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Grey Wolf Optimization Based DC-DC Boost Converter & DC Link Voltage Controller For Grid Tied PV Inverter

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Abstract

This study proposes a control strategy for a PV system that includes a DC-DC boost converter and grid connected inverter The study's target consists of a series and parallel combination of solar panel, DC-DC boost converter, DC-AC inverter, DC-DC buck-boost converter, Li-ion battery, and DC load. The main objectives of this work are: (i) PV voltage regulation: the PV panel voltage must track a given reference voltage corresponding to the maximum power point. (ii) DC link voltage regulation: The DC link voltage must track a reference voltage as closely as possible. (iii) PFC requirement: The grid currents must be sinusoidal with the same frequency and in phase with the voltage grid. The major purpose of the suggested technique is to enhance power quality of the three-phase grid connected inverter system by optimizing the proportional integral (PI) controller. In this scheme, the current controller, voltage regulator, reference signal controller, and boost controller of the three-phase inverter are enhanced with additional PI controllers, tuned using the Grey Wolf Optimization (GWO) algorithm. Results are compared with values obtained using Particle Swarm Optimization (PSO). Comparative analysis of several Maximum Power Point Tracking (MPPT) methods, including Perturb and Observe (P&O), PSO, Hybrid Bee Algorithm (HBA), and Artificial Bee Colony (ABC), is also provided. Experiments demonstrate that the proposed control strategy performs more efficiently with the P&O-based MPPT method, which minimizes error and ensures optimal performance and among them P&O optimized with Grey Wolf Optimization (GWO) achieved the best results, delivering 100.1 kW of power at 1000 W/m^2 irradiance with a settling time of 0.0077s and overshoot of 0.1355. In contrast, other methods achieved up to 97–98 kW with higher oscillation and longer response times.

Key Words : *MPPT algorithm, P&O, PSO, GWO, ABC, DC link voltage.*

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Chapter 1: Introduction

The U.S. Department of Energy projects that new consumption models, such as smart plug-in electric cars and smart homes, will cause energy demand to rise by 30% by 2035 [1]. Greenhouse gas emissions is reduced by renewable energy sources have gained attention as environmentally beneficial and non-polluting power generation units. Renewable energy sources like wind turbines, fuel cell system and photovoltaic (PV) systems are frequently employed in various power systems. Solar energy is the fastest-growing renewable energy source globally, being reasonably priced, clean, and renewable [2]. It serves as a cost-effective energy source for tasks such as water pumping, battery charging, and rural area power supply [3]. However, PV systems are primarily limited by high installation costs and low energy conversion efficiency. To address the first issue, more affordable photovoltaic technologies are being developed using more efficient semiconductors [4]. To maximize energy conversion efficiency, each component of PV system must be optimized. Maximum output power of the PV system under varying climatic conditions can be determined using Maximum Power Point Tracking (MPPT) controller [5]. Output power of PV panels is influenced by temperature and irradiance levels, with PV panels exhibiting nonlinear voltage-current characteristics and single maximum power point (MPP) [6]. As environmental conditions shift, both the operating point and MPP will vary, necessitating an MPPT system as a real-time control strategy to continuously optimize output power of the photovoltaic generator (PVG) [7].

Numerous studies have aimed to increase the performance of MPPT methods compared to traditional methods, including using Artificial Neural Networks (ANN) optimized with Genetic Algorithms (GA) [8], [9]. Other works have applied Particle Swarm Optimization (PSO) for tuning Proportional-Integral (PI) control parameters, optimizing response time and reducing oscillations [2]. Various MPPT methods have been employed in previous research, such as Fuzzy Logic Control (FLC) [7], sliding mode control [2], Perturb and Observe (P&O) [9], and Incremental Conductance (INC) [7], with maximum power tracking accuracy as the primary objective. These methods perform efficiently under changing weather conditions [3], [9]. They differ in several aspects, such as simplicity, convergence speed, system stability, and overall popularity [4]. Consequently, GWO is applied in this research for optimization of PI controller settings. Its purpose is to obtain optimum levels of proportional and integral gain during operation. Main role is to boost quality of output power of the three-phase grid-tied inverter system by improving proportional-integral (PI) controller settings [10], [12].

For getting rapid dynamic reaction with chance weather, compensation is implemented in control loop. From earlier research, there are several drawbacks with PSO and GA, low convergence speed, high settling time, parameters value complexity, high THD of current and issue to discover minimal fitness value [13], [14]. Furthermore there are no appropriate information regarding DC link voltage management, optimization of inverter controller, boost converter control strategy in grid-connected PV inverter [15], [16]. Aim of this work is optimization of controller parameter using GWO and comparison analysis with PSO[19], [20]. Also enable four MPPT techniques comparison study. Major contribution of this work is:

- In this research, a control scheme is proposed for a three-phase inverter system, enhancing current controller, voltage regulator, reference signal controller, and buck controller with additional PI controllers.
- The PI controllers are tuned using the Grey Wolf Optimization (GWO) algorithm, which improves performance under both linear and varying weather conditions, maximizing power extraction to enhance power quality and stability in grid connected PV inverter system.
- Model is designed to generate a target signal that enables the inverter to meet load requirements with minimum settling time, reduced overshoot, low Total Harmonic Distortion (THD), and minimal power loss.
- The control methodology estimates the maximum power and DC link voltage using four MPPT techniques for comparison. Perturb and Observe (P&O) approach works best, with no oscillation near to the Maximum Power Point (MPP) and harvests 100KW of power. In contrast, the other methods PSO, HBA, and ABC achieve roughly 97KW, resulting to some power loss.

1.1 Objectives

- To design and simulate a grid-connected PV system that includes a PV generator, DC-DC boost converter, three-phase inverter, bidirectional DC-DC converter, battery energy storage, and DC load using MATLAB/Simulink.
- To implement and compare multiple MPPT techniques Perturb and Observe (P&O), Particle Swarm Optimization (PSO), Artificial Bee Colony (ABC), and Hybrid Bee Algorithm (HBA) to determine the most effective method for maximum power extraction.

- To optimize PI controller parameters used in various parts of the system (boost converter, inverter, DC-link voltage control, and bidirectional converter) using the Grey Wolf Optimization (GWO) algorithm for improved dynamic response and system stability.
- To manage battery charging and discharging operations based on State of Charge (SOC) and load demand using a bidirectional converter operating in buck and boost modes.

1.2 Organization of the Report

This thesis is organized into eight structured chapters to systematically present the design, simulation, and analysis of a Grey Wolf Optimization (GWO)-based control strategy for a grid-tied photovoltaic (PV) inverter system:

Chapter 1: Introduction

Provides a general overview of renewable energy systems with a focus on photovoltaic technology, its challenges, and the motivation behind developing an optimized control strategy for grid-connected PV systems.

Chapter 2: Literature Review

Reviews previous research on MPPT techniques, controller optimization using metaheuristic algorithms, and highlights the existing gaps addressed in this study.

Chapter 3: Methodology

Describes the overall system configuration and simulation setup in MATLAB/Simulink, including PV modeling, control strategies, and optimization algorithms. Details the system components such as the PV generator, DC-DC boost converter, and inverter, and discusses control strategies for MPPT, DC-link voltage, and grid synchronization. Also explains the biological inspiration, mathematical modeling, and implementation of the GWO algorithm for tuning PI controller parameters. AND Focuses on control schemes for the DC-link voltage, inverter, and battery, along with a comparative study of different MPPT methods.

Chapter 4: Results and Analysis

Presents simulation results under standard and dynamic irradiance conditions. Comparative performance analysis is carried out between GWO and PSO, and among various MPPT algorithms.

Chapter 5: Conclusion and Future Work

Summarizes key findings and performance benefits of the proposed control scheme. Future research directions are suggested, including hardware implementation and integration with smart grid technologies.

1.3 Summary

The introduction highlights the growing global demand for clean and efficient energy, with solar photovoltaic (PV) systems emerging as a leading renewable energy source due to their sustainability and environmental benefits. Despite their advantages, PV systems face challenges such as high installation costs and low energy conversion efficiency. To overcome these, it is crucial to optimize each system component, especially under varying climatic conditions. The chapter emphasizes the importance of Maximum Power Point Tracking (MPPT) techniques in ensuring maximum energy extraction from solar panels, which exhibit nonlinear characteristics influenced by temperature and irradiance. Several intelligent methods, such as Artificial Neural Networks (ANN), Fuzzy Logic, and Particle Swarm Optimization (PSO), have been explored in past research to enhance MPPT performance and control system dynamics. This thesis focuses on developing a control strategy for a grid-tied PV system, integrating optimized PI controllers using the Grey Wolf Optimization (GWO) algorithm, and comparing different MPPT methods to ensure improved power quality, stability, and efficiency under dynamic weather conditions.

Chapter 2: Literature Review

R. Ramaprabha et al. [1] proposed *Maximum Power Point Tracking using GA Optimized Artificial Neural Network for Solar PV System*. The study presents an improved solar photovoltaic (SPV) model offering better performance prediction. A genetic algorithm (GA) is used to optimize the input-output mapping of an artificial neural network (ANN), enhancing MPPT controller performance. The system is simulated in MATLAB-SIMULINK, achieving accuracy with error rates as low as 0.05% to 4.46% under various operating conditions.

Layachi Zaghba et al. [2] introduced *Enhancing Grid Connected Photovoltaic System Performance with Novel Hybrid MPPT Technique in Variable Atmospheric Conditions*. This work proposes a hybrid MPPT method that combines fuzzy logic and sliding mode control to improve stability and accuracy in PV systems. Additionally, Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) are applied to optimize PI controller parameters on the grid side, resulting in a tracking efficiency of up to 99.86% and reduced system power loss.

Naamane Debdouche et al. [3] presented *Genetic Algorithm-Super-Twisting Technique for Grid-Connected PV System Associate with Filter*. The authors developed a hybrid controller using GA and the Super-Twisting Algorithm (STA) to enhance Direct Power Control (DPC). This controller improves both MPPT and active power filtering, minimizing total harmonic distortion (THD) and power ripples, while improving dynamic response.

Mohamed Ahmed Ebrahim Mohamed et al. [4] proposed *Arithmetic Optimization Algorithm Based Maximum Power Point Tracking for Grid Connected Photovoltaic System*. The paper introduces the Arithmetic Optimization Algorithm (AOA) for tuning PI controller parameters in an Incremental Conductance (IC)-based MPPT technique. Comparative analysis with other methods like GWO, GA, and PSO shows that AOA achieves faster rise and settling times with higher tracking efficiency under five climate scenarios.

Layachi Zaghba et al. [5] developed *A Genetic Algorithm Based Improved P&O–PI MPPT Controller for Stationary and Tracking Grid-Connected Photovoltaic System*. An optimized Perturb and Observe (P&O) method enhanced by GA is proposed to improve MPP tracking performance. Simulation results reveal that dual-axis tracking systems with the proposed controller enhance energy output by 25-30% compared to fixed PV installations.

Nagwa F. Ibrahim et al. [6] introduced *Operation of Grid-Connected PV System With ANN-Based MPPT and an Optimized LCL Filter Using GRG Algorithm for Enhanced Power Quality*. This study uses both ANN and Cuckoo Search (CS) for MPPT, where ANN outperforms CS in response and stability. Additionally, the LCL filter is optimized using the Generalized Reduced Gradient (GRG) method, significantly reducing THD by up to 99.78%.

Majid Dehghani et al. [7] proposed *Optimized Fuzzy Controller for MPPT of Grid-connected PV Systems in Rapidly Changing Atmospheric Conditions*. The authors developed a fuzzy logic controller (FLC) optimized using a hybrid PSO-GA approach. This method enhances MPPT speed and accuracy under rapidly changing irradiance and temperature, improving output power by 2%-8% compared to conventional methods like P&O and INC.

Mahmoud N. Ali et al. [8] introduced *Promising MPPT Methods Combining Metaheuristic, Fuzzy-Logic and ANN Techniques for Grid-Connected Photovoltaic Systems*. Two AI-based MPPT systems are developed: one using FLC optimized with GA and PSO, and another based on a GA-optimized ANN. The integration of these approaches improves tracking speed and energy conversion efficiency under varying environmental conditions.

