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DESIGN AND IMPLEMENTATION OF 2 KW OFF-GRID PHOTOVOLTAIC SYSTEMS WITH MAXIMUM POWER POINT TRACKING USING PSO ALGORITHM OPERATING UNDER PARTIAL SHADING CONDITIONS

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ABSTRACT

This paper presents the design and implementation of a metaheuristic control method for maximum power point tracking (MPPT) methodology in photovoltaic systems under partial shading conditions. To attain maximum efficiency, photovoltaic (PV) panels should operate at their maximum power point (MPP). Therefore, to maximize the power from the PV system, an MPP tracker is inserted between the PV arrays and the load to ensure that the operating point of the system is adjusted to be placed on the MPP. When the radiation distribution over PV panels is uniform, many traditional MPPT techniques can effectively monitor MPP. However, when the PV arrays are partially shaded, more MPPs are displayed, which usually results in the inability to find the overall MPP. To overcome this difficulty, this proposed work presents a particle swarm optimization algorithm-based MPPT scheme for PV systems. This PSO heuristic algorithm-based technique not only ensures the ability to find the global MPP but also gives a simpler control scheme. The feasibility of this proposed method is verified by various partial shading conditions using Matlab. The proposed method is implemented with a 2KW PV system and the power output is compared with the existing system.

Keywords: MPPT, photo voltaic systems, DC-DC converter, PSO algorithm.

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1. INTRODUCTION

The necessity for renewable and clean energy sources is increasing worldwide because of the several advantages related to environmental sustainability [1] [2]. With the increasing popularity of solar systems, there is still an excessive requirement to make photovoltaic systems as efficient as possible. The efficiency of energy conversion in the solar power system is indeed affected by the voltage and current conditions. The power output will be maximum only if the panels need to operate at their maximum power point. The power-voltage characteristic of a PV panel is nonlinear and depends on the incident sunlight irradiance and temperature of PV cells [3]. As solar radiation is not constant during the day, the output power of a photovoltaic panel will not be constant either. Moreover, the MPP may also trade with changes in sun radiation and atmospheric temperature. Hence, to extract maximum power at any irradiance and temperature, there is a need to maintain MPP. Keeping the operating point of a PV panel at MPP at any temperature and irradiance is called Maximum Power Point Tracking (MPPT). In the past years, many researchers have studied MPPT algorithms [4] [5]. Another major problem related to solar energy generation is the management of partial shade conditions (PSC) due to the passage of clouds. Under partial shading conditions, the PV panels are subjected to non-uniform irradiance and in this situation, the power-voltage characteristics exhibit multiple power peaks. The maximum of this power peak is called Global Power Peak (GPP). The power of a PV system under partial shade conditions will only be maximum when operating on GPP. Therefore, under partial shading conditions, the operating point should be maintained at GPP to extract maximum power from a partially shaded PV system. The output power of the PV systems is mainly dependent on their ambient temperature and operating irradiance. Different MPPT techniques have been proposed to find the location of the maximum power point [6]-[11].

2. PV MODELLING

The solar cell is the fundamental component of a solar module. The most common equivalent circuit of the solar cell is presented in Figure-1. The single diode model is the most widely used circuit-based PV model because of its simplicity and acceptable accuracy. It consists of shunt resistance (R_{sh}), a series resistance (R_{se}), and a linear independent current source in parallel to a diode. In the single diode model, simple and accurate techniques can be used to obtain the parameters of PV systems practically.

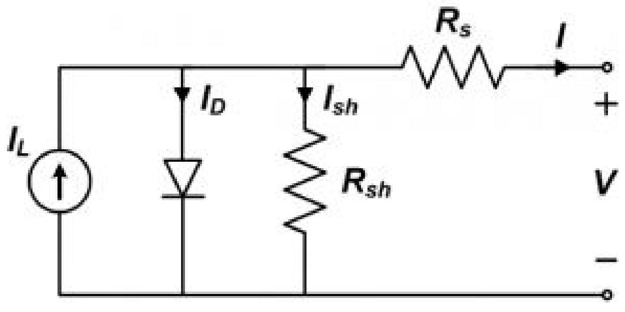

Figure-1. Single diode model.

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The PV array can be mathematically modelled using its functional equations. The mathematical model of the PV panel is attained from the equivalent circuit of a single diode solar cell. The mathematical model of the PV panel is developed from the expression for the output current from the PV module (I_{PV}) given by,

$$I_{pv} = N_p * I_{ph} - N_p * I_0 \left[\exp\left\{ \frac{q * \left(V_{pv} + I_{pv} R_s \right)}{N_s AKT} \right\} - 1 \right] \quad (1)$$

In this equation, Ipv is the photocurrent, Is is the reverse saturation current of the diode, q is the electron charge, V_{pv} is the voltage across the diode, K is the Boltzmann's constant, T is the junction temperature and Rs and Rsh are the series and shunt resistors of the cell.

