

1 Mohammed Asim
 2 Md Aftab Alam
 3 Afroz Alam
 4 Mohammad Saood Manzar
 5 Shaikh Sadaf Afzal Ahmed

Hardware-In-the-Loop Implementation of Particle Swarm Optimization based MPPT System under Partial Shading Condition



Abstract: - The use of renewable energy sources is prevalent to generate electricity owing to the depletion rate of conventional fossil fuels. Solar energy is plentiful and is the most preferred renewable energy source to produce electricity. Consequently, solar photovoltaic (PV) systems are employed to meet the electricity demand, especially in remote areas. On the basis of this motivation, four houses are designed in a remote area of India. Correspondingly, the PV system is designed and tested in Hardware-In-the-Loop virtual environment. PV systems are designed to operate efficiently in both normal and challenging conditions, including partial shading, by employing various maximum power point (MPP) tracking algorithms. Furthermore, Particle Swarm Optimization (PSO) and Perturb and Observe (P&O) are compared in order to track PV system's global MPP.

Keywords: Solar Photovoltaic (PV), Hardware-In-the-Loop (HIL), Optimization, MPPT, Remote Area

I. INTRODUCTION

The necessity for energy is rising daily with the development of modern technology. On the other hand, the reserves of fossil fuels are progressively running out due to their widespread use to produce power [1]. The rise in global energy consumption and environmental degradation has made the development of alternative energy sources a critical necessity in recent years. The increasing shift towards renewable energy sources like solar, hydro, wind, and biomass has gained significant momentum. Among them, solar energy emerges as the most prominent option, offering abundant availability, noiseless operation, and exceptional feasibility. As a result, it is anticipated that solar photovoltaic (PV) systems will soon be an essential energy source for meeting the power demand. This can further be confirmed by the increment in solar energy usage in recent years, as shown in Fig.1. Renewable energy capacity has increased worldwide, according to the International Renewable Energy Agency (IRENA) to 4.4 TW by the close of 2024, with solar power contributing 2.2 TW and wind energy closely following at 1.1 TW. That year, renewable energy production capacity saw an overall increase of 585 GW, marking a 15.1% growth. In recent past, among all renewable sources, solar energy led considerable expansion, which represents a significant rise [2].

Renewable power capacity growth (GW)

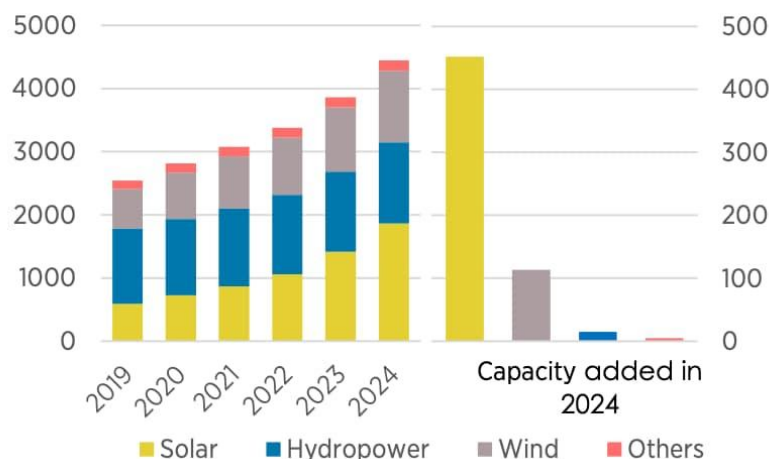


Fig.1. Global renewable energy capacity growth.

1 Department of Electrical Engineering, Integral University, Lucknow 226026, India

2 Department of Electronics and Communication Engineering, Lingaya's Vidyapeeth Nachauli Jasana Road, Faridabad, India

3 Department of Electrical Engineering, Harcourt Butler Technical University, Kanpur, India. E-mail: afroz@hbtu.ac.in

4 Department of Environmental Engineering, Imam Abdul rahman Bin Faisal University, 31451 Dammam, Arab Saudi

5 Department of Computer Science, University of Mumbai, Konan Gayanpeeth College of Engineering, Maharashtra, India

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A PV module is formed by joining many solar cells together. Then, a solar array is created by grouping the PV modules. A solar cell converts solar rays into DC power and has a nonlinear characteristic. As a result, PV modules give a relatively poor conversion efficiency. For PV systems to be as efficient and effective as possible, it is crucial to maximize the amount of electricity that can be extracted from them. The power generated by a photovoltaic module is not constant; it fluctuates based on environmental influences like sunlight intensity, temperature variations, dust buildup, and site-specific factors such as geographical location. This variation highlights the importance of implementing power optimization techniques to track and maintain the maximum power point (MPP) in PV frameworks [3]. The (MPPT) algorithm is therefore used to ensure the maximum output from solar modules. MPPT methods are often classified into advanced (soft computing) approaches and conventional methods [4]. Conventional MPPT approaches were introduced long ago, gaining tremendous popularity. The primary benefits of using conventional strategies lie in their ease of use because of less computation and require a few external elements for implementation. Under uniform irradiation, these approaches can only monitor a local MPP. P&O and INC are the two most widely used MPPT techniques [6]. There is a problem with identifying the GMPP using these techniques as they take a significant time and have poor tracking precision with high oscillations. Thus, to extract the optimum GMPP, soft computing techniques are exploited. These techniques are highly flexible, robust, reliable, and provide better tracking results in PSC circumstances. In soft computing, meta-heuristic algorithms are favoured for their ability to handle multi-modal problems. Optimization challenges are addressed using both global search algorithms and non-linear programming techniques [7]. These non-linear methods help reduce discrepancies between calculated and expected performance. There have been many metaheuristic algorithms developed over the years to determine the optimal solar PV cell and module parameters. A comprehensive review of PV parameter estimation using Evolutionary Algorithms (EA) was conducted in [8]. According to Hachana et al., four algorithms were used to extract the intrinsic parameters of a solar PV cell: differential evolution (DE), artificial bee colonies with differential evolution (ABC-DE), modified particle swarm optimization (MPSO), and a hybrid approach were developed for extracting their intrinsic parameters.