Nassir Deghfel et al. [9] developed *A New Intelligently Optimized Model Reference Adaptive Controller Using GA and WOA Based MPPT Techniques for Photovoltaic Systems*. The paper introduces a Model Reference Adaptive Controller (MRAC) optimized using both GA and Whale Optimization Algorithm (WOA). Coupled with an Adaptive Neuro-Fuzzy Inference System (ANFIS), this method ensures faster and more accurate MPPT under fluctuating environmental conditions, enhancing overall system efficiency.

2.1 Research gap

While significant progress has been made in improving PV system performance through advanced MPPT techniques and metaheuristic optimization (e.g., GA, PSO, ANN, FLC), several shortcomings remain. Many existing approaches face slow convergence, high total harmonic distortion (THD), and suboptimal settling times, particularly under rapidly changing irradiance and temperature. Furthermore, most studies focus on optimizing individual components such as MPPT or inverter control without providing a unified control strategy that simultaneously optimizes MPPT, DC-link voltage regulation, inverter performance, and battery energy management. The integration of all these subsystems, optimized through a Grey Wolf Optimization (GWO) framework, remains underexplored. This creates an opportunity to develop a comprehensive GWO-based controller that addresses dynamic performance, power quality, and energy storage coordination in grid-connected PV systems.

2.2 Summary

This chapter reviews previous research related to photovoltaic (PV) systems, Maximum Power Point Tracking (MPPT) techniques, and optimization algorithms for controller tuning. Various studies have proposed enhancements to MPPT performance using methods such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Artificial Neural Networks (ANN), and Fuzzy Logic Control (FLC). These approaches aim to improve tracking accuracy, convergence speed, and system stability under rapidly changing environmental conditions. Several works also focus on optimizing PI controller parameters using metaheuristic algorithms to improve inverter performance and power quality. While GA and PSO have shown promising results, limitations like slow convergence and high total harmonic distortion (THD) remain. Recent studies suggest the Grey Wolf Optimization (GWO) algorithm as a superior alternative due to its fast convergence, low overshoot, and better dynamic response. This review highlights the research gap in unified control strategies combining MPPT, inverter control, and battery management optimized via GWO, which forms the foundation of the current study.

Chapter 3: Methodology

In this research, a comprehensive control scheme for a grid-connected photovoltaic (PV) inverter system was developed and implemented using MATLAB/Simulink. In Figure 3.1 it is shown. The system comprises a PV generator, a DC-DC boost converter, a three-phase inverter, a DC-DC bidirectional converter interfaced with a battery, and a DC resistive load which is divided into two cases. In first case a PV, DC-DC boost converter, DC-AC inverter, and grid is designed and controlled. And for the case two, a battery with a bidirectional converter is simulated and also a buck converter with DC load is simulated. The methodology involves four main control strategies: Maximum Power Point Tracking (MPPT), DC-link voltage regulation, inverter control, and battery power management. To ensure efficient power extraction, four MPPT algorithms Perturb and Observe (P&O), Particle Swarm Optimization (PSO), Artificial Bee Colony (ABC), and Hybrid Bee Algorithm (HBA) were tested. Among these, P&O was selected as the optimal method due to its minimal oscillation near the Maximum Power Point (MPP). To enhance system stability and dynamic response, PI controllers were applied to the boost converter, DC link, inverter, and bidirectional converter. These controllers were optimized using the Grey Wolf Optimization (GWO) algorithm, selected for its fast convergence and minimal overshoot. The battery management strategy was implemented using a bidirectional converter operating in buck mode for charging and boost mode for discharging, with control logic based on battery SOC and load demand. The proposed control scheme is shown in Figure 3.2. The simulation model was tested under standard and dynamic irradiance conditions to evaluate performance in terms of power tracking, voltage stability, current regulation, and load management.

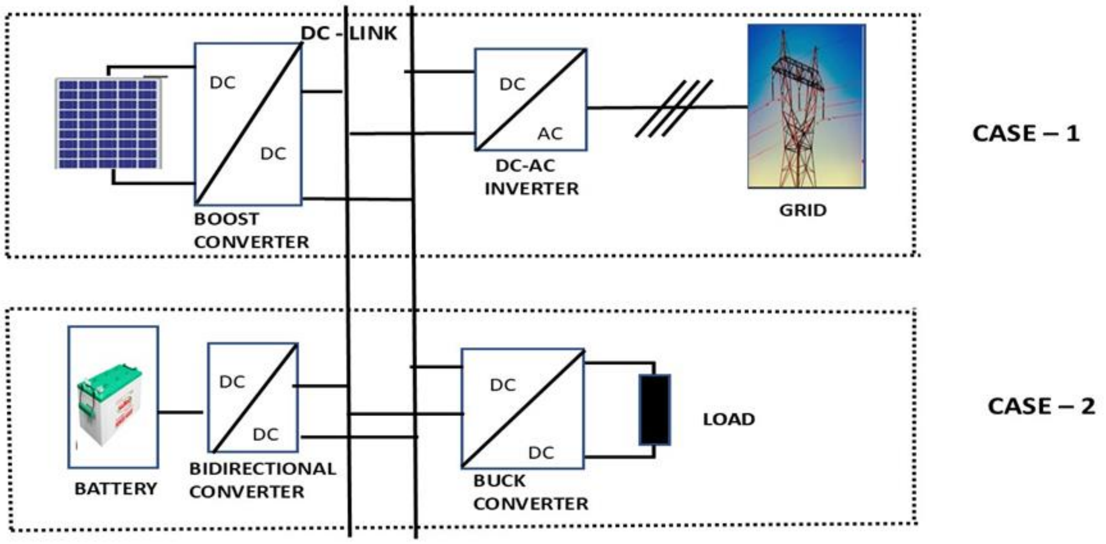

Figure 3.1: The proposed grid tied PV system with battery storage system

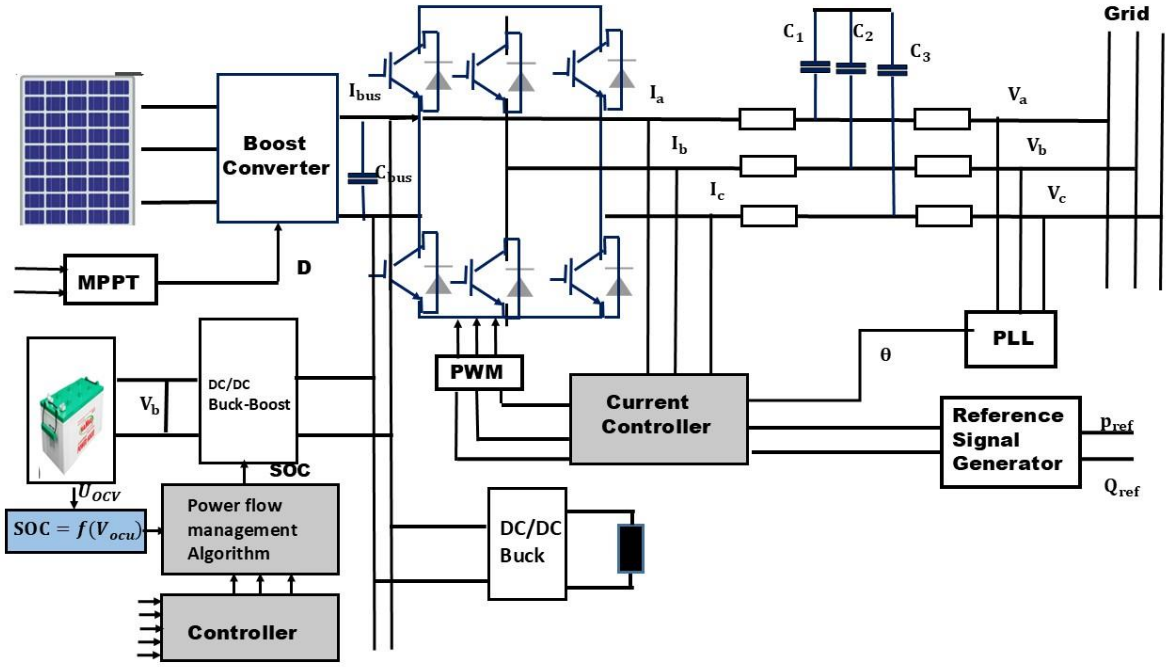

Figure 3.2: Scheme of proposed control strategy.

3.1 Implementation of Grid-Tied PV System

A grid-connected PV system is a renewable energy system that generates electricity using solar panels and is also known as grid-tied PV system. It has three parts- a PV generator, DC-DC boost converter and grid. There are four control strategies- MPPT control, DC-DC boost converter control, DC link voltage control, DC-AC inverter control. A PV generator is fitted with this converter. Figure 3.3. illustrates grid linked inverter with a PV system-

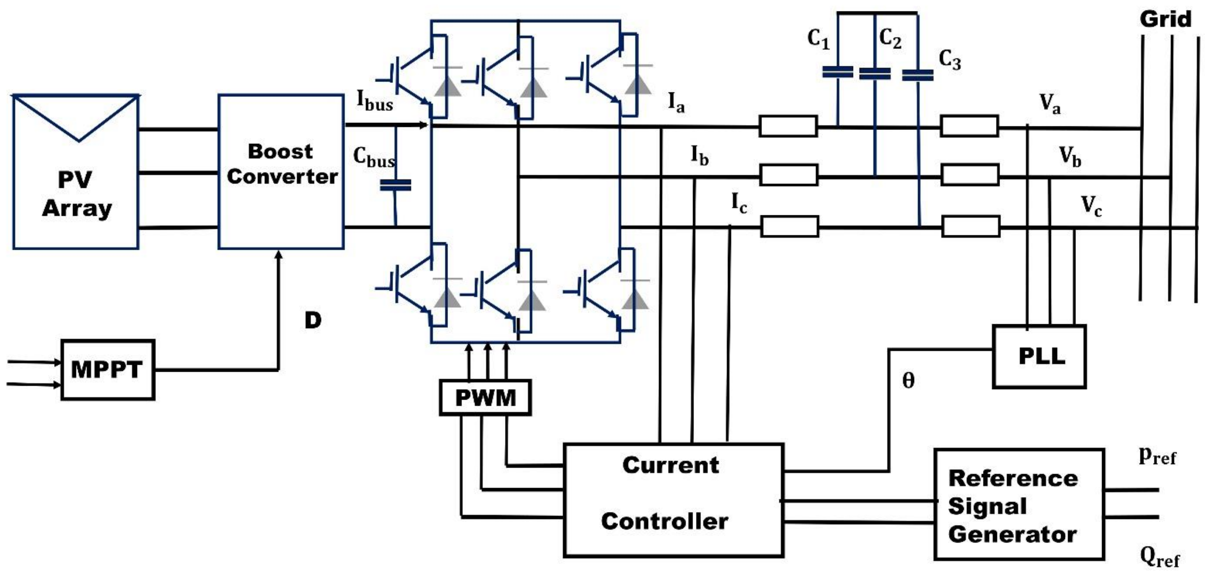

Figure 3.3: Simulation of Grid connected PV

3.2 The Photovoltaic Generator

The input parameters of a PV generator are irradiance(G), temperature(T). Primary function of a PV generator relies on G, T. The corresponding circuit of a PV model is represented by a current source and a genuine PN junction diode in parallel with it. Solar panels current is proportional to the amount of irradiation and fluctuates with temperature. Figure 3.4. is showing basic model of PV generator.

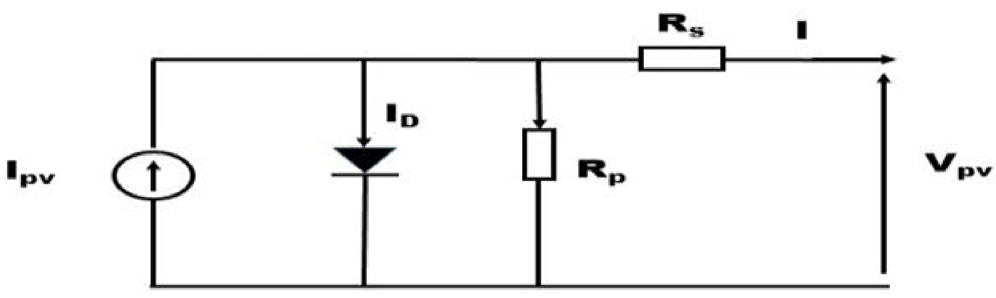

Figure 3.4: Model of PV

Current and voltage of PV cell represented by this equation-

$$I=I_{pv}-I_0\left[exp\left(\frac{q.(V_{pv}+I.R_S)}{nKT}\right)-1\right]-\frac{(V_{pv}+I.R_S)}{R_S} \quad (3.1)$$

$$I_{pv} = I_{pv-ref}\left[\mathbf{1} + \propto (\boldsymbol{T} - \boldsymbol{T_{ref}}\right] \frac{\boldsymbol{G}}{\boldsymbol{G_{ref}}} \quad (3.2)$$

Here,

I_{pv} = Photovoltaic cell current.

I_0 = Saturation current.

q = 1.6 * 10^{-19} C(charge of electron).

k = 1.38 * 10^{-23} J/K Boltzmann's constant.

T = Temperature of cell.

n = Ideality factor.

G_{ref} = Irradiance reference(1000W/m2).

T_{ref} = Ambient temperature(25^0C).

I_{pv-ref} =Short circuit current at T=25^0C and

G= 1000W/m^2

$\propto$ = Coefficient.

Figure. 3.5 & 3.6 exposes the PV voltage current and power at 1000W/m^2 & 500W/m^2 irradiance

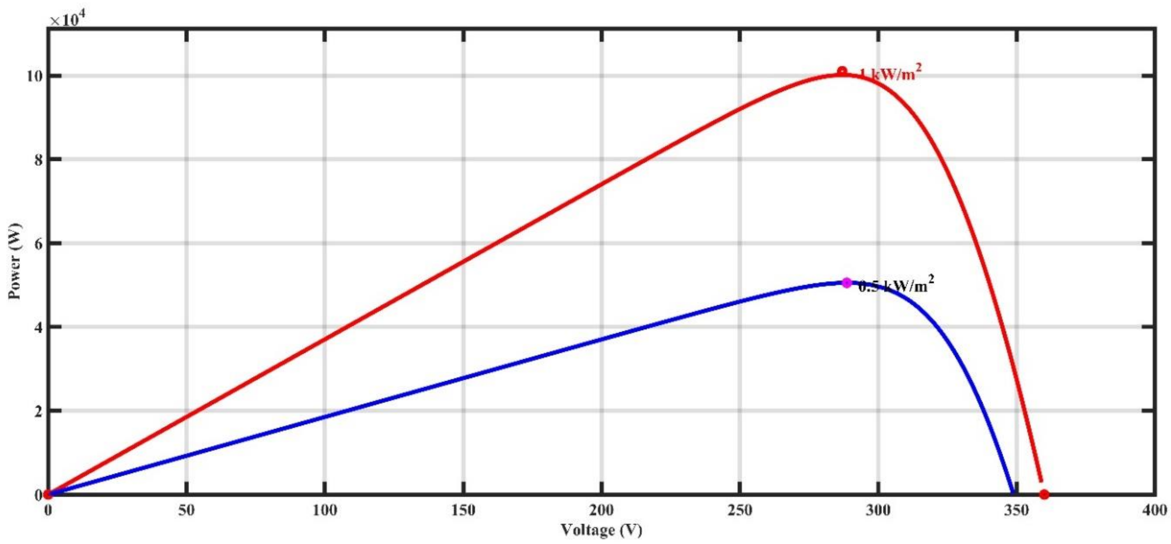

Figure 3.5: Characteristics curve of PVG.

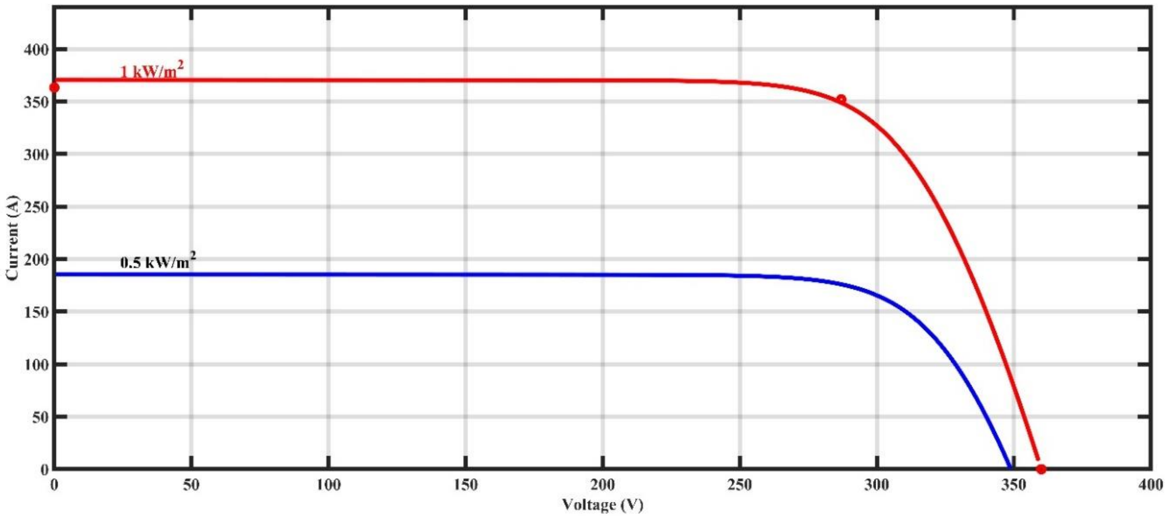

Figure 3.6: Characteristics curve of PVG.

3.3 DC-DC Boost Converter

Using numerous formulae and comparable circuits of DC DC converter described, this paper may propose a mathematical model for boost converter as follows.

$$\frac{dV_{pv}}{dt} = \frac{1}{C_{pv}} i_{pv} - i_L \tag{3.3}$$

$$\frac{di_L}{dt} = \frac{1}{L} V_{pv} - (1 - D)\frac{1}{L} V_{bus} \tag{3.4}$$

When the PV panel output voltage represented by V_{pv} and current represented I_{pv}, DC-DC converter electrical characteristics are represented by C_{pv} and L, duty cycle is represented by D, DC-link voltage by V_{bus} and inductor current by i_L.

3.4 Grey Wolf Optimization

Grey wolf (Canis lupus) belongs to Canidae family. Grey wolves are considered as apex predators, meaning that they are at the top of the food chain. Grey wolves mostly prefer to live in a pack. The group size is 5–12 on average. Of particular interest is that they have a very strict social dominant hierarchy as shown in Fig.3.7. The leaders are a male and a female, called alphas. The alpha is mostly responsible for making decisions about hunting, sleeping place, time to wake, and so on. The alpha's decisions are dictated to the pack. However, some kind of democratic behavior has also been observed, in which an alpha follows the other wolves in the pack. Figure 3.7 is showing hieracry of grey wolf. In gatherings, the entire pack acknowledges the alpha by holding their tails down. The alpha wolf is also called the dominant wolf since his/her orders should be followed by the pack. The alpha wolves are only allowed to mate in the pack. Interestingly, the alpha is not necessarily the strongest member of the pack but the best in terms of managing the pack. This shows that the organization and discipline of a pack is much more important than its strength.

The second level in the hierarchy of grey wolves is beta. The betas are subordinate wolves that help the alpha in decision-making or other pack activities. The beta wolf can be either male or female, and he/she is probably the best candidate to be the alpha in case one of the alpha wolves passes away or becomes very old. The beta wolf should respect the alpha, but commands the other lower-level wolves as well. It plays the role of an advisor to the alpha and discipliner for the pack. The beta reinforces the alpha's commands throughout the pack and gives feedback to the alpha. The lowest ranking grey wolf is omega. The omega plays the role of scapegoat. Omega wolves always have to submit to all the other dominant wolves. They are the last wolves that are allowed to eat. It may seem the omega is not an important individual in the pack, but it has been observed that the whole pack face internal fighting and problems in case of losing the omega. This is due to the venting of violence and frustration of all wolves by the omega(s). This assist satisfying the entire pack and maintaining the dominance structure. In some cases the omega is also the babysitters in the pack. a wolf is not an alpha, beta, or omega, he/she is called subordinate (or delta in some references). Delta wolves have to submit to alphas and betas, but they dominate the omega. Scouts, sentinels, elders, hunters, and caretakers belong to this category. Scouts are responsible for watching the boundaries of the territory and warning the pack in case of any danger. Sentinels protect and guarantee the safety of the pack. Elders are the experienced wolves who used to be alpha or beta. Hunters help the alphas and betas when hunting prey and providing food for the pack.

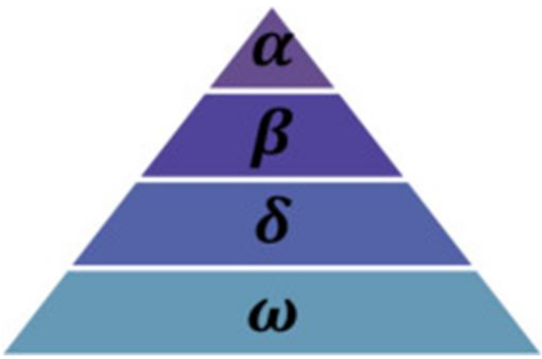

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Figure 3.7: Hierarchy of grey wolf (dominance decreases from top down)

In addition to the social hierarchy of wolves, group hunting is another interesting social behavior of grey wolves. The main phases of grey wolf hunting are as follows:

- Tracking, chasing, and approaching the prey.
- Pursuing, encircling, and harassing the prey until it stops moving.
- Attack towards the prey.

These steps are shown in Figure 3.8. In this work this hunting technique and the social hierarchy of grey wolves are mathematically modeled in order to design GWO and perform optimization.

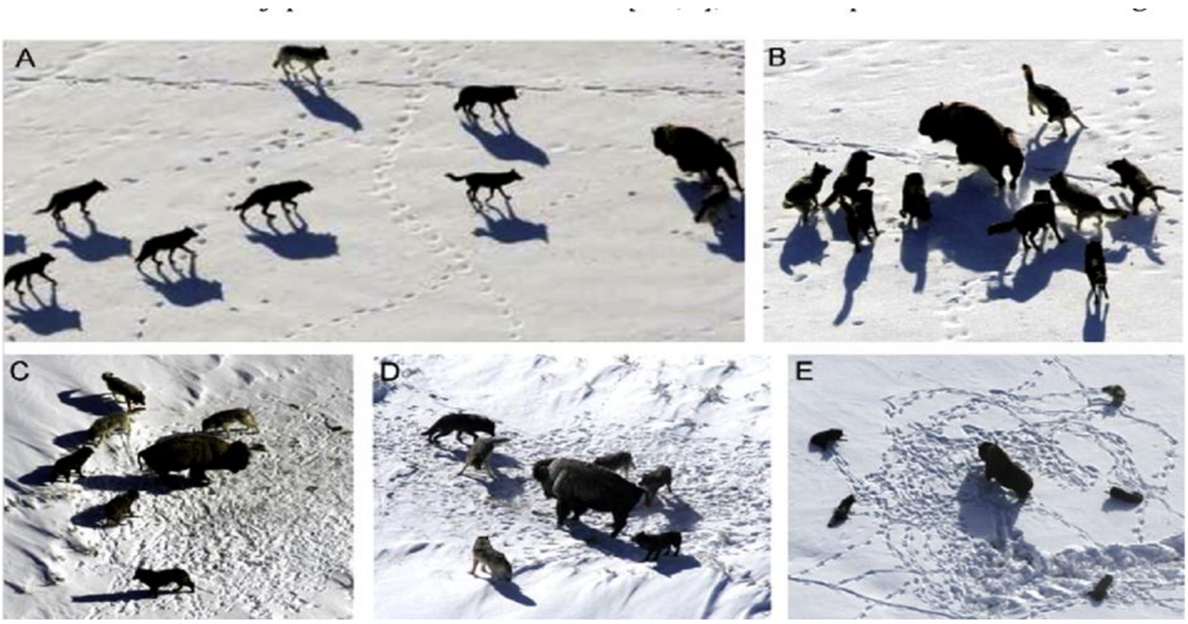

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Figure 3.8: Hunting behavior of grey wolves: (A) chasing, approaching, and tracking prey (B–D) pursuing, harassing, and encircling (E) stationary situation and attack.

3.4.1 Mathematical Model and Algorithm

In this subsection the mathematical models of the social hierarchy, tracking, encircling, and attacking prey are provided. Then the GWO algorithm is outlined.

3.4.2 Social Heirarchy

In order to mathematically model the social hierarchy of wolves when designing GWO, this paper considers the fittest solution as the alpha (a). Consequently, the second and third best solutions are named beta (b) and delta (d) respectively. The rest of the candidate solutions are assumed to be omega (x). In the GWO algorithm the hunting (optimization) is guided by a, b, and d. The x wolves follow these three wolves.

3.4.3 Encircling Prey

As mentioned above, grey wolves encircle prey during the hunt. In order to mathematically model encircling behavior the following equations are proposed

$$\vec{D} = \left|\vec{C} \cdot \overrightarrow{X_p}(t) - \vec{X}(t)\right| \tag{3.5}$$

$$\vec{X}(t+1) = \overrightarrow{X_p}(t) - \vec{A} \cdot \vec{D} \tag{3.6}$$

where t indicates the current iteration, $\vec{A}$ and $\vec{C}$ are coefficient vectors, $\overrightarrow{X_p}$ is the position vector of the prey, and $\vec{X}$ indicates the position vector of a grey wolf.

The vectors $\vec{A}$ and $\vec{C}$ are calculated as follows:

$$\vec{A} = 2\vec{a} \cdot \overrightarrow{r_1} - \vec{a} \tag{3.7}$$

$$C = 2 \cdot \overrightarrow{r_2} \tag{3.8}$$

where components of $\vec{a}$ are linearly decreased from 2 to 0 over the course of iterations and r_1, r_2 are random vectors in [0, 1].

To see the effects of Eqs. (3.5) and (3.6), a two-dimensional position vector and some of the possible neighbors are illustrated in Figure 5.3(a). As can be seen in this figure, a grey wolf in the position of (X, Y) can update its position according to the position of the prey (X^*, Y^*). Different places around the best agent can be reached with respect to the current position by adjusting the value of $\vec{A}$ and $\vec{C}$ vectors. For instance, $(X^* - X,\ Y^*)$ can be reached by setting $\vec{A} = (1,0)$ and $\vec{C} = (1,1)$.The possible updated positions of a grey wolf in 3D space are depicted in Figure 3.9(b). Note that the random vectors r_1 and r_2 allow wolves to reach any position between the points illustrated in Figure 3.9. So a grey wolf can update its position inside the space around the prey in any random location by using Eqs. (3.7) and (3.8). The same concept can be extended to a search space with n dimensions, and the grey wolves will move in hyper-cubes.

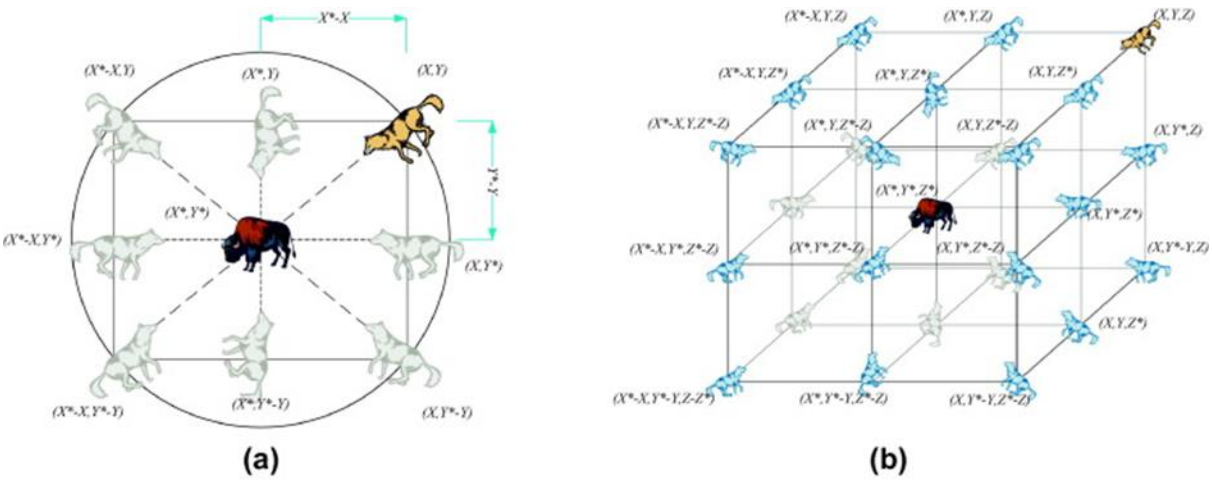

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Figure 3.9: 2D and 3D position vectors and their possible next locations.

3.4.4 Hunting

Grey wolves have the ability to recognize the location of prey and encircle them. The hunt is usually guided by the alpha. The beta and delta might also participate in hunting occasionally. However, in an abstract search space no one has any idea about the location of the optimum (prey). In order to mathematically simulate the hunting behavior of grey wolves, this paper supposes that the alpha (best candidate solution) beta, and delta have better knowledge about the potential location of prey. Therefore, this paper saves the first three best solutions obtained so far and oblige the other search agents (including the omegas) to update their positions according to the position of the best search agents. The following formulas are proposed in this regard.

$$\overrightarrow{D_\alpha} = |\overrightarrow{C_1} \cdot \overrightarrow{X_\alpha} - \vec{X}|, \overrightarrow{D_\beta} = |\overrightarrow{C_2} \cdot \overrightarrow{X_\beta} - \vec{X}|, \overrightarrow{D_\delta} = |\overrightarrow{C_\delta} \cdot \overrightarrow{X_\delta} - \vec{X}| \tag{3.9}$$

$$\overrightarrow{X_1} = \overrightarrow{X_\alpha} - \overrightarrow{A_1} \cdot (\overrightarrow{D_\alpha}), \overrightarrow{X_2} = \overrightarrow{X_\beta} - \overrightarrow{A_2} \cdot (\overrightarrow{D_\beta}), \overrightarrow{X_3} = \overrightarrow{X_\delta} - \overrightarrow{A_3} \cdot (\overrightarrow{D_\delta}) \tag{3.10}$$

$$\vec{X}(t+1) = \frac{\overrightarrow{X_1}+\overrightarrow{X_2}+\overrightarrow{X_3}}{3} \tag{3.11}$$

Figure 3.10 shows how a search agent updates its position according to alpha, beta, and delta in a 2D search space. It can be observed that the final position would be in a random place within a circle which is defined by the positions of alpha, beta, and delta in the search space. In other words alpha, beta, and delta estimate the position of the prey, and other wolves updates their positions randomly around the prey.

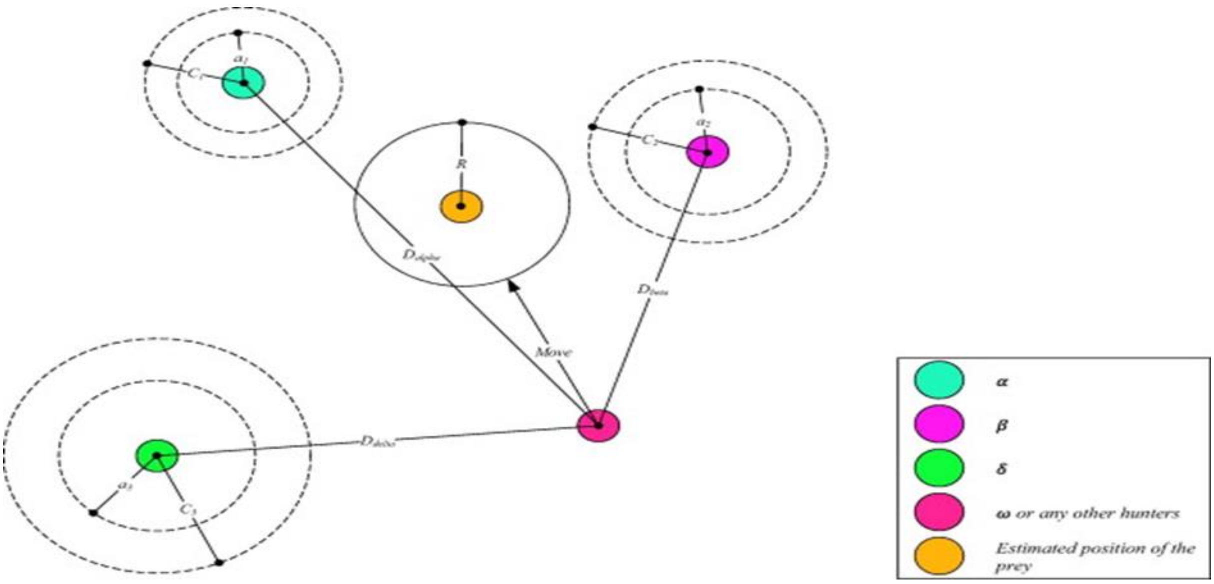

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Figure 3.10: One day hourly load pattern of 5 years

3.4.5 Attacking Prey (Exploitation)

As mentioned above the grey wolves finish the hunt by attacking the prey when it stops moving. In order to mathematically model approaching the prey this paper decreases the value of $\vec{a}$. Note that the fluctuation range of $\vec{A}$ is also decreased by $\vec{a}$. In other words $\vec{A}$ is a random value in the interval [-2a, 2a] where a is decreased from 2 to 0 over the course of iterations. When random values of $\vec{A}$ are in [-1,1], the next position of a search agent can be in any position between its current position and the position of the prey. Figure 3.10 shows that $|A| < 1$ forces the wolves to attack towards the prey. With the operators proposed so far, the GWO algorithm allows its search agents to update their position based on the location of the alpha, beta, and delta; and attack towards the prey. However, the GWO algorithm is prone to stagnation in local solutions with these operators. It is true that the encircling mechanism proposed shows exploration to some extent, but GWO needs more operators to emphasize exploration.

3.4.6 Search For Prey (Exploration)

Grey wolves mostly search according to the position of the alpha, beta, and delta. They diverge from each other to search for prey and converge to attack prey. In order to mathematically model divergence, this paper utilizes $\vec{A}$ with random values greater than 1 or less than -1 to oblige the search agent to diverge from the prey. This emphasizes exploration and allows the GWO algorithm to search globally. Figure 3.9(b) also shows that $|A| > 1$ forces the grey wolves to diverge from the prey to hopefully find a fitter prey. Another component of GWO that favors exploration is $\vec{C}$. As may be seen in Eq. (3.9), the $\vec{C}$ vector contains random values in [0,2]. This component provides random weights for prey in order to stochastically emphasize ($C > 1$) or deemphasize ($C < 1$) the effect of prey in defining the distance in Eq. (3.11). This assists GWO to show a more random behavior throughout optimization, favoring exploration and local optima avoidance. It is worth mentioning here that C is not linearly decreased in contrast to A. This paper deliberately requires C to provide random values at all times in order to emphasize exploration not only during initial iterations but also final iterations. This component is very helpful in case of local optima stagnation, especially in the final iterations.

The C vector can be also considered as the effect of obstacles to approaching prey in nature. Generally speaking, the obstacles in nature appear in the hunting paths of wolves and in fact prevent them from quickly and conveniently approaching prey. This is exactly what the vector C does. Depending on the position of a wolf, it can randomly give the prey a weight and make it harder and farther to reach for wolves, or vice versa. To sum up, the search process starts with creating a random population of grey wolves (candidate solutions) in the GWO algorithm. Over the course of iterations, alpha, beta, and delta wolves estimate the probable position of the prey. Each candidate solution updates its distance from the prey. The parameter a is decreased from 2 to 0 in order to emphasize exploration and exploitation, respectively. Candidate solutions tend to diverge from the prey when $|\vec{A}| > 1$ and converge towards the prey when $|\vec{A}| < 1$. Figure 3.11 demostrating the flowchart of GWO algorithm.

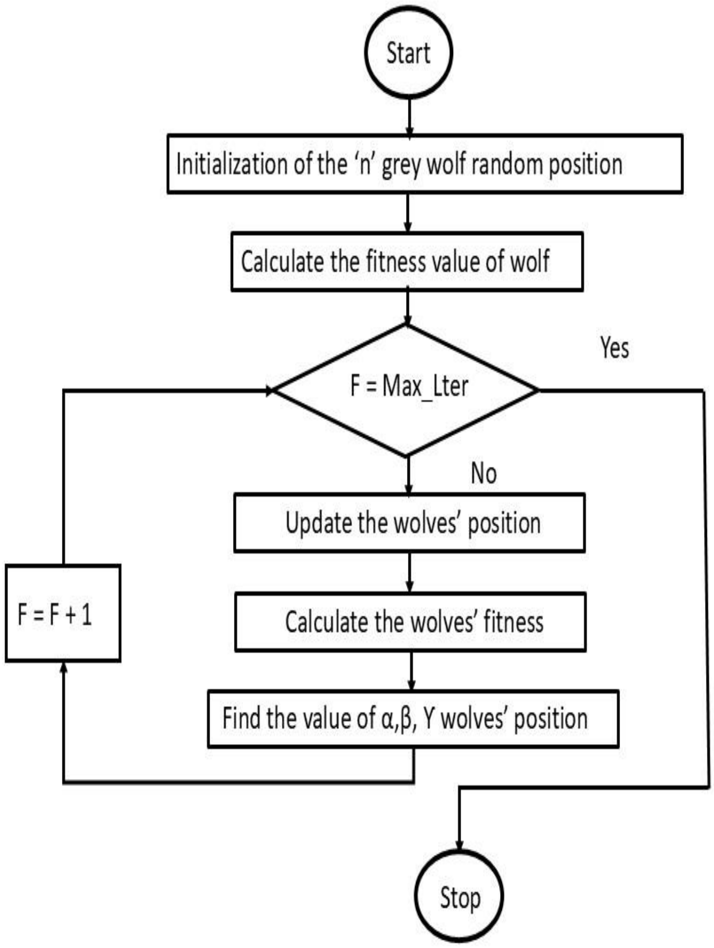

Figure 3.11: Flowchart of GWO

3.5 System Control

Three phase voltage source inverters (VSI) may be regulated using either voltage control or current control. The phase difference between the grid and the inverter output voltage is employed by voltage controlled VSI to manage power flow.

When applying a current control approach, PWM methods are employed to separately regulate actual and reactive current components injected into the utility grid. DC-Link voltage control system will be detailed in the next section

3.5.1 Control of DC link Voltage

DC bus voltage management is meant to keep the value constant (see Figure. 4.7).

The DC link current is given by,

$$i_{dc} = C_{bus}\frac{dV_{bus}}{dt} = i_L - i_{inv} \tag{3.12}$$

The equation above can be rewritten in the Laplace domain as:

$$V_{bus} = \frac{i_{dc}}{C_{bus}.s} \tag{3.13}$$

3.5.2 Control of Grid tied Inverter

Control of the grid side inverter is performed by controlling real, reactive power and current passing across it. Here the power factor is unity and only real power is passing. Real and reactive power control is performed by Clarke transform and park transform. Power equations of inverter are respectively

$$P_{dq} = \frac{3}{2}(V_d I_d + V_q I_q) \tag{3.14}$$

$$Q_{dq} = \frac{3}{2}(V_q I_d + V_d I_q) \tag{3.15}$$

Avoiding losses in the current filter V_d=V, V_q= 0. From the two equation the reference current are given by

$$i_{d-ref} = \frac{2}{3}\frac{Q_{ref}}{V_{q-mea\cdot}} \tag{3.16}$$

$$i_{q-ref} = \frac{2}{3}\frac{P_{ref}}{V_{q-mea.}} \tag{3.17}$$

in this portion, PI controllers perform continuous switching frequency, reduced current ripple, better reaction with time and also make up for current components that are employed in the inverter. Here I_d and I_q are dc components which help decrease error between reference current and real current. PLL is utilized for synchronization of voltage and frequency of the inverter and the grid. PLL determine the angle is θ.

3.5.3 Maximum Power Point Tracking(MPPT)

There are numerous maximum power point tracking techniques (MPPT) that enable to acquire maximum power from PV. In this portion, among four approaches Hybrid Bee Algorithm (HBA), Particle Swarm Optimization (PSO), ABC, Perturb and Observe (P&O) the efficacy of Perturb and Observe method is shown.

- **Hybrid Bee Algorithm (HBA):** Hybrid Bee Algorithm is the simplest and widely used MPPT technique. Initial problem of the HBA is that, It causes oscillation close to the Maximum Power Point (MPP) once it is reached. These oscillations create continuous power losses and losses system stability. It typically uses fixed step sizes for perturbations, which can result in slow convergence to the MPP.

- **PSO algorithm:** Particle Swarm Optimization (PSO) approach is a sophisticated optimizer algorithm used for Maximum Power Point Tracking (MPPT). PSO is a population-based approach inspired by social behavior of birds flocking or fish schooling. Enhanced PSO is good in managing difficult situations, where numerous peak are present in power showing curve.

- **ABC algorithm:** It has been used for various optimization methods and Maximum Power Point Tracking (MPPT) method in photovoltaic (PV) systems. ABC exhibits slower responses to sudden changes of environment (rapid changes in irradiance). ABC algorithm takes more time to differentiate multiple local maxima, which results in slowing down the tracking process.

- **Perturb and observe method (P&O):** Perturb and Observe (P&O) approach has been extensively utilized methodology for Maximum Power Point Tracking (MPPT) in photovoltaic (PV) systems. It operates by regularly altering starting voltage of PV system and noting change in power. Depending on whether power rises or decreases, voltage is changed correspondingly to meet the Maximum Power Point (MPP)

3.5.4 Objective function

Controller parameter of the system is optimized with GWO and PSO, by continuously calculating error of PV parameters and limiting the error to minimize fitness value. The equation for error calculation is shown.

$$E(K) = \int_1^N t.\left(\Big||e_v(t)| + |e_i(t)| + |e_p(t)|\Big|\right)dt \qquad (3.18)$$

Here, $e_v(t)$=V_{pv-max}−$V_{pv-measure}$,

$e_i(t)$ = I_{pv-max}−$I_{pv-measure}$

and $e_v(t)$= P_{pv-max}−$P_{pv-measure}$,

N = Number of samples and K= Iteration number. Gain parameters value is obtained by limiting the lower limit 0 and upper limit 100. Figure 3.12 is GWO optimization technique for grid tied PV inverter. Fitness function is applied for minimizing error and with GWO optimization technique four PI controller values is optimized.

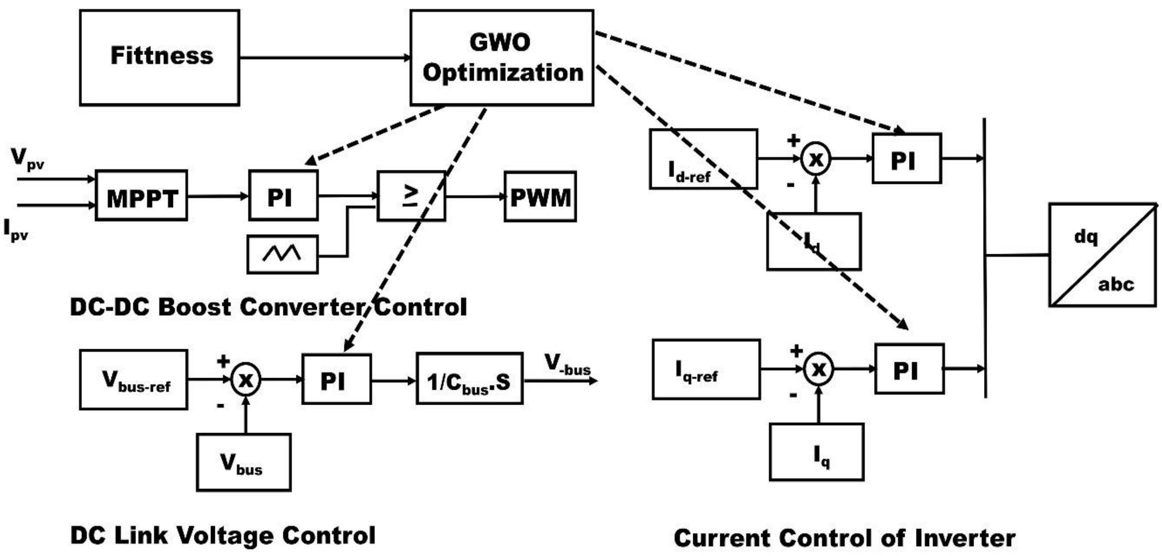

Figure 3.12: GWO optimization technique for grid connected inverter.

3.6 Summery

This research develops a complete GWO-optimized control scheme for a grid-connected PV system with battery storage, implemented in MATLAB/Simulink. The system includes a PV generator, DC-DC boost converter, three-phase inverter, bidirectional converter, and DC load. Four MPPT algorithms P&O, PSO, ABC, and HBA were evaluated, with P&O optimized by GWO delivering the most stable and efficient performance. The proposed method achieved a 100.1 kW output at 1000 W/m² irradiance, minimal oscillations near the MPP, a settling time of 0.0077 seconds**,** and overshoot of only 0.1355, outperforming other methods in both speed and stability. PI controllers for all subsystems (boost converter, DC link, inverter, and bidirectional converter) were tuned using GWO, leading to reduced current ripple, faster dynamic response, and improved voltage stability. The strategy also ensured reliable battery charging/discharging based on SOC and load demand, maintaining power flow balance between PV, battery, grid, and load. The simulation results confirm that the proposed approach enhances power quality, robustness, and adaptability under both standard and dynamic weather conditions.

Chapter 4: Results and Analysis

4.1 Case 1

In this simulation, controller parameters is optimized using Grey Wolf Optimization (GWO) and Particle Swarm Optimization (PSO) algorithms. The results were obtained using MATLAB/Simulink, with 20 iterations and a population size of 30. Table 4.1 presents optimized controller parameters for both GWO and PSO and Table 4.2 presents comperasions parameter values with GWO ans PSO, while Figure 4.1 illustrates convergence curves of two optimization algorithms.

Table 4.1: Optimized parameter with GWO & PSO

Gain	Controller	GWO	PSO
P_1	Converter Controller	4.827	6.306
I_1		100.00	95.70
P_2	Current Controller 1	91.76	14.45
I_2		6.95	60.48
P_3	Current Controller 2	61.03	33.99
I_3		21.65	44.49
P_4	DC link voltage controller	60.30	41.26
I_4		31.87	98.53

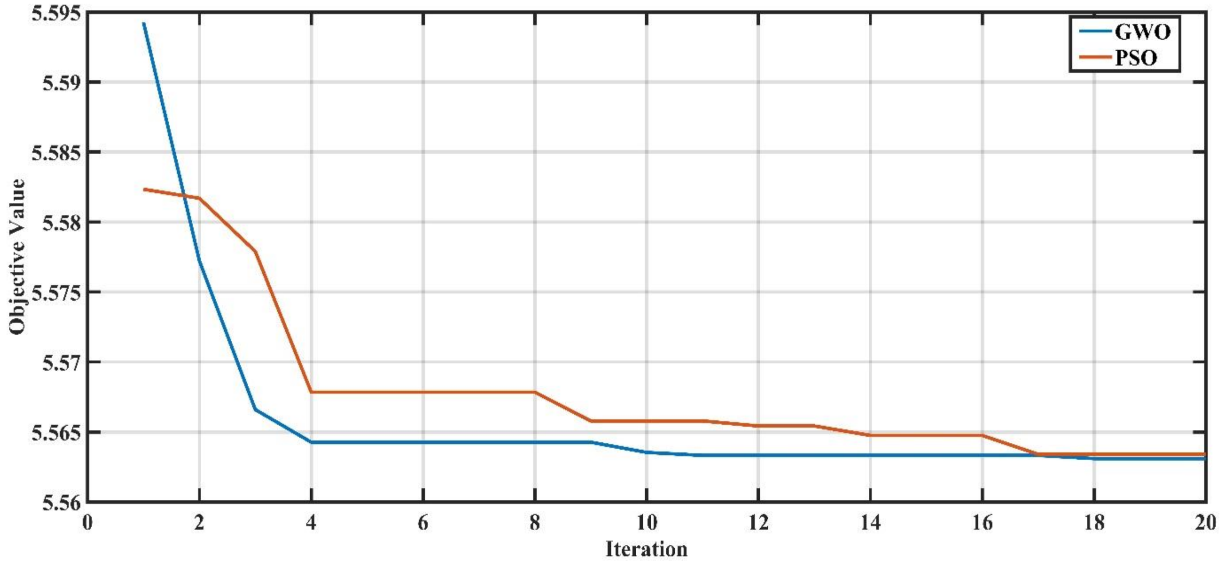

Figure 4.1: Convergence curve for GWO and PSO.

Table 4.2: Comparison of GWO and PSO.

Parameters	**Settling Time**	**Overshoot**	**ITAE**	**Convergence Speed**
GWO	0.0077	0.083	5.567	High
PSO	0.0078	0.09	5.67	Low

Simulated output waveforms for four different maximum power point tracking algorithms are shown in figure. Figure 4.2 & 4.3 shown PV power at 1000W/m^2 irradiation and at change weather condition at (1000W/m^2, 500W/m^2).

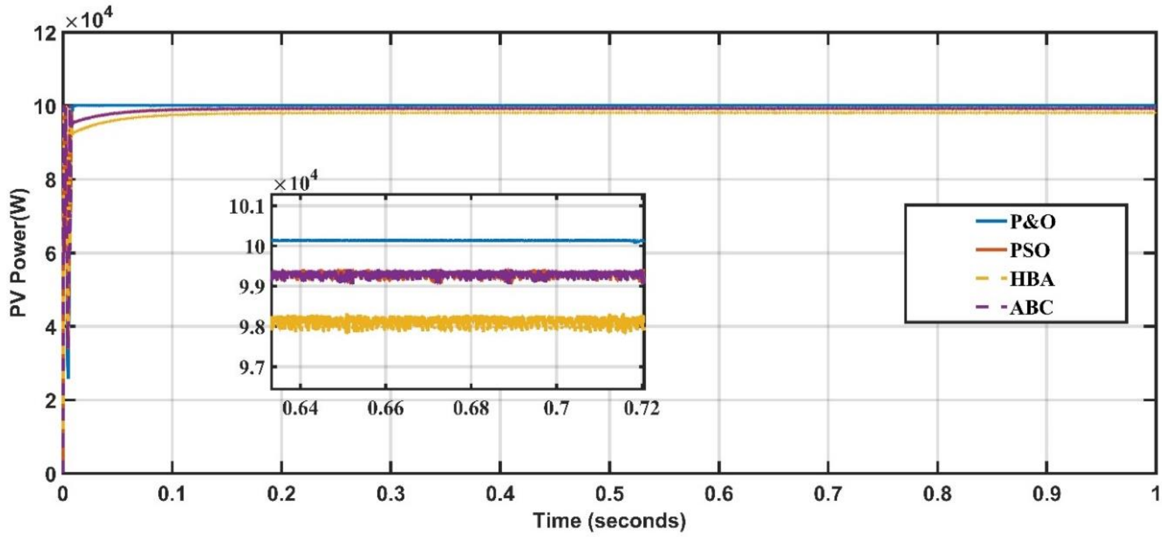

Figure 4.2: Power curve at 1000W/m^2

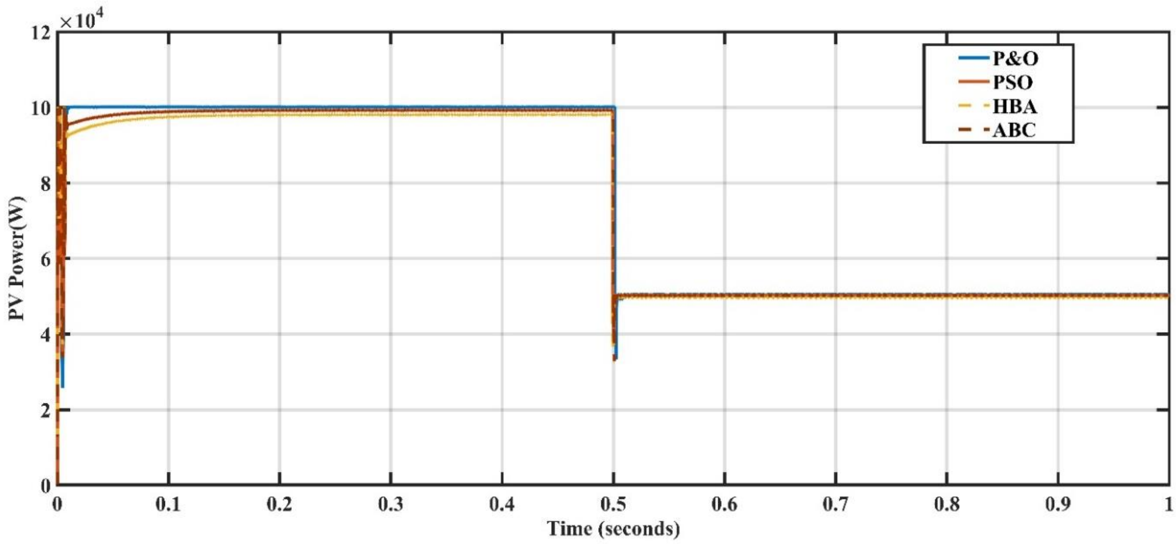

Figure 4.3: Power at changing weather (1000W/m^2, 500W/m^2).

At 1000W/m^2 irradiance the boost converter obtained 100.1KW power using P&O MPPT algorithm optimized with GWO, where the PV cell input was 101KW and at change irradiance and temperature it also performed better. PSO, HBA, ABC algorithm create oscillation around MPP and obtain power respectively 98KW, 98KW and 93KW.

Three phase current (I_{abc}) from grid side at 1000W/m^2 irradiation and changing weather condition (1000W/m^2, 500W/m^2) with P&O MPPT method optimized with GWO are shown in Figure 4.4 and 4.5.

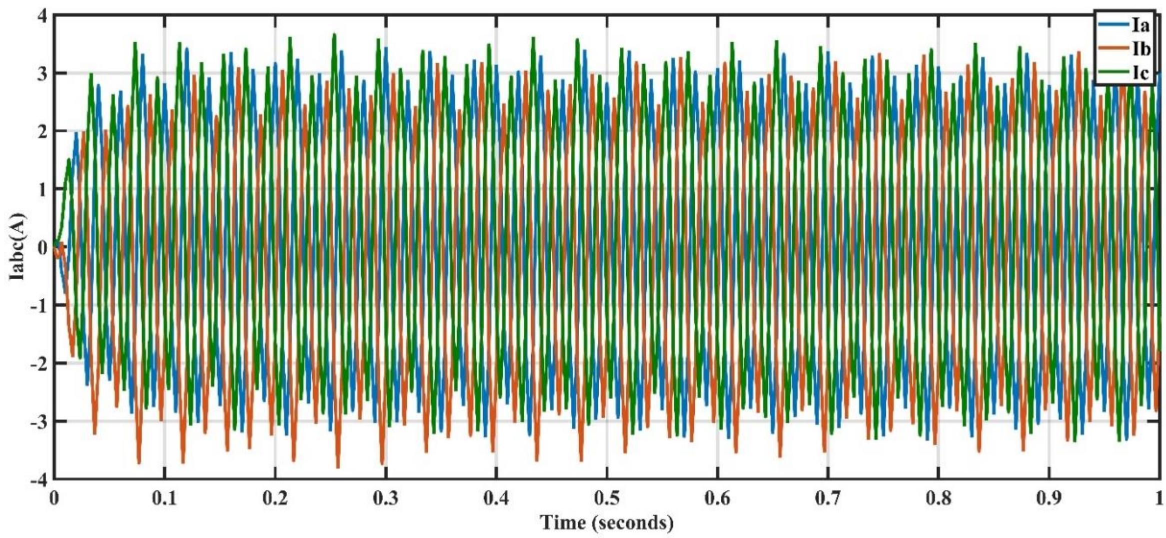

Figure 4.4: Grid side current (I_{abc}) at 1000W/m^2 irradiance.

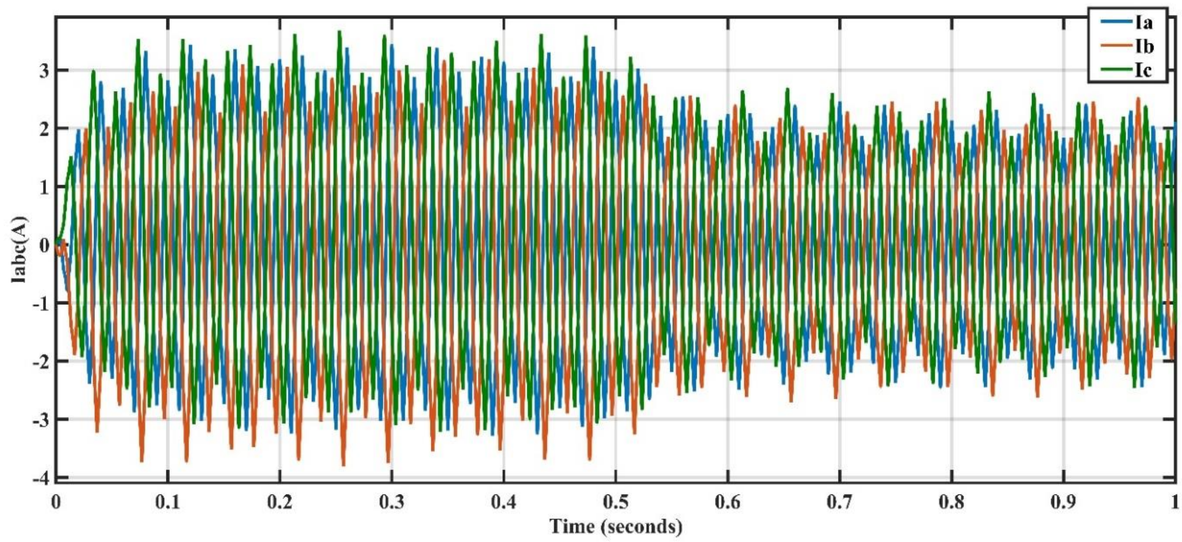

Figure 4.5: Grid side current (I_{abc}) at changing weather condition (1000W/m^2, 500W/m^2).

Table 4.3:Changing parameters using P&O, PSO, HBA, ABC MPPT methods optimized with GWO

Methods	**P&O**	**PSO**	**HBA**	**ABC**
Settling Time	0.0077	0.039	0.051	0.04
Overshoot	0.1355	0.9	2.42	0.881

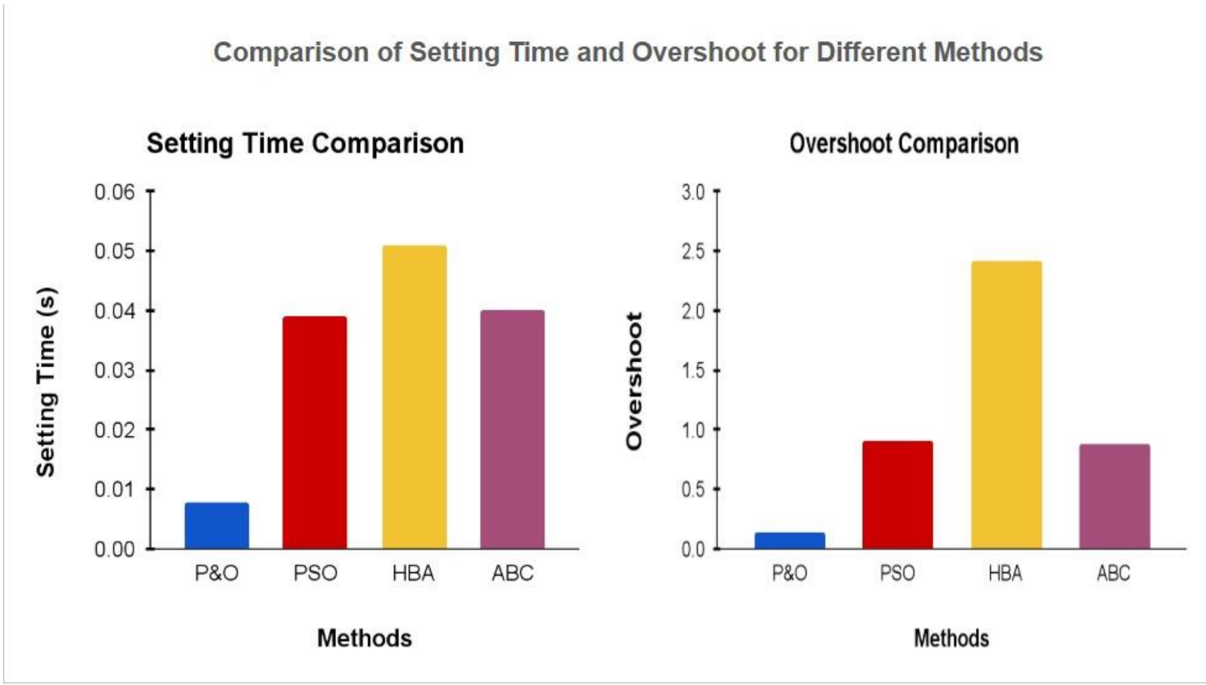

Figure 4.6: Comparison of MPPT methods in Bar chart.

Table 4.3 and Figure 4.6. compare settling times and overshoots for four methods P&O, PSO, HBA and ABC. When comparing the performance of MPPT methods (P&O, PSO, HBA, and ABC) optimized with GWO, P&O method exhibits significantly lower values for both settling time and overshoot, highlighting its superiority. For settling time, P&O achieves a remarkable response time of 0.0077 seconds, which is approximately 80.26% lower than that of PSO, 84.90% lower than HBA, and 80.75% lower than ABC. This demonstrates P&O's ability to respond more quickly to changes, enhancing overall system performance.

In terms of overshoot, P&O again stands out with an overshoot of 0.1355. This value is 84.94% lower than PSO, 94.40% lower than HBA, and 84.62% lower than ABC. The significantly lower overshoot indicates that P&O can maintain stability more effectively, avoiding excessive fluctuations in output. Overall, P&O method optimized with GWO proves to be the most efficient and stable among the evaluated methods, showcasing lower settling times and overshoot percentages that enhance power system performance. DC link voltage across DC link capacitor (C_{bus}) shown in Figure 4.7, DC link voltage is constant at fixed value 700V. A control loop with a proportional integral (PI) controller is used to obtain a fixed value as inverter input.

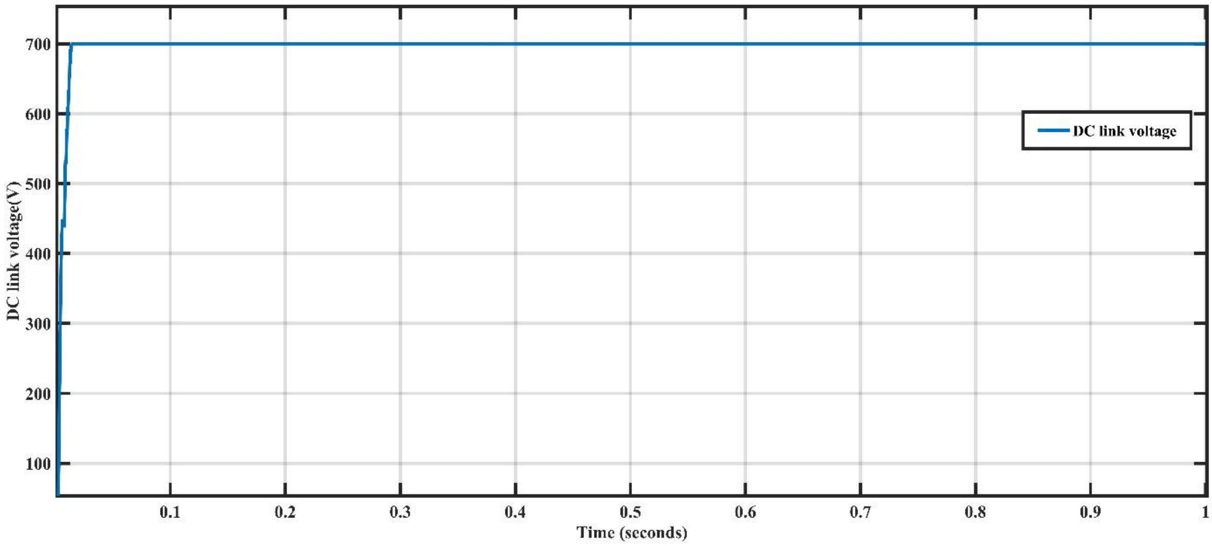

Figure 4.7: DC link voltage.

4.2 Case 2

The aim now is to elaborate a model of the half-bridge bidirectional DC to DC power converter and the battery. Here i_b is the battery current, V_b is the battery voltage, SOC is the battery state of charge. let us first define the switching variable ‘‘S’’ which describes the bidirectional DC/DC power converter’s two operating modes:

S= 1(Buck mode) &

S= 0(Boost mode)

This power converter consists of two switches ‘‘Q’’ and ‘‘Q′’’, a resistor r_1 in series with an inductance L_1, a filtering capacitor C1 followed by a battery energy storage system. This power converter is mainly used to interface the battery with the DC-link. It can operate as a buck or a boost converter depending on the direction of energy flow. The buck mode(S=1), ensures an adequate battery charging, shown in Figure 4.8, the switch ‘‘Q’’ is controlled by a PWM signal ($\mu_4 \in \{0,1\}$) while the switch ‘‘Q'’’ remains open (μ_5=0). The boost mode (S=0), guarantees the safety battery discharging the switch ‘‘Q′’’ is controlled by a PWM signal ($\mu_5 \in \{0,1\}$) while the switch ‘‘Q’’ remains open (μ_4=0). According to the electric circuit, shown in Figure 4.8, and considering the two operating modes described previously, applying Kirchhoff's laws, the instantaneous model of the bidirectional DC/DC power converter connected to the battery. And illustrates the operation of a bidirectional DC-DC converter used for managing the charging and discharging of a lithium-ion battery in the proposed PV system. The converter operates in two distinct modes buck mode (for charging) and boost mode (for discharging) based on system demand and battery state of charge (SOC).

In buck mode (S=1), the converter steps down the DC-link voltage to charge the battery. Here, switch Q is controlled via a PWM signal while Q′ remains open. Conversely, in boost mode (S=0), the battery discharges power into the system by stepping up its voltage through the converter. In this case, Q′ is controlled by a PWM signal, and Q remains off.

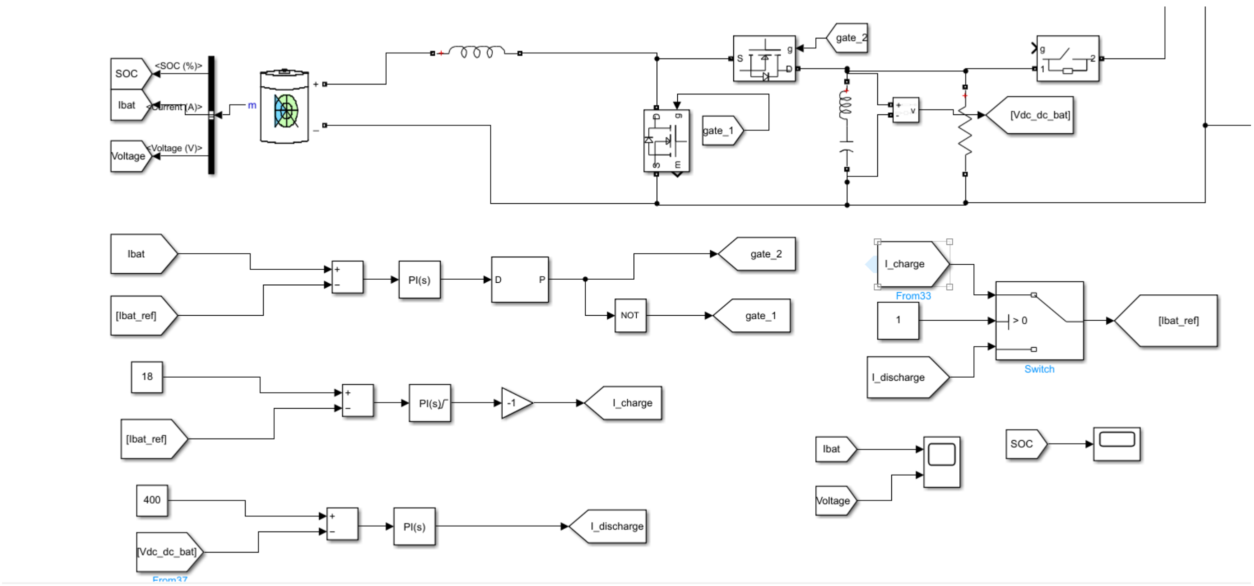

Figure 4.8: Battery charging and discharging with Bidirectional converter.

Achieving global optimization of battery state of charge (SOC) involves implementing strategies and techniques to ensure the battery operates efficiently and effectively. Generally a BMS is used for optimizing battery SOC. Various parameters, including voltage, temperature, and current can be controlled. One of the aims of this work is to well-design a control algorithm to manage charging and discharging processes and ensure the battery operates within its optimal SOC range. Implementing advanced charge/discharge controller algorithm, depending of different fact or such as battery chemistry, capacity, and balancing the power demands of connected loads and grid, to determine the optimal charging rate and duration. They prevent over charging or deep discharging, which can degrade battery life and affect performance. The system can manage the battery's charging and discharging cycles for maximum efficiency.

Based on the available optimal PV power, battery state of charge, load power demand, and grid availability, several power flow management (PFM) scenarios are considered to balance the power flows between the load and different energy sources. These scenarios aim to minimize system costs (economic view), ensure grid stability, and improve power quality (technical view). Figure 4.9 is showing battery current after controlling and Figure 4.10 is showing battery power.

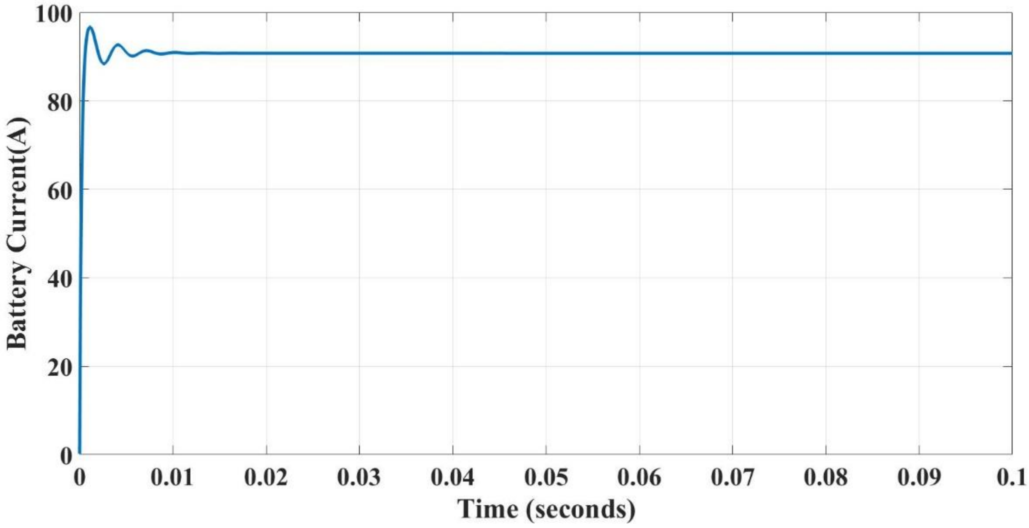

Figure 4.9: Battery current after controlling.

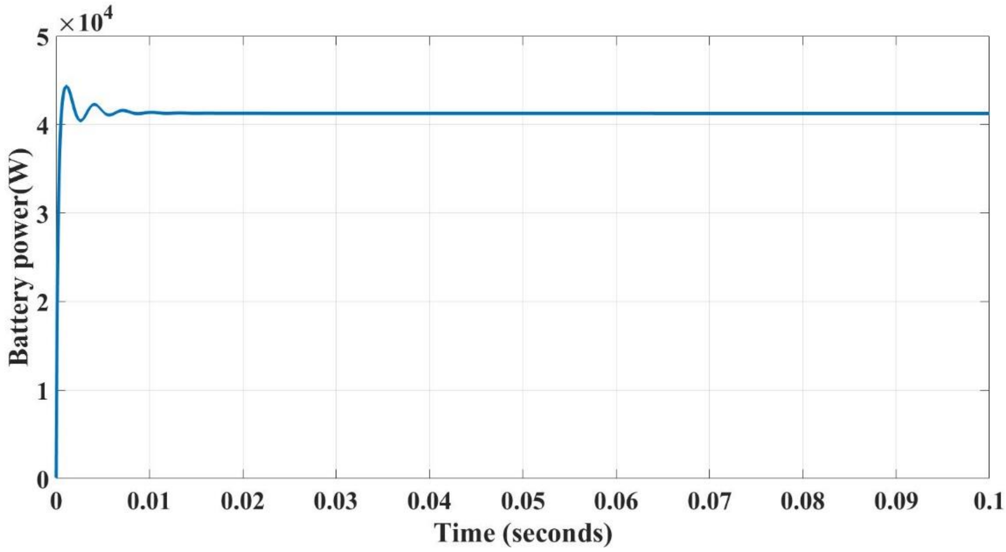

Figure 4.10: Battery power after controlling.

700V DC link voltage has converted to 400V using buck converter to pass through 20ohm resistive load. It is offered for ensuring reliable supply under any mode condition. Figure 4.11

is about simulation of DC load and buck converter. And Figure 4.12 is about simulation output power curver of DC load.

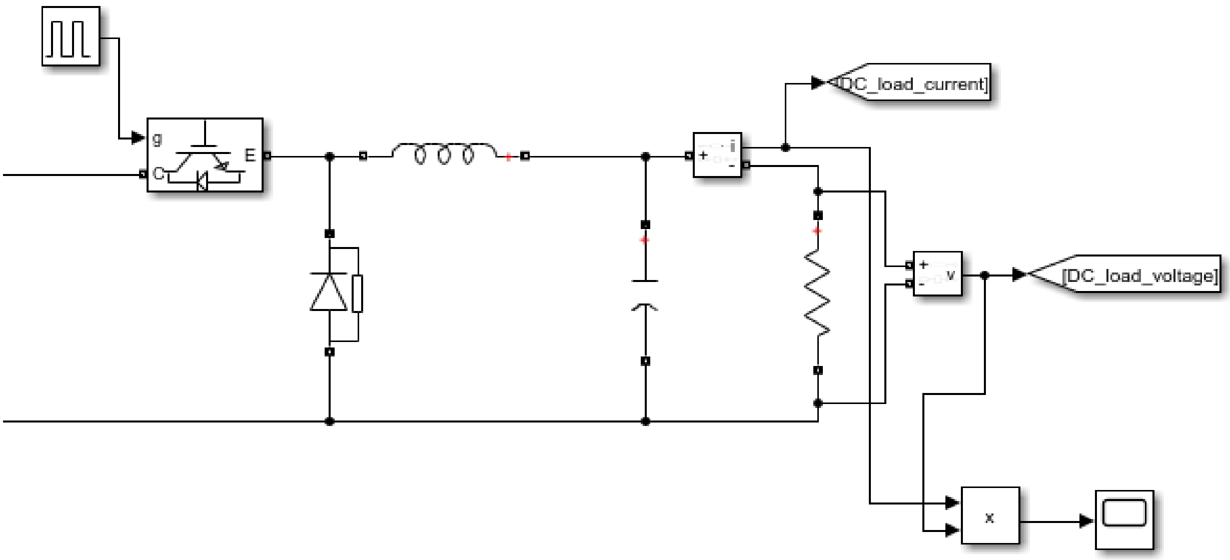

Figure 4.11: Buck converter for low voltage supply to load.

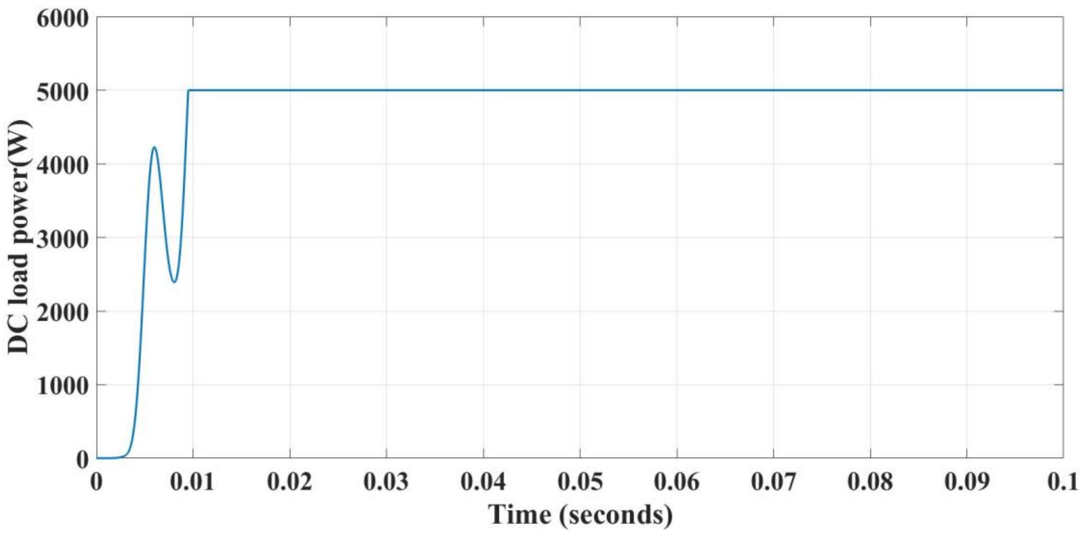

Figure 4.12: Load power curve.

Figure 4.13 indicating all power curve in a window. Here using PV this paper finds 101kW power, through battery this paper can store and supply 40KW, and load power is 5KW.

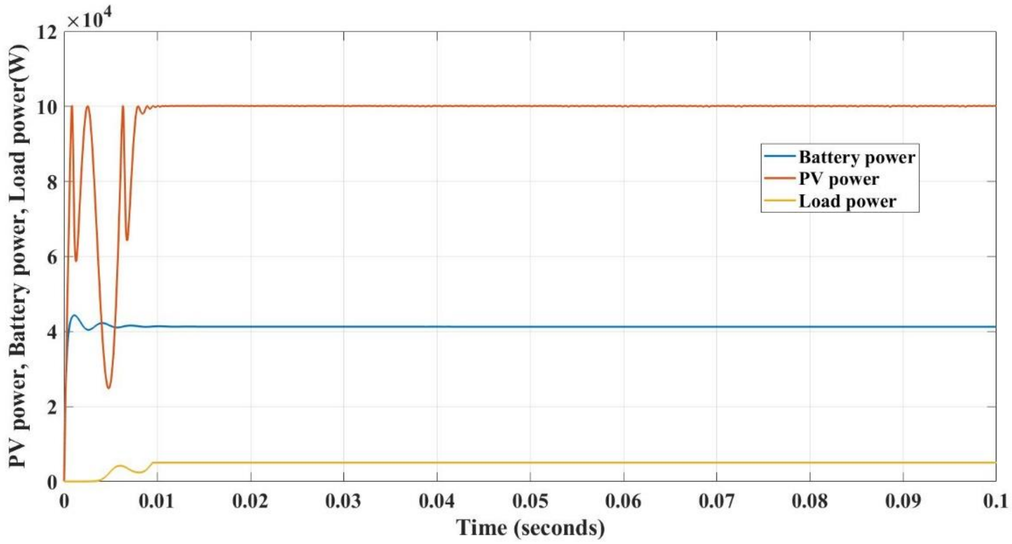

Figure 4.13: Power according to PV, battery, and DC load.

4.3 Summary

This chapter presents the simulation results and performance analysis of the proposed grid-connected PV system using MATLAB/Simulink. Two main cases are analyzed: the first focuses on PV-grid integration with MPPT and inverter control, while the second includes battery storage with a bidirectional converter and DC load. Controller parameters were optimized using Grey Wolf Optimization (GWO) and Particle Swarm Optimization (PSO), with GWO demonstrating superior performance in terms of settling time, overshoot, and convergence speed. Among four MPPT techniques P&O, PSO, ABC, and HBA the P&O method optimized with GWO performed best, achieving a stable power output of 100.1 kW under 1000 W/m² irradiance, while others showed oscillations near the MPP. The chapter also highlights grid current behavior, DC-link voltage stability, and battery charging/discharging performance. Power flow management between PV, battery, grid, and load is effectively maintained. Overall, the results confirm the robustness and efficiency of the proposed control strategy under both standard and dynamic conditions.

Chapter 5: Conclusion and Future Works

5.1 Conclusion

This research has developed a nonlinear control strategy and an energy management algorithm for a solar photovoltaic energy conversion system with an energy storage system. The latter comprises a PV generator connected to a three-phase grid through a DC to DC boost converter, an inverter, a DC to DC buck-boost converter, a lithium-ion battery, and a DC load. a control scheme for PV-connected, grid-tied inverter and DC-DC boost converter has been analyzed and simulated. Four MPPT methods P&O, PSO, HBA, and ABC are compared, along with an optimization algorithm which is Grey Wolf Optimization (GWO) algorithm. The results are compared with those obtained using PSO for tuning. GWO outperforms PSO by offering faster convergence speed, less overshoot and shorter settling time. Among the four MPPT methods, P&O optimized with GWO performs the best under various weather conditions. It demonstrates stable tracking of maximum power output of 100 kW at an irradiance level of 1000 W/m², with a minimum settling time of 0.0077 seconds, less overshoot (0.1355), and higher efficiency. In contrast, other MPPT methods exhibit oscillation close to the Maximum Power Point (MPP), resulting in power loss. The simulation results effectively illustrate performance curves. The current control technique is applied in the inverter, with Phase Locked Loop (PLL) used for generating reference signal, and constant DC link voltage is maintained as the inverter input.

5.2 Future Work

The present work has been focused on simulation-based analysis and performance comparison of optimization algorithms for a grid-tied PV inverter system. To further improve the system and contribute to the development of smart and efficient renewable energy systems, the following directions are proposed for future work:

1. **Hardware Implementation:** The current simulation model can be extended into real-time hardware implementation using digital signal processors (DSP), FPGA, or microcontroller-based platforms (e.g., Arduino, STM32). This will validate the simulation results and ensure system performance under real-world conditions.

2. **Exploration of Advanced Metaheuristic Algorithms**: The proposed GWO algorithm can be compared with other recent and hybrid optimization techniques such as the

Whale Optimization Algorithm (WOA), Harris Hawks Optimization (HHO), or hybrid GWO-PSO and GWO-ABC models for enhanced controller tuning performance.

3. **Integration with Real-Time Weather Data**: Incorporating real-time irradiance and temperature data can improve the dynamic adaptability and efficiency of the MPPT algorithm under rapidly changing environmental conditions.
4. **Hybrid Renewable Energy Systems**: The system can be extended to integrate other renewable sources such as wind energy or fuel cells. Optimization of power sharing and source prioritization in such a hybrid system would be an interesting avenue for further research.
5. **Development of Intelligent MPPT Controllers**: Future work may include GWO-optimized Artificial Neural Network (ANN) or Fuzzy Logic-based MPPT controllers to improve tracking accuracy and reduce oscillations near the Maximum Power Point (MPP).
6. **Minimization of Total Harmonic Distortion (THD)**: Further enhancement of the inverter control strategy can be made by incorporating harmonic analysis and minimizing THD using GWO-based optimization, ensuring better power quality at the grid interface.
7. **Robustness and Stability Analysis**: The system can be subjected to various fault conditions and disturbances such as grid voltage dips, sudden irradiance changes, or load transients to assess the robustness and stability of the proposed control scheme.
8. **Multi-Objective Optimization**: Future research can employ multi-objective optimization to simultaneously consider efficiency, power loss, component stress, and controller stability to design more balanced and resilient PV systems.
9. **Economic and Lifecycle Evaluation**: The lifecycle cost (LCC), energy payback time, and financial viability of the optimized PV system can be assessed under realistic operating conditions to support commercial implementation.
10. **Smart Grid and IoT Integration**: Finally, the proposed system can be connected to a smart grid environment and controlled via Internet of Things (IoT) devices. This would allow remote monitoring, control, and performance optimization of the PV system using cloud-based platforms.

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