3. I-V and P-V CHARACTERISTICS

The solar panel absorbs the sun's rays into the modules and converts them into electrical energy. Solar Panel Specifications. The parameters for the PV systems are listed below.

Table-1. Parameters for a single PV panel.

SOLAR PANAL SPECIFICATIONS	
Peak (Maximum) Power P_{max}	335Wp
The voltage at Maximum Power V_{mpp}	38.1
Current at Maximum Power I_{mpp}	8.8
Open circuit voltage V_{oc}	46.5
Short Circuit Current I_{sc}	9.35

Figure-2 and Figure-3 show the Characteristics of I-V and P-V for different solar irradiance and temperatures. The maximum power points are marked with red circles on the characteristics curve.

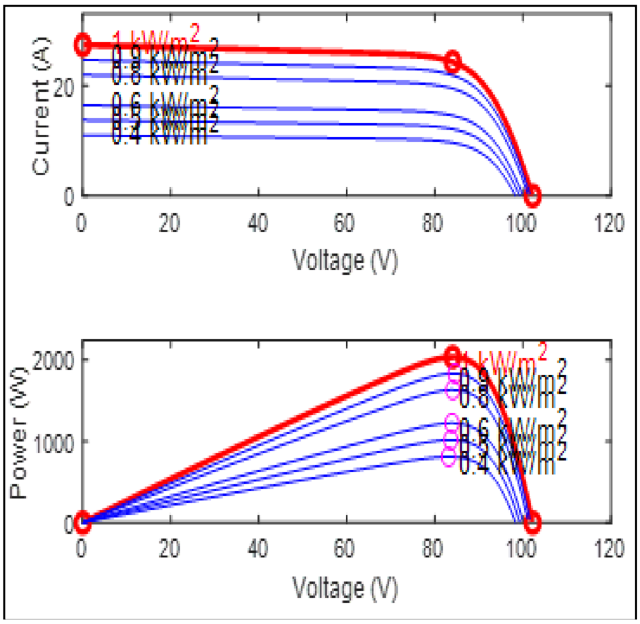

Figure-2. Power-voltage (P-V) characteristic of photovoltaic arrays with different solar irradiance levels at 25° C.

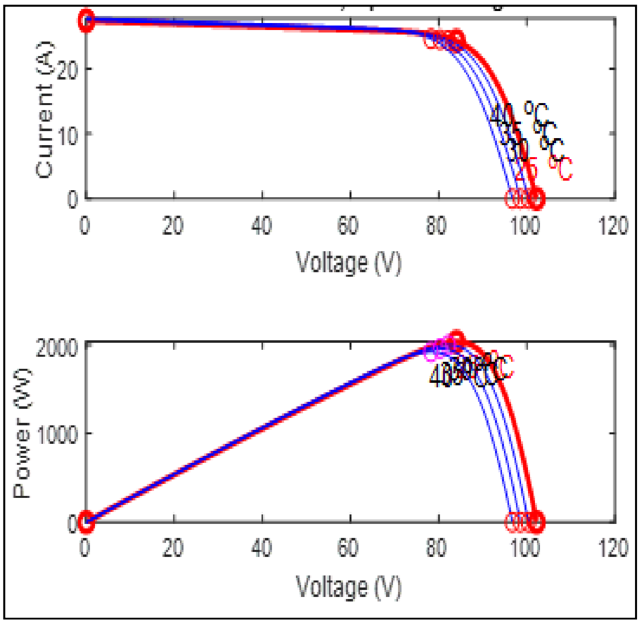

Figure-3. Power-voltage (P-V) characteristic of photovoltaic arrays with different ambient temperature at 1000 W/m^2.

From the characteristics of P-V and I-V, it is observed that multiple peaks occur under partially shaded conditions. The voltage and current of a PV panel change concerning the temperature and irradiance. From the equation, the increase in the temperature causes the decrease in open circuit voltage and it does not affect the short circuit current. The increase in irradiation causes to increase in the short-circuit current and it has a negligible effect on open-circuit voltage. From this characteristic, it

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is observed that power is a maximum only at a particular value called optimum voltage. Also, the power decreases when the voltage is higher or lower than the optimum value.

4. MPPT TRACKING CONTROLLER

The power structure supplies a DC load by the PV generation through a static converter driven by an MPPT controller shown in Fig.4. Consists of a PV array, MPPT controller, load, and a load interface which is provided by a DC-DC converter.

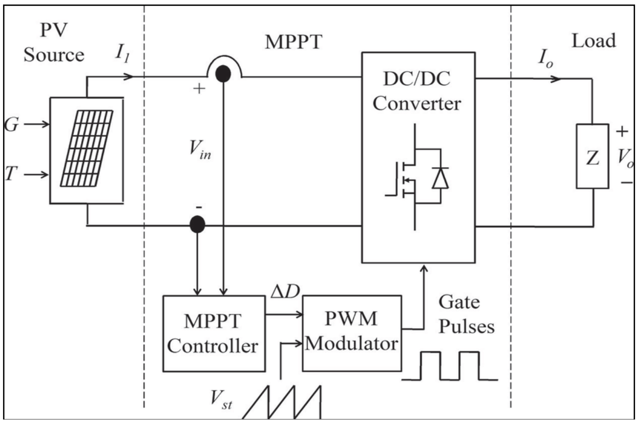

Figure-4. The schematic diagram of a typical PV system.

In this case, a CUK converter provides the control action to force the PV system to operate at the maximum power point. It can be used as a switching regulator. The regulation is achieved by pulse width modulation technique (PWM) at a fixed frequency.

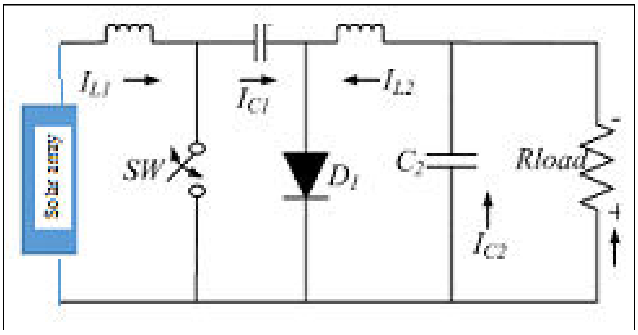

Figure-5. CUK Converter.

The MPPT algorithms can be used to find automatically the panel operating voltage that allows maximum power output. To regulate the voltage of PV arrays, a converter provides the main control variable by adjusting the duty cycle D. The duty cycle of the switching signal is influenced and controlled by a suitable control algorithm that competes for the optimum operating voltage and current required for operation at the maximum power point. The specification of the implemented CUK converter depicted in Figure-5 is shown in Table-2.

Table-2. Parameters of cuk converter.

Parameters	Values
Input voltage (V_{in})	(65-80)V
Output voltage (V_{out})	48V
L1(mH)	$0.8X10^{-3}$
L2(mH)	$0.7X10^{-3}$
C1(mF)	$6X10^{-6}$
C2(mF)	$900X10^{-6}$

5. SOLAR POWER GENERATION

A. Assessment of Simulation of PSC PV System Without MPPT Controller

This section analysis the behavior of the photovoltaic system without having an MPPT controller. For the implementation of the PV system, two panels are connected in series and three sets are connected in parallel. The PV arrays can be affected by partial shading caused by nearby objects. For this assessment, a PV array with three legs is considered. Each leg has two panels connected in series (6 modules in total) shown in Figure-6.

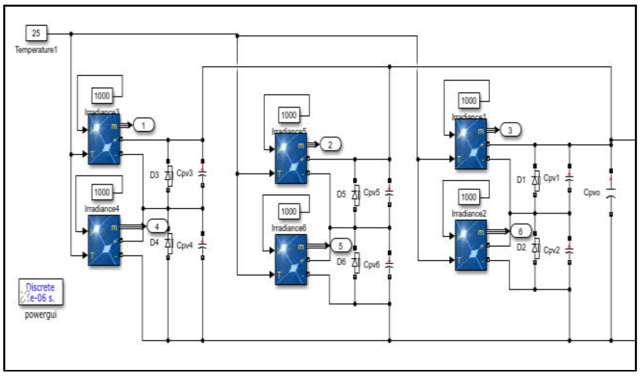

Figure-6. PV Panels connection diagram.

The power generated by the system is obtained when the irradiations of the panels are set at different values shown in Table-3.

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Table-3. Different cases of shading patterns.

CASE (W/m^2)	P1	P2	P3	P4	P5	P6	PV Power
1	1000	1000	1000	1000	1000	1000	1953
2	900	900	1000	1000	1000	800	1794
3	1000	900	800	700	1000	1000	1685

Three shading patterns were considered, and the shading patterns were created by varying the insulation level on each panel (Table-3).

B. Simulation of PