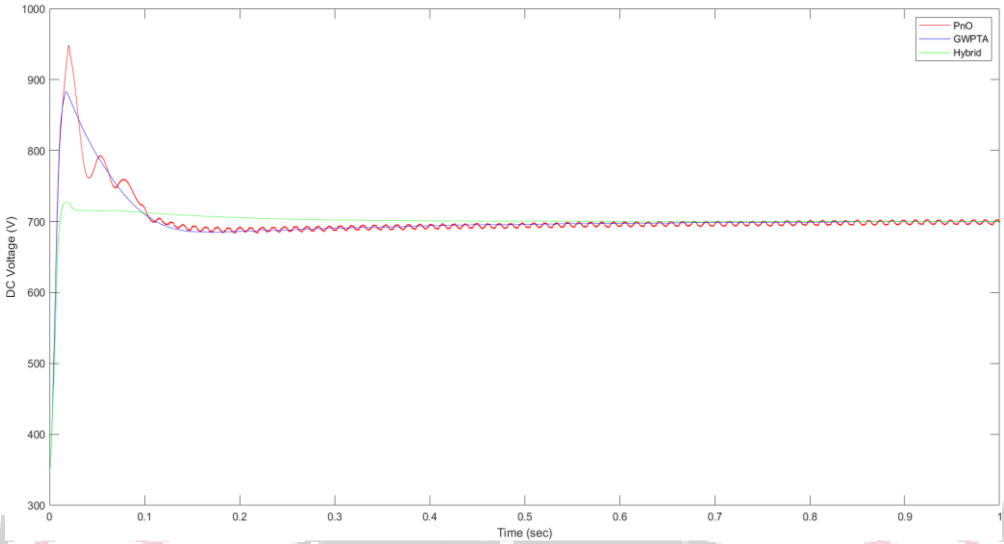

Figure 19: Comparative analysis of DC output voltage in GI_SS having different controllers for DC-DC converters

Figure 19 illustrates the comparative analysis of DC output voltage in a Grid-Connected Solar System (GI_SS) with three different controllers for DC-DC converters which displays the performance of each controller and it has been found that GWPTA algorithm has better voltage stability results than the P&O algorithm and it is further concluded that system with hybrid approach has more stable voltage outputs.

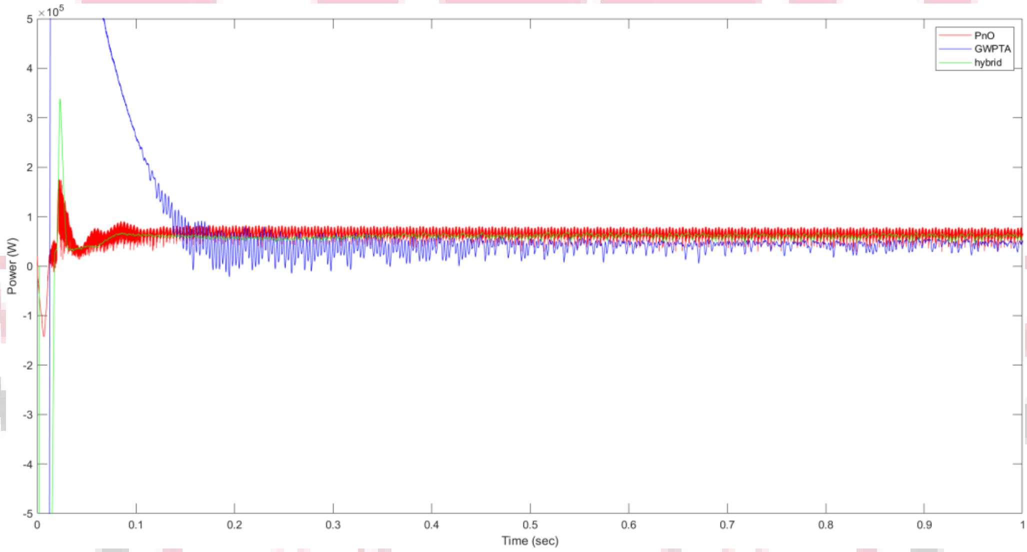

Figure 20: Comparative analysis of DC power in GI_SS having different controllers for DC-DC converters

Figure 20 illustrates the comparative analysis of DC output power in a Grid-Connected Solar System (GI_SS) with three different controllers for DC-DC converters which displays the performance of each controller and it has been found that GWPTA algorithm has better power stability results than the P&O algorithm and it is further concluded that system with hybrid approach has more stable power outputs.

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

Following the examination of the DC output, the research extends to the alternating current (AC) side of the system. This involves an in-depth analysis of the AC power quality issues that may arise, especially when the system is connected to nonlinear loads. Nonlinear loads, such as those associated with electronic devices, can introduce harmonic distortions and other power quality issues into the AC waveform. The analysis at the nonlinear load terminal encompasses investigations into voltage distortions, and harmonic content. Researchers seek to identify potential issues related to waveform integrity and power quality degradation. Gaining insights into these challenges is imperative, as nonlinear loads harbor the potential to introduce disturbances that could influence the stability and reliability of the overall power distribution system. Understanding and addressing the impact of nonlinear loads on system dynamics are crucial aspects in ensuring the robustness and effectiveness of power distribution networks.

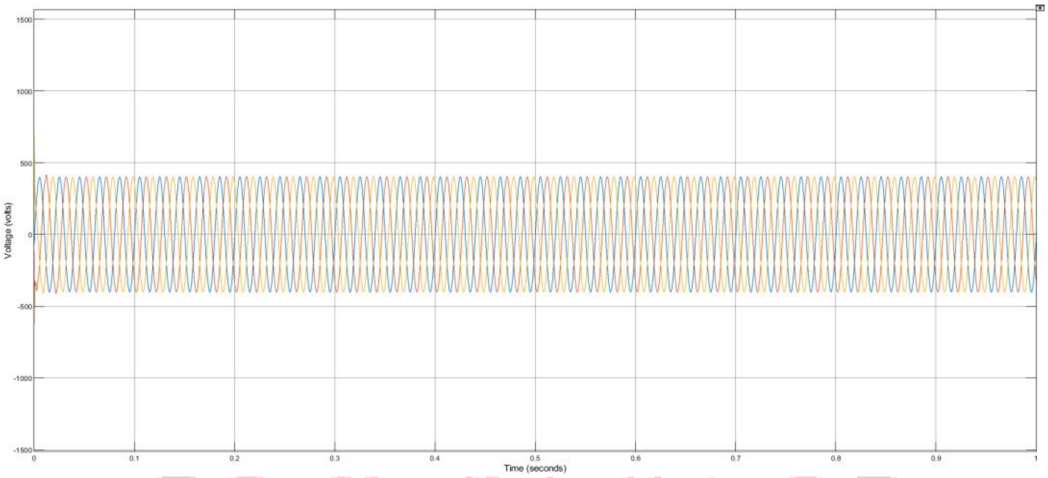

Figure 21: Nonlinear load terminal AC voltage present in system 1

Figure 21 is representing the three phase AC voltage waveform available at the load terminal after DC/AC conversion from the inverter whose input is derived from the DC-DC converter is being driven by the P&O algorithm

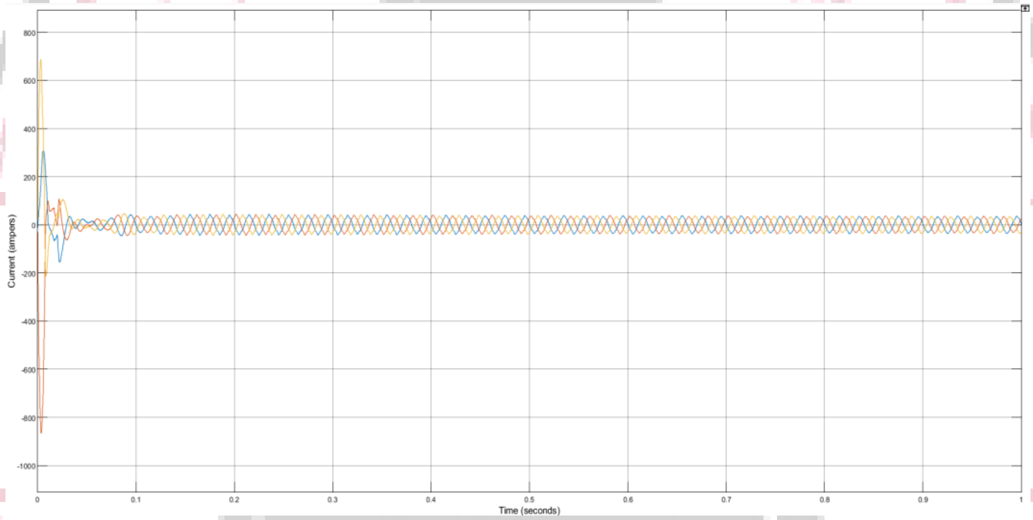

Figure 22: AC current drawn at the terminal in system 1

Figure 22 is representing the three phase AC current waveform drawn at the load terminal in the grid integrated solar energy system where the DC-DC converter is being driven by the P&O algorithm

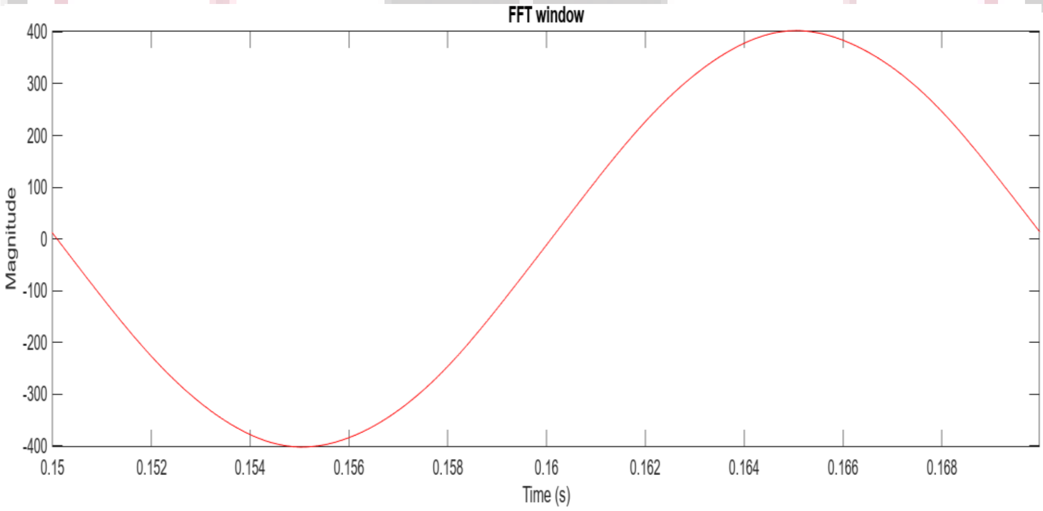

Figure 23: FFT analysis of AC voltage present in system 1 in the MATLAB

The figure 23 represents the results of a Fast Fourier Transform (FFT) analysis conducted on the AC voltage signal from System 1 having DC-DC converter controlled by P&O algorithm using MATLAB. This type of analysis is valuable in understanding the harmonic content and potential issues in the electrical system.

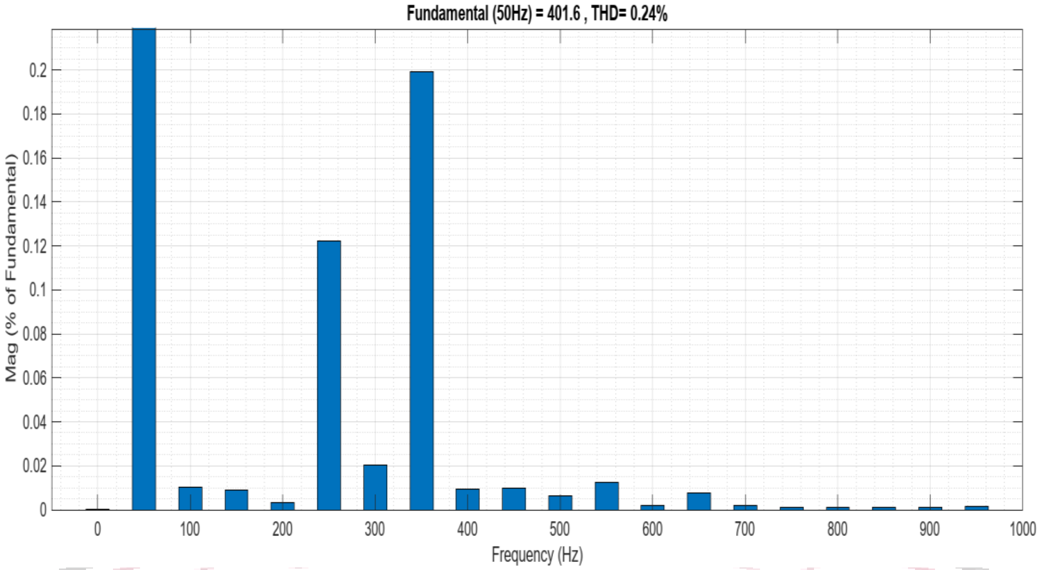

Figure 24: THD% evaluation of AC voltage present in system 1

In Figure 24, the evaluation of Total Harmonic Distortion (THD%) is presented for the AC voltage signal derived from System 1. The identified THD% is established at 0.24%, and this result is associated with the implementation of the Perturb and Observe (P&O) algorithm for controlling the DC-DC converter within the solar system.

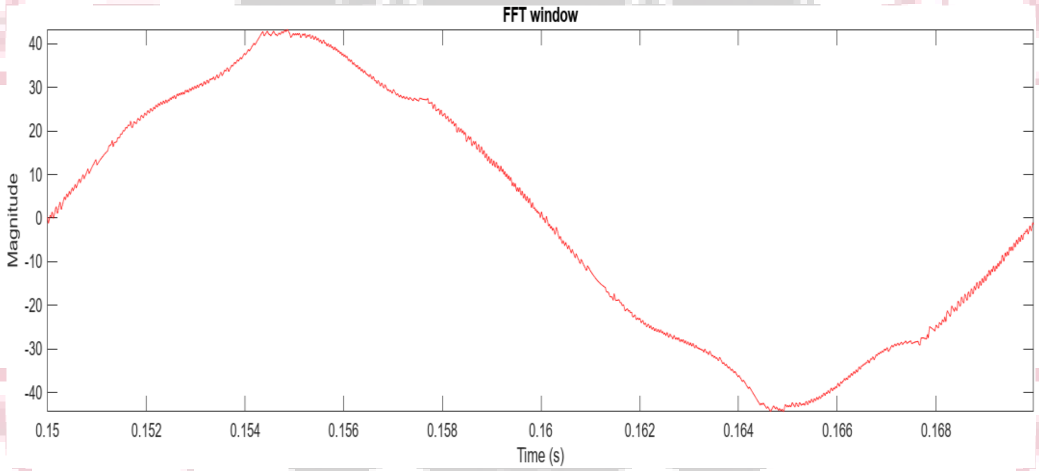

Figure 25: FFT analysis of AC current drawn at the loading terminals of system 1

The figure 25 represents the results of a Fast Fourier Transform (FFT) analysis conducted on the AC current signal from System 1 having DC-DC converter controlled by P&O algorithm using MATLAB. This type of analysis is valuable in understanding the harmonic content and potential issues in the electrical system