The accuracy of these methods was assessed by comparing their results with experimentally measured I-V characteristics [9]. Among them, the ABC-DE algorithm outperformed the others by achieving the fastest convergence, proving to be a highly efficient solution for parameter estimation.

GMPP tracking was also accomplished using another nature-inspired optimization algorithm. The Cuckoo Search (CS) algorithm, encouraged by the unique upbringing strategy of certain cuckoo species, has been explored for solar PV parameter estimation. Its effectiveness was evaluated on both the single-diode model and an enhanced diode model, which adapts to varying environmental conditions based on an operating factor [10]. It was found to have the lowest RMSE value among Genetic Algorithms, Particle Swarm Optimization, and PS meta-heuristics algorithms. The latest MPPT algorithm implementation work performed in a real-time simulation environment using Typhoon Hardware in Loop (HIL) framework is summarized in Table I.

In this study, a solar PV system has been designed to meet the total daily electricity demand of a cluster of four households, which amounts to approximately 4.864 kWh/day. The selection of system components has been made based on their specific properties to ensure optimal performance. To maximize power extraction from the proposed PV system, MPPT was implemented using two algorithms: P&O and PSO. The system's effectiveness was assessed through HIL simulation, ensuring accurate tracking of the global MPP.

In Section II, we analyse the load demand of the household cluster, while in Section III, we provide a detailed design of the PV system. Specifically, it describes the PV array layout tailored to meet the specified load requirements, as well as the solar cell configuration and key characteristics. Section IV presents a inclusive overview of the MPPT algorithms. Section V showcases the Hardware-In-the-Loop (HIL) simulation results for MPP tracking. Finally, Section VI summarizes the key findings of this research.

II. LOAD DESIGN

For a remote location, such as rural areas in India, a cluster of four houses is taken for load design. Each household contributes to 1.216 kWh of electrical energy requirement corresponding to the use of load: two fans, led lights, and mobile chargers as enlisted in Table II.

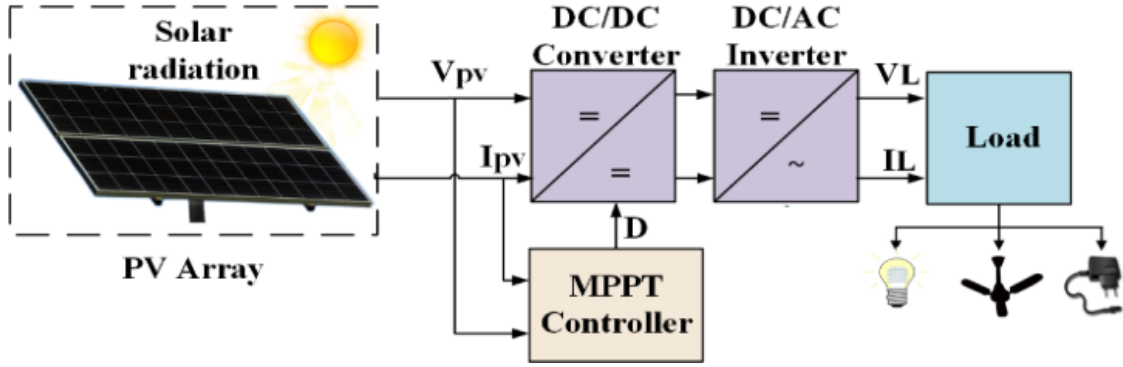


Fig.2. Typical PV system block diagram.

III. DESCRIPTION OF PV SYSTEM

Figure 2 illustrates the fundamental structure of the solar PV system, designed to optimize power delivery to the load. The system comprises four key components: a PV array, an MPPT controller, an inverter, and the connected load.

When sunlight hits the PV panels, they directly convert solar energy into electrical power. In order to optimize power extraction, the MPPT controller dynamically regulates the PV array's voltage and current. Additionally, a DC-DC boost converter steps up the PV output voltage to a stable, higher DC level for efficient energy utilization. Finally, a DC/AC inverter transforms the DC electricity into AC, ensuring compatibility with conventional AC-powered appliances.

A. Equivalent Circuit Model of Solar Cell

Figure 3 depicts the one-diode equivalent circuit of a PV cell, which is modelled using mathematical equations that define its electrical characteristics. The one-diode equivalent circuit comprises a combination of linear and non-linear elements. In the linear section, a series resistor ($R_{s'}$) accounts for the internal resistance of the cell. Meanwhile, the $R_{sh'}$ (shunt resistor) denotes the losses caused by diode leakage currents.

The non-linear portion is used to describe the cell polarizing processes and is represented by a diode (D'). In an ideal scenario, the $R_{sh'}$ has an infinite value and can be disregarded whereas $R_{s'}$ becomes zero [11]. The elemental equations for modeling a PV system are as follows:

The PV cell output current, ($I_{out,c'}$) is computed by applying KCL to the circuit as in eq. (1):

$$I_{out,c'} = I_{in,c'} - I_{D'} - I_{sh'} \quad (1)$$

Here, the current source ($I_{in,c'}$) imitates the light-generated current, generally determined by a cell's temperature and irradiance. A diode is represented by $I_{D'}$, while a shunt resistance is represented by $I_{sh'}$. The I-V characteristics of a solar cell incorporating a diode are derived using the Shockley equation, as expressed in eq. (2):

$$I_{out,c'} = I_{in,c'} - I_{rsc} \left[\exp \left(\frac{q_{ce} (R_{s'} I_{out,c'} + V_{out,c'})}{d_f k_{BC} T_c} \right) - 1 \right] - \frac{R_{s'} I_{out,c'} + V_{out,c'}}{R_{sh'}} \quad (2)$$

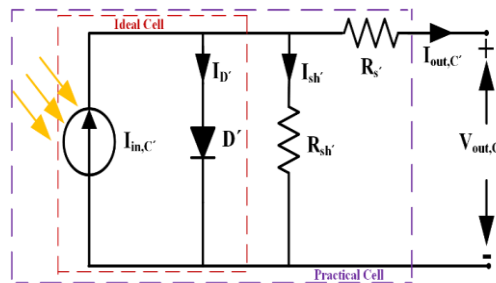


Fig. 3. PV-Cell one diode equivalent circuit.

A diode's reverse-biased saturation current is I_{rsc} . The d_f symbolises ideality factor of the diodes. T_c is measured in Kelvin, symbolises cell's operating temperature. k_{BC} symbolises Boltzmann constant and q_{ce} symbolises electron charge, respectively.

TABLE I. ELECTRICAL LOAD PROFILE OF A HOUSEHOLD.

Load	No. of loads	Power rating (W)	Operation (24-hr system) time clock	Load duration (hr)	Power (W)	Energy per day (Whr)
Fan	2	30	10:00-4:00	18	60	1080
Led Lights	2	9	18:00-24:00	6	18	108
Mobile Charger	2	7	8:00-10:00	2	14	28
Total					92	1216
In a cluster of four households, total electrical energy consumption per day					1216×4 = 4864Whr	

B. Characteristics of Solar Cell

Solar PV cells under standard test conditions (STC) with an irradiance of 1000 W/m² are shown in figure 4. In an open-circuit condition, where no load is connected, no current flows, and the terminal voltage reaches its maximum. Conversely, when the voltage drops to zero, the current attains its highest value, known as the short-circuit current.

The voltage-current relationship is a direct result of the power generation process in the solar cell [18]. When subjected to uniform solar irradiation, it is not difficult to ascertain the MPP. The MPP may be determined accurately if the measurement is correct. The MPPT should alter per the changing pace of the working environment.

Authors, year	MPPT algorithm	HIL Implementation	Converter	Findings
M. Asim, et al. [12], 2022	Bat algorithm	Yes	Boost converter	Bat algorithm is simple, efficient. Easy to be implemented on low-cost microcontroller.
I. Pervez, et al. [13]; 2022	Radial Movement Optimization and teaching-learning based optimization (RMOTLBO)	Yes	Boost converter	RMOTLBO successfully tracks the maximum power point in a lesser amount of time and lesser fluctuations compared to P&O.
A. A. Al-Shammaa, et al. [14], 2022	Cuckoo Search Optimization (CSO) Algorithm	Yes	Boost converter	CSO is capable of tracking GMP within 0.99–1.32 s under various shading patterns. CSO outperformed the conventional techniques in terms of steady-state fluctuations and tracking time.
M. C. Tiong, et al. [15], 2022	Moth flame optimization (MFO)	Yes	Boost converter	MFO has shown its capability in tracking for the maximum power operating point effectively, with zero steady state oscillation. Track the maximum power operating point with output efficiency up to 99% in both simulation and real-time platform.
H. Malik, et al. [16], 2022	Black Widow Optimization (BWO)	Yes	Boost Converter	BWO approach may be used to increase overall productivity and minimize costs for the operation of e-vehicles based on the PV framework.
M. Salunke, et al. [17], 2021	Perturb and observe technique	Yes	Boost Converter	Real-time hardware in the loop (HIL) simulators can enable the emulation of test beds while developing the real-time control hardware to implement and verify theoretical optimal control strategies.

TABLE II.. RECENT RESEARCH WORK DONE IN THE FIELD OF MPPT STRATEGIES USING HIL

C. Partial Shading Condition

A unique challenge impacting both the efficiency and longevity of PV systems is the occurrence of partial shading conditions (PSC). In residential installations, partial shadowing might result in an annual 10–20% loss in power generation or more. It may be caused by various factors, including moving clouds, objects, trees, etc. The I-V mismatch between the modules that make up the array leads the array to lose a significant amount of energy when exposed to partial shade. Due to solar irradiation variations, the PSC's PV array generates numerous local MPPs. The received solar irradiation primarily determines the local MPP (LMMP) value. Therefore, the P-V curve no longer has a singular point, as seen in Fig.5, but rather many working zones with distinct peaks. Due to the hotspot phenomena, the PSC also shortens the lifespan of the PV system. Utilizing a bypass diode prevents the generation of hotspots [19].

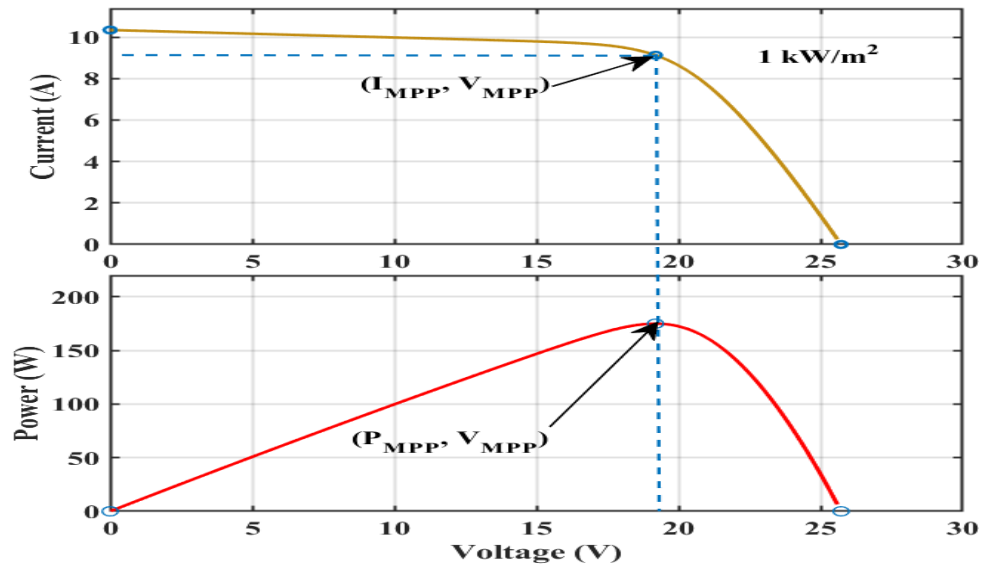


Fig. 4. PV panel I-V and P-V feature characteristic.

D. PV System Design

According to Table II, the total daily energy consumption for running a cluster of four households is projected to be 4.864 kWh. In India, sun intensity is typically accessible for 7 hours on average. Therefore, the required power capacity for the PV system is determined as follows:

$$\text{Power Capacity} = 4864 \text{ Wh}/7\text{h} = 694.85 \text{ W} \quad (3)$$

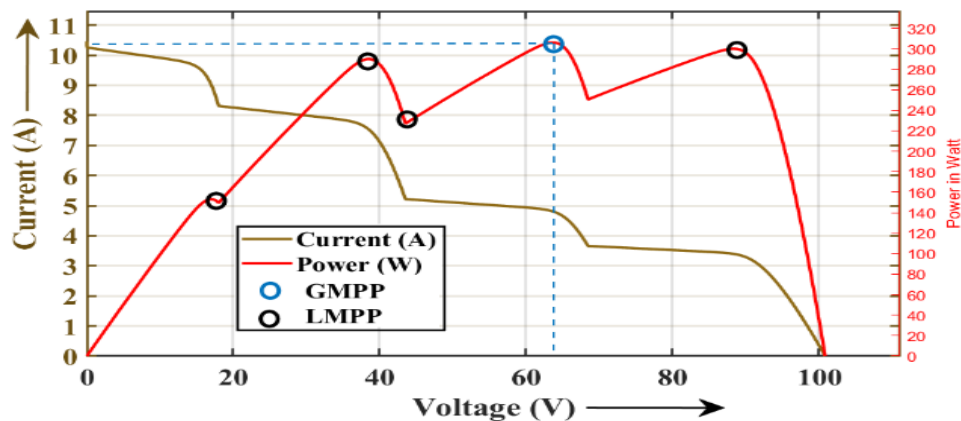


Fig. 5. I-V and P-V feature curves of a PV panel under PSC.

To design the PV system, a 175 W PV panel is selected as the basic building block for constructing a 694.85 W system. Table III contains details of the PV module's specifications.

Thus, the total number of required modules is calculated as follows:

$$\frac{694.85\text{W}}{175\text{W}} = 3.97 \cong 4 \text{ modules} \quad (4)$$

Parameters	Values
Maximum Power (P_{mp})	175 W
Voltage at maximum power point (V_{mp})	19.19 V
Current at maximum power point (I_{mp})	9.12 A
Short circuit current (I_{sc})	10.3366 A
Open circuit voltage (V_{oc})	25.7200 V
Cells per module (N_{cell})	72
Ideality factor	1.3

TABLE III PV MODULE SPECIFICATION

IV. MAXIMUM POWER POINT TRACKING

In a MPPT system, the most efficient voltages and currents are identified to maximize system performance. The MPPT system functions by altering the operating point on the solar panel's P-V characteristic curve, allowing DC-DC converters to compel the solar panels to produce the peak power potential in accordance with their capabilities at various light intensity levels. Raising and decreasing the voltage until the panel's maximum power point is discovered is one of the simple approaches that may be used with MPPT devices.

A. Perturb and Observe

The P&O technique is popular for its straightforward design and easy enactment. Additionally, it requires fewer sensors, reducing overall costs. This algorithm follows principles similar to the "Hill Climb Search" technique. The P&O approach iteratively determines the maximum power point by introducing small disturbances in the PV array's voltage and observing their impact on power output.

The DC-DC converter's duty cycle can be adjusted to increase or decrease PV module voltage, affecting power output. If a voltage increase leads to higher power, the operating point is on the left side of the P-V curve, requiring further adjustments in the same direction. Conversely, if power decreases with rising voltage, the operating point lies on the right side, necessitating a shift in the opposite direction. The system will continue to evolve until the MPP has been achieved. The P&O method operates efficiently under steady insolation conditions; however, it has some drawbacks. These include oscillations around the MPP, slow tracking response, and difficulty in accurately locating the true MPP under partial shading scenarios. Figure 6 presents the standard flowchart outlining the implementation of the P&O algorithm [20].

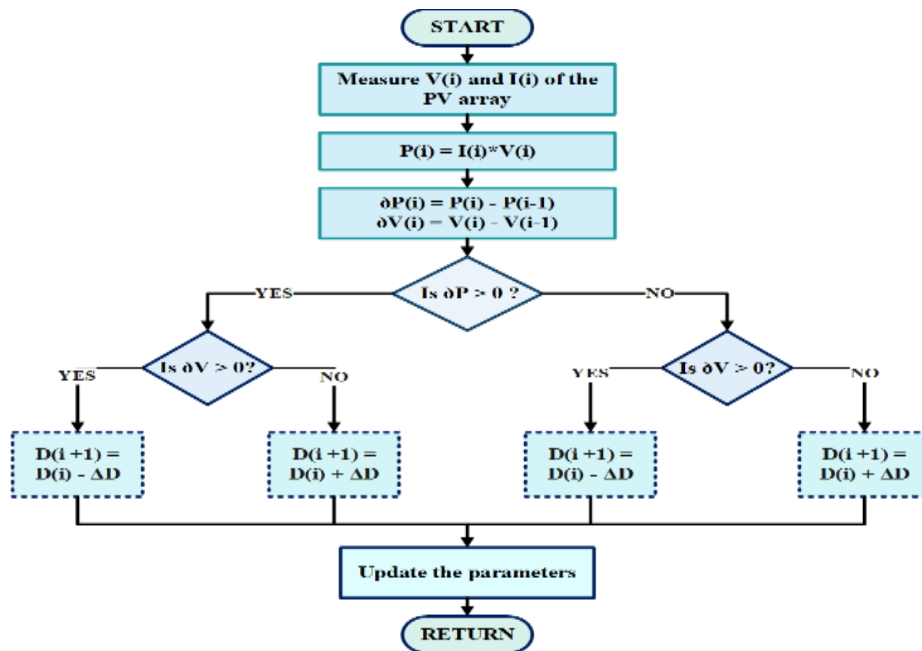


Fig. 6. P&O flowchart.

B. Particle Swarm Optimization

The PSO technique is a widely adopted stochastic search method. It is particularly effective for optimizing nonlinear continuous functions. Originally introduced by Eberhart and Kennedy in 1995 [21], PSO mimics the

social behaviour of swarms to achieve optimal solutions. The natural behaviour of fish schooling and bird flocking is used to illustrate how the PSO algorithm behaves. Several cooperative birds are engaged in this method, and each bird symbolizes a particle. For the intent of discovering an objective function's maximal or minimal values, N_p particles are utilized. The particles are arbitrarily initiated and begin to travel with a certain velocity in a particular search arena. In each iteration, the velocity is updated using the current velocity, the individual's best-recorded position, and the globally optimal position. This updated velocity is then used to determine the agent's new position. Throughout the optimization process, agents explore different directions within the search space, continuously adjusting their movement to find the optimal solution. The velocity of particle i^{th} is symbolized by the notation, $\hat{V}_i$, which stands for the step size, and may be computed as:

$$\begin{aligned} \hat{V}_i^{k+1} = & \omega \hat{V}_i^k + \alpha_1 c_1 \{P_{(best,i)} - \hat{X}_i^k\} \\ & + \alpha_2 c_2 \{G_{(best)} - \hat{X}_i^k\} \end{aligned} \quad (5)$$

The following equation is used to adjust the position of the i^{th} particle, $\hat{X}_i$:

$$\hat{X}_i^{k+1} = \hat{X}_i^k + \hat{V}_i^{k+1} \quad (6)$$

Here, ω means inertia mass, α_1 and α_2 symbolises the acceleration coefficients, c_1 and c_2 denotes random integers lie in the range of 0 and 1. $P_{(best,i)}$ means personal best position of i particle, and $G_{(best)}$ symbolises global best position of swarm and k characterizes the iterative number. Equation (5) and (6), so-called flight equations demonstrate how three factors affect each particle's new position. The particle's current velocity is reflected by the first term and inertia mass; ω . A particle's attraction towards its individual best (cognitive influence) is governed by the second term, which is determined by the cognitive acceleration coefficient; α_1 , while a particle's attraction towards its global best is influenced by the third term, which is determined by the social acceleration coefficient; α_2 . The individual's best position $P_{(best,i)}$ is updated by Equation (7), if the criterion is as given in Equation (8) is met.

$$P_{(best,i)} = \hat{X}_i^k, \quad (7)$$

$$f_o(\hat{X}_i^k) > f_o(P_{(best,i)}) \quad (8)$$

Where, f_o represents the objective function that is PV array's operating power.

C. MPPT using PSO

The PSO algorithm tracks the MPP by utilizing the direct control approach. The optimization process starts by initializing a solution vector of duty cycles with particles that must be specified as follows:

$$\hat{X}_i^k = \hat{D} = [\hat{D}_1, \hat{D}_2, \hat{D}_3 \dots \hat{D}_i] \quad (9)$$

Here, $i = 1, 2, \dots, N_p$ indicates particles count and the selection of N_p is determined to optimize the convergence procedure.

The objective function is expressed in the following way:

$$P_{pv}(D_i^k) > P_{pv}(D_i^{k-1}) \quad (10)$$

Here, P_{pv} signifies the PV power, $\hat{D}$ denotes the duty cycle. The flowchart of MPPT based PSO is depicted in Fig.7 [22].

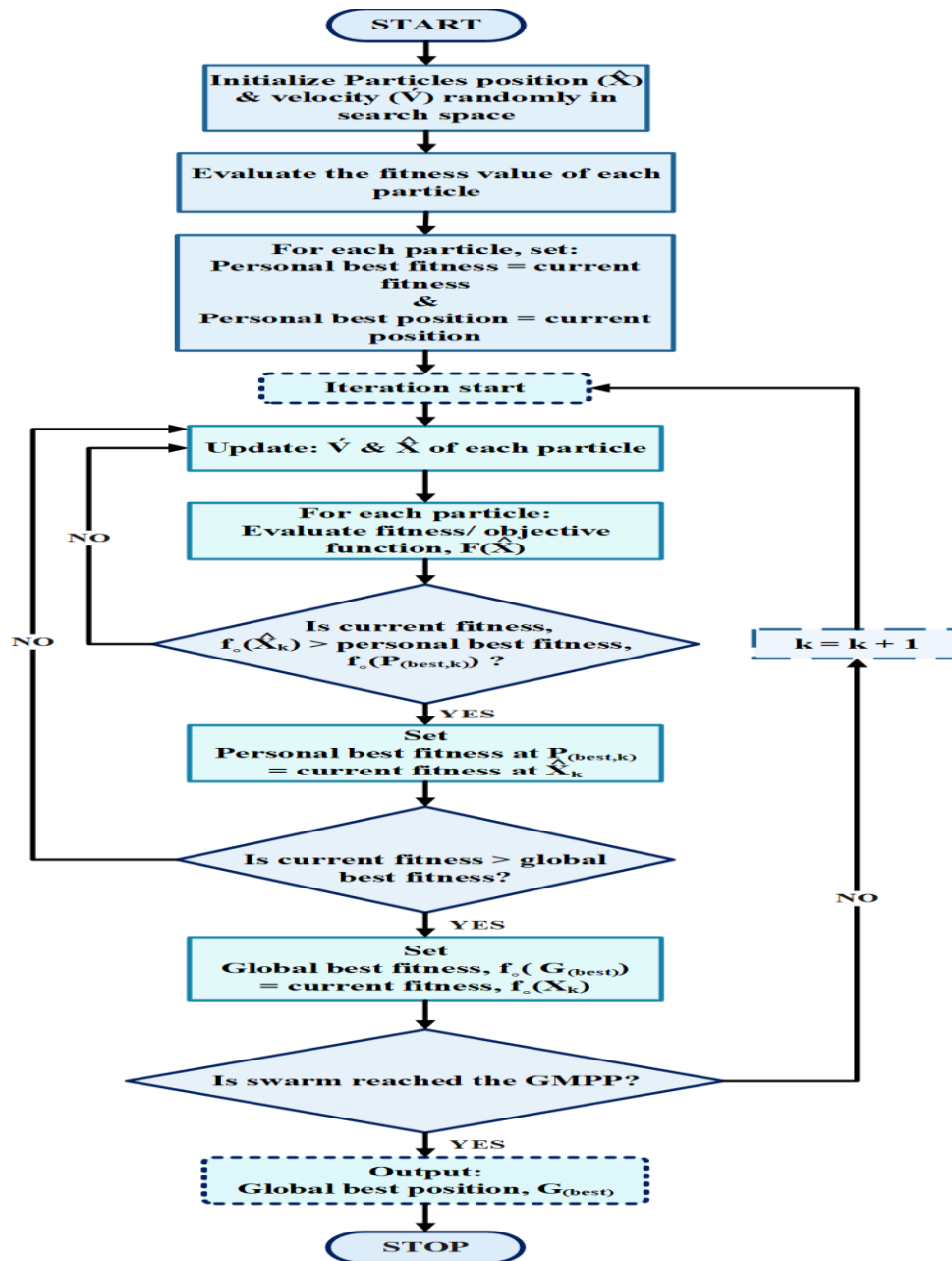


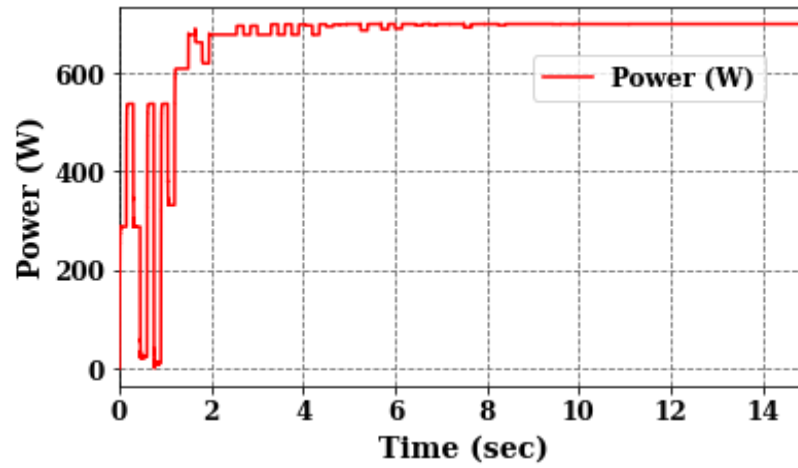
Fig. 7. PSO flowchart.

V. HARDWARE IN THE LOOP RESULTS AND DISCUSSION

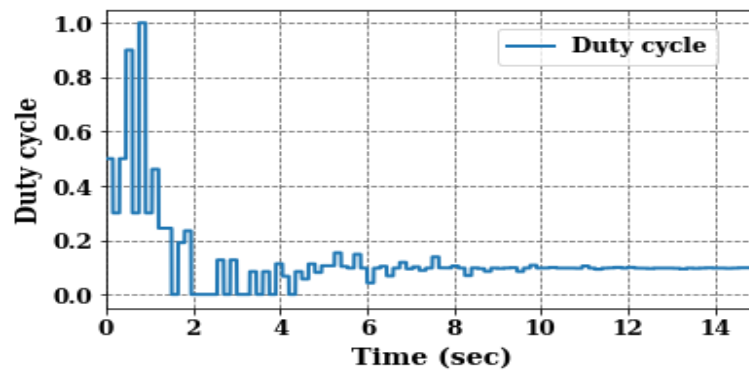
The P&O and PSO algorithms are implemented using Typhoon Hardware-In-the-Loop (HIL) Control Center software, version V2022.2. To assess their effectiveness in tracking the GMPP, three different cases are simulated and analyzed.

In the first simulation, a constant irradiation condition of 1000 W/m² is applied to all four solar panels, with the PV system's temperature set at 25°C. The results for power output and duty cycle using the PSO and P&O techniques are illustrated in Fig. 8(a) and (b) and Fig. 9(a) and (b), respectively.

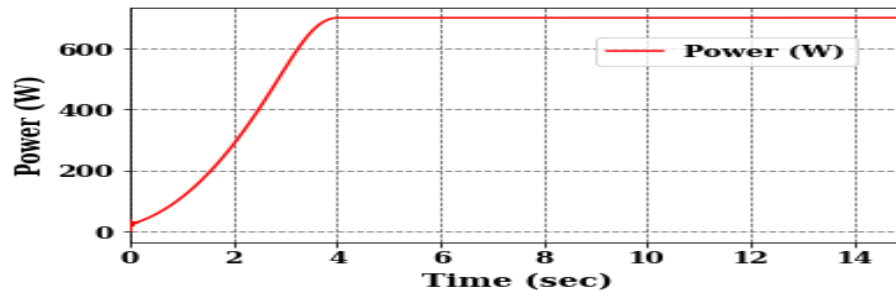
The results from these figures suggest that both P&O and PSO methods tracked the optimal MPP approximate to 699.7 W. However, tracking time varies for both. P&O followed the MPP in less time, which is 4.013 sec, whereas PSO took 11.57 sec. This difference in time is because of the simple computational nature of P&O as compared to the PSO algorithm.



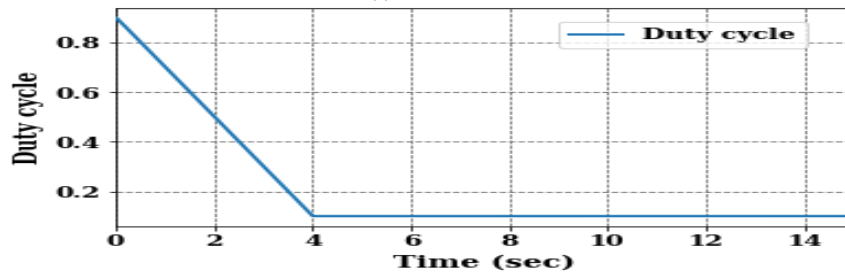
(a) Power curve



(b) Duty cycle curve

Fig. 8. (a) and (b) PSO 1000, 1000, 1000, and 1000 W/m²

(a) Power curve



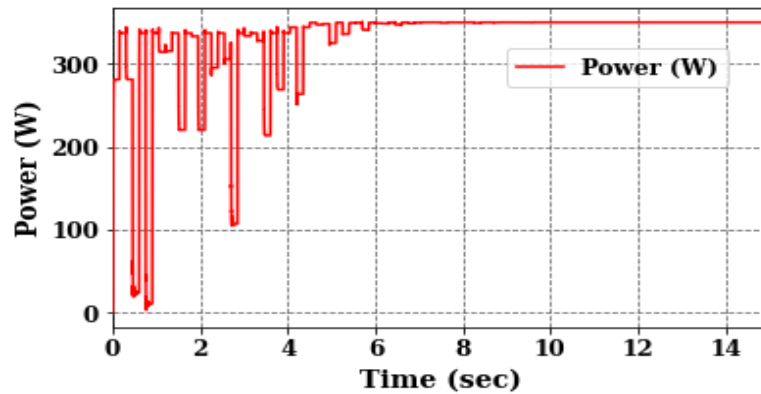
(b) Duty cycle curve

Fig. 9. (a) and (b) P&O 1000, 1000, 1000, and 1000 W/m².

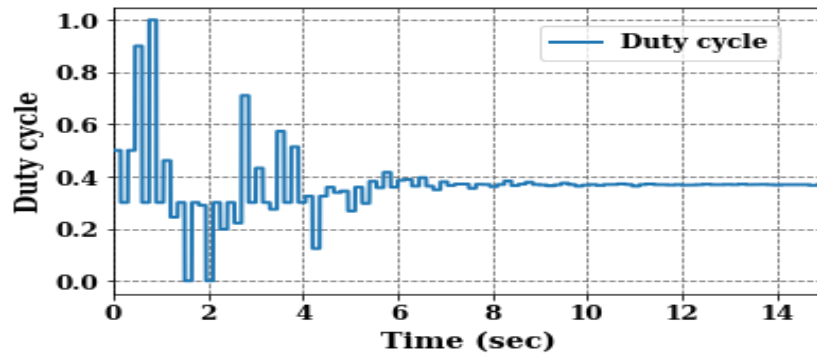
In Fig. 10(a) and (b) and Fig. 11(a) and (b), the four PV panels were set to insolation levels of 1000, 1000, 450, and 450 W/m², known as the partial shading conditions (PSC) and each panel's temperature is kept constant at

25°C. In this case, the MPP tracked down by PSO and P&O techniques are the same, i.e., 349.7 W. Although, similar to normal insolation level condition, PSO again took more tracking time compared to the P&O method with the difference of 9 sec.

The solar modules were then adjusted to various insolation levels, such as 1000, 800, 500, and 350 watts per square meter. The power and duty cycle versus tracking time curve for the

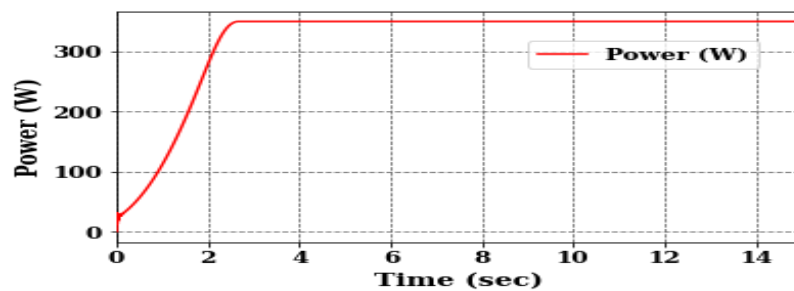


(a) Power curve

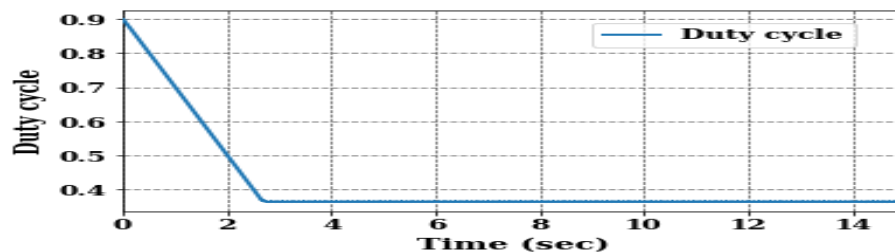


(b) Duty cycle curve

Fig. 10. (a) and (b) PSO 1000, 1000, 450, 450 W/m².



(a) Power curve



(b) Duty cycle curve

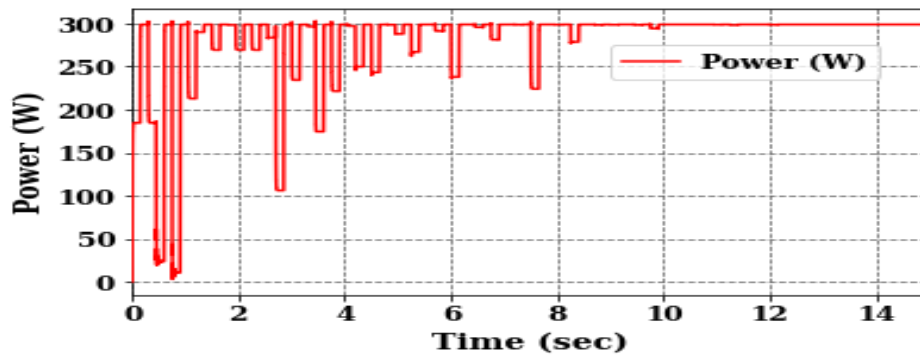
Fig. 11. (a) and (b) P&O 1000, 1000, 450, and 450 W/m².

prescribed PSC conditions for PSO and P&O strategies are depicted in Fig 12 and 13, respectively. For this setting, the PSO algorithm tracked the global MPP as 298.96 W, while the P&O technique tracked it as 174.92W. This difference of 124 W in maxima tracking proves that the PSO algorithm performs better in the case of PSC

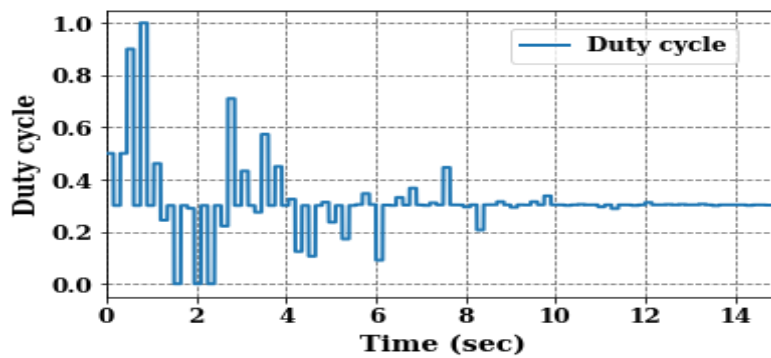
conditions in contrast to the P&O method. At the same time, the P&O algorithm wins in uniform insolation circumstances as it has fast tracking speed. The results for all three cases of simulation are enumerated in Table IV.

The research work can further be progressed in the future by including:

- Whole load demand of remote villages or areas can be considered to design a remote PV system to provide electricity to all households and small factories in a village.
- Hot spot effect on PV system and working of mppt strategies in real-time evaluation with time frame of one week or a month.
- Implementation of hybrid or newly proposed algorithm for MPP tracking of PV system.

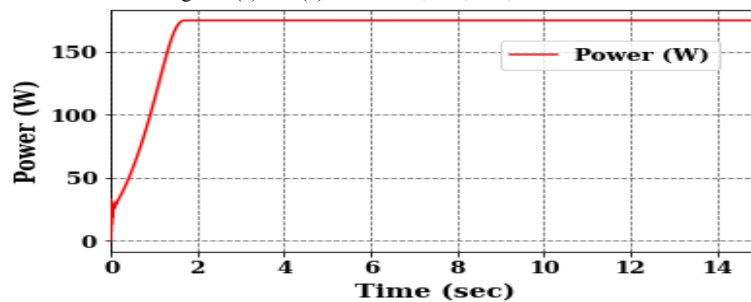


(a) Power curve

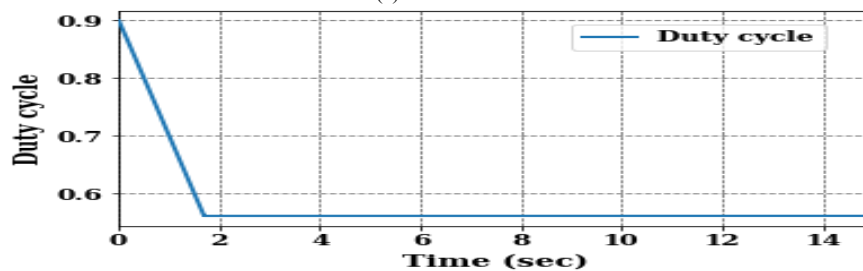


(b) Duty cycle curve

Fig. 12. (a) and (b) PSO 1000, 800, 500, 350 W/m².



(a) Power curve



(b) Duty cycle curve

Fig. 13. (a) and (b) P&O 1000, 800, 500, 350 W/m².

TABLE IV. HARDWARE-IN-THE-LOOP SIMULATED OUTCOMES FOR PSO AND P&O ALGORITHMS UNDER VARIOUS INSOLATION CONDITIONS

Parameters	Insolation level [1000, 1000, 1000, 1000] W/m ²		Insolation level [1000, 1000, 450, 450] W/m ²		Insolation level [1000, 800, 500, 350] W/m ²	
	PSO	P&O	PSO	P&O	PSO	P&O
Global maximum power (W)	699.78	699.73	349.77	349.71	298.96	174.92
Duty cycle at global maxima	0.097	0.1	0.368	0.37	0.302	0.56
Tracking time (s)	11.57	4.01	12.00	2.65	13.00	1.80

VI. CONCLUSION

This paper presents the design of solar photovoltaics (PV) framework to meet the electrical energy demand of a cluster of four households situated in a remote area found in India. As part of this study, a detailed mathematical analysis of the solar module system is provided along with a detailed description of PSO and P&O optimization algorithms. PV systems are monitored using PSO and P&O strategies under a variety of irradiation conditions to determine the global maximum power point. Hardware-In-the-Loop (HIL) software is utilized to take the results for different insolation conditions. The detailed analysis of the experimental results indicates that the PSO algorithm outperforms the P&O strategy regarding global optimal power tracking during partial shading conditions. Hence, this work put forth the implementation of the PSO algorithm in recently developed HIL software models. To conclude, this work can further progress by considering designing PV systems for remote industries where electrical supply fluctuates a lot. Moreover, it can be taken as a reference to implement the complex and newly developed optimization algorithms in HIL real-time simulation model.

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