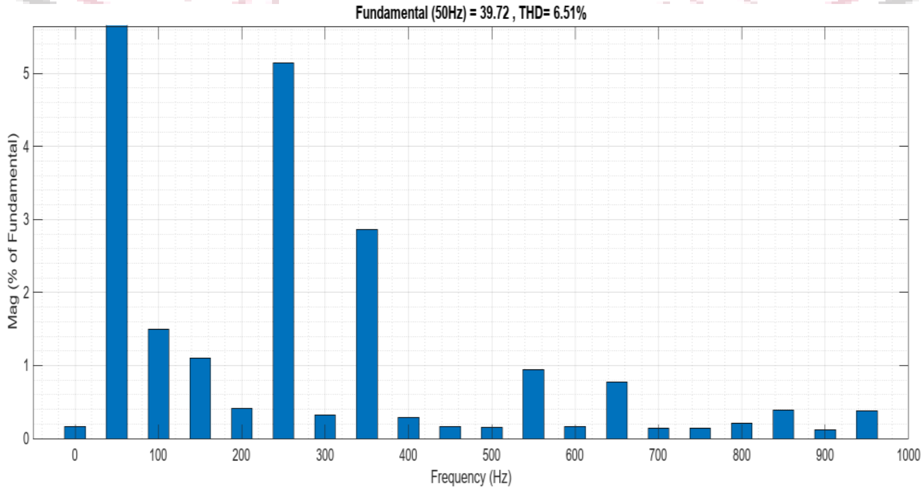

Figure 26: THD% evaluation of AC current drawn at the loading terminals of system 1

Figure 26 illustrates the analysis of Total Harmonic Distortion (THD%) performed on the AC current signal derived from System 1. The determined THD% is recorded at 6.51%, with the DC-DC converter of the solar system being controlled by the Perturb and Observe (P&O) algorithm.

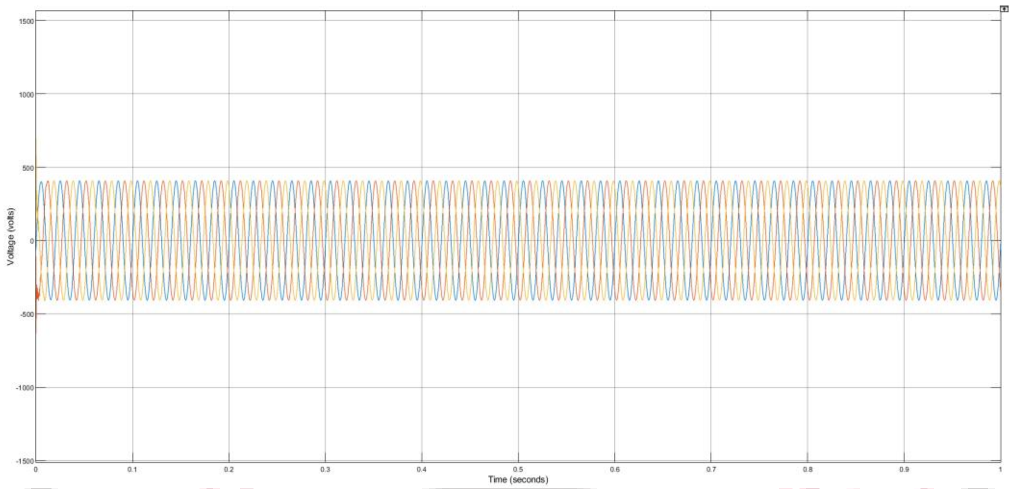

Figure 27: Nonlinear load terminal AC voltage present in system 2

Figure 27 is representing the three phase AC voltage waveform available at the load terminal after DC/AC conversion from the inverter whose input is derived from the DC-DC converter is being driven by the GWPTA algorithm

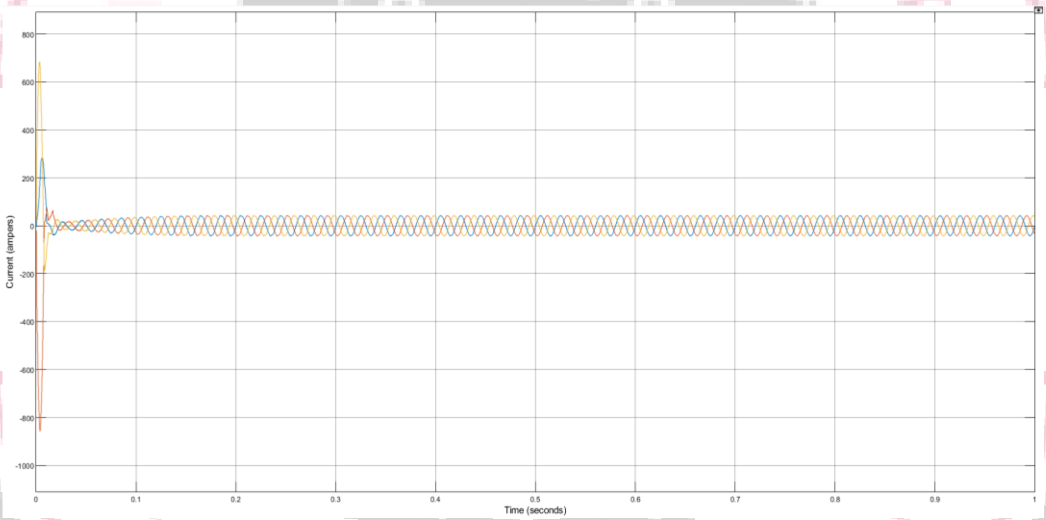

Figure 28: AC current drawn at the terminal in system 2

Figure 28 is representing the three phase AC current waveform drawn at the load terminal in the grid integrated solar energy system where the DC-DC converter is being driven by the GWPTA algorithm

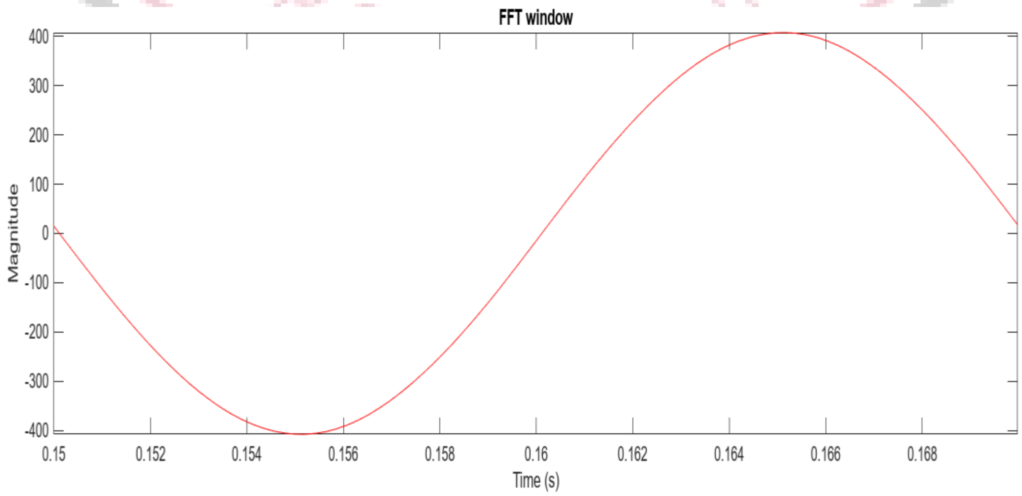

Figure 29: FFT analysis of AC voltage present in system 2 in the MATLAB

The figure 29 represents the results of a Fast Fourier Transform (FFT) analysis conducted on the AC voltage signal from System 2 having DC-DC converter controlled by GWPTA algorithm using MATLAB. This type of analysis is valuable in understanding the harmonic content and potential issues in the electrical system.

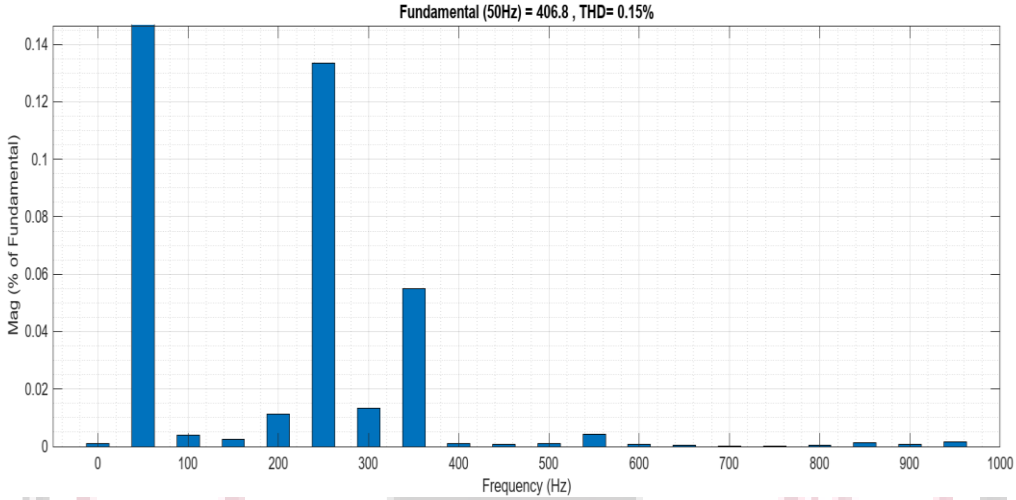

Figure 30 THD% evaluation of AC voltage present in system 2

The figure 30 represents the Total Harmonic Distortion (THD%) analysis conducted on the AC voltage signal from System 2 and it was found to be 0.15% where the GWPTA algorithm is driving the DC-DC converter of the solar system

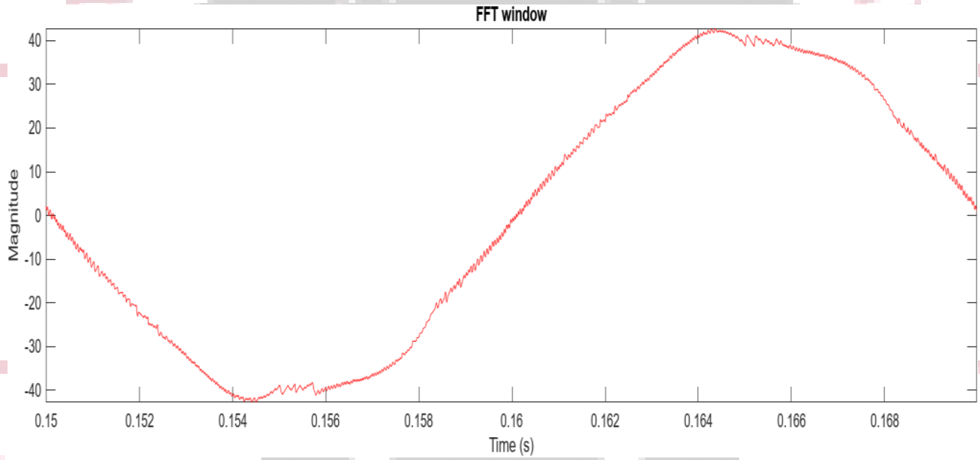

Figure 31 FFT analysis of AC current drawn at the loading terminals of system 2

The figure 31 represents the results of a Fast Fourier Transform (FFT) analysis conducted on the AC current signal from System 2 having DC-DC converter controlled by GWPTA algorithm using MATLAB which is further used to evaluate the THD% in the waveform.

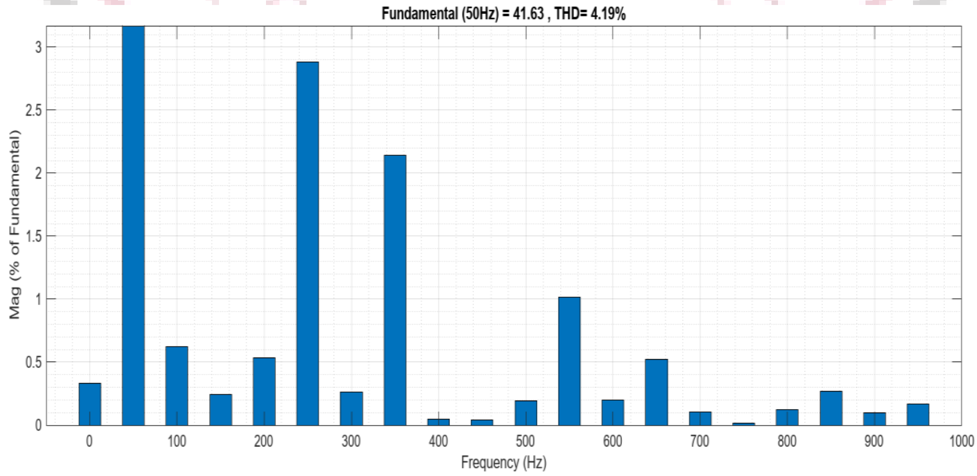

Figure 32 THD% evaluation of AC current drawn at the loading terminals of system 2

The figure 32 represents the Total Harmonic Distortion (THD%) analysis conducted on the AC current signal from System 2 and it was found to be 4.19% where the GWPTA algorithm is driving the DC-DC converter of the solar system

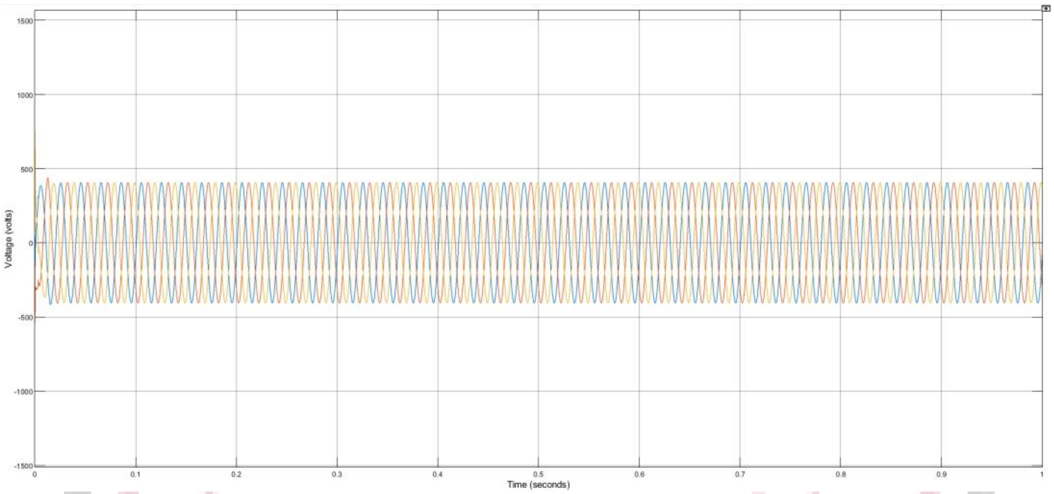

Figure 33 Nonlinear load terminal AC voltage present in system 3

Figure 5.24 is representing the three phase AC voltage waveform available at the load terminal after DC/AC conversion from the inverter whose input is derived from the DC-DC converter is being driven by the P&O_WPTA algorithm

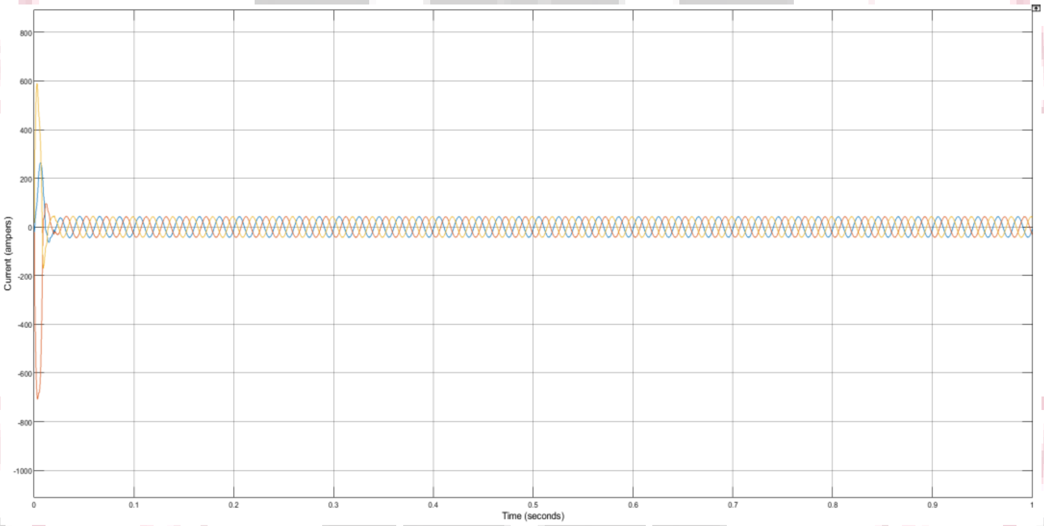

Figure 34: AC current drawn at the terminal in system 3

Figure 34 is representing the three phase AC current waveform drawn at the load terminal in the grid integrated solar energy system where the DC-DC converter is being driven by the P&O_WPTA algorithm

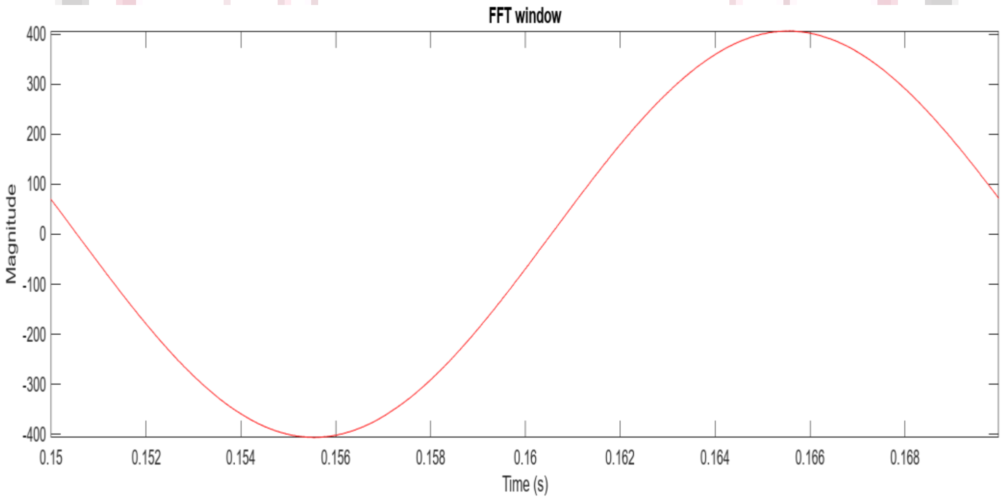

Figure 35: FFT analysis of AC voltage present in system 3 in the MATLAB

The figure 5.26 represents the results of a Fast Fourier Transform (FFT) analysis conducted on the AC voltage signal from System 3 having DC-DC converter controlled by P&O_WPTA algorithm using MATLAB. This type of analysis is valuable in understanding the harmonic content and potential issues in the electrical system.

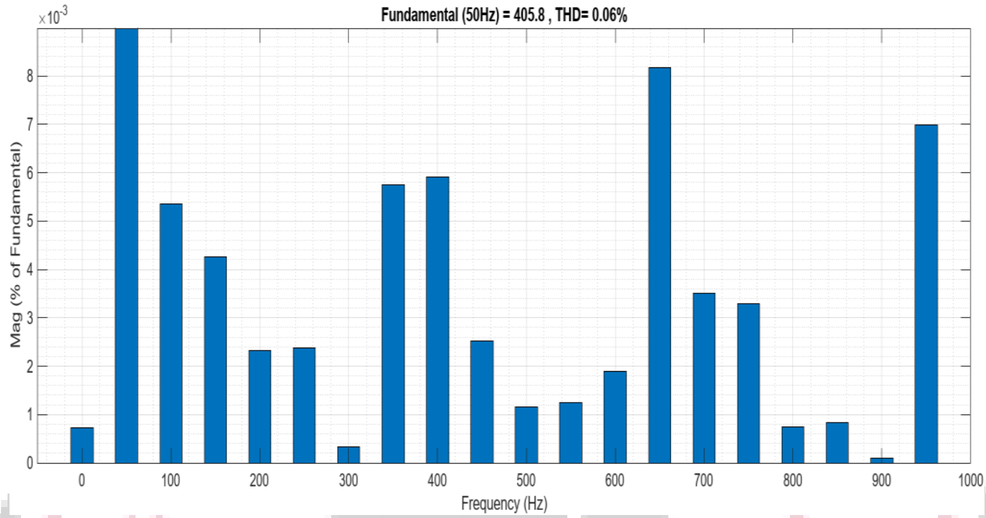

Figure 36: THD% evaluation of AC voltage present in system 3

The figure 36 represents the Total Harmonic Distortion (THD%) analysis conducted on the AC voltage signal from System 3 and it was found to be 0.06% where the P&O_WPTA algorithm is driving the DC-DC converter of the solar system

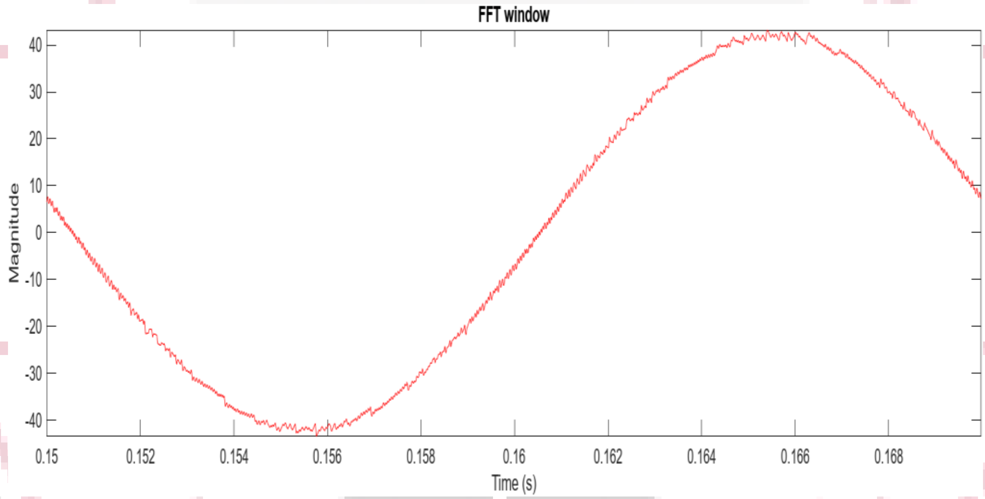

Figure 37: FFT analysis of AC current drawn at the loading terminals of system 3

The figure 37 represents the results of a Fast Fourier Transform (FFT) analysis conducted on the AC current signal from System 3 having DC-DC converter controlled by P&O_WPTA algorithm using MATLAB which is further used to evaluate the THD% in the waveform.

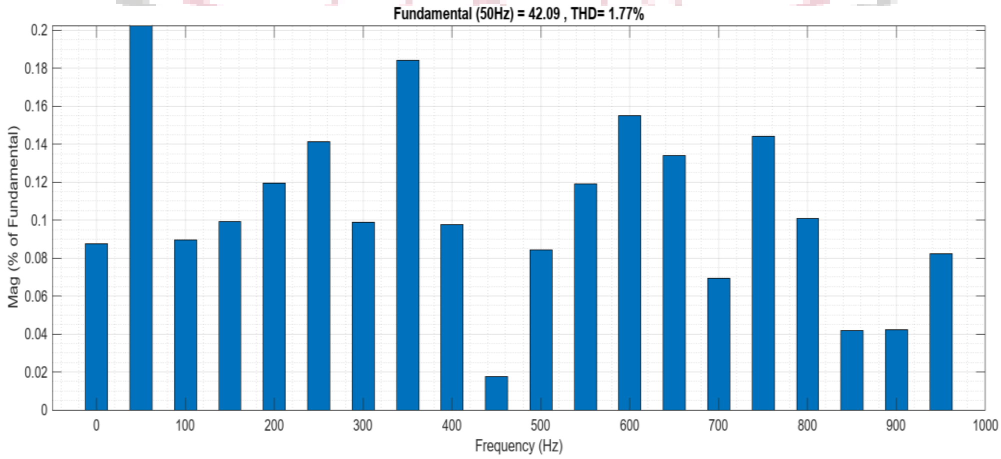

Figure 38: THD% evaluation of AC current drawn at the loading terminals of system 3

In Figure 38, the Total Harmonic Distortion (THD%) analysis is depicted for the AC current signal derived from System 3. The identified THD% is measured at 1.77%, and this outcome is associated with the utilization of the P&O_WPTA algorithm for controlling the DC-DC converter within the solar system.

Table 1: 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 1 showcases Total Harmonic Distortion (THD%) in voltage and current waveforms in a Grid-Connected Solar System (GI_SS) using three algorithms. The cells in the table contain actual THD percentage values for both voltage and current waveforms under each algorithm. The distortion levels are reduced by the algorithm used in system 2 when compared with that of system 1 specifically in current waveform. The Minium distortion levels have been found in system 3 where DC-DC converter driven by hybrid approach with P&O and wolf power tracking algorithm (P&O_WPTA

VI. CONCLUSION

This research underscores the critical role of advanced control algorithms in optimizing the performance of grid-integrated solar systems. By employing innovative strategies such as the Grey Wolf Optimization Algorithm and hybrid approaches, significant improvements in system efficiency, stability, and power quality are achievable. The findings emphasize the importance of meticulous analysis spanning from DC generation to AC distribution phases, enabling a comprehensive understanding of system dynamics. The proposed methodologies pave the way for enhancing the reliability and effectiveness of grid-connected solar energy systems, thereby advancing sustainable energy initiatives and contributing to a greener future.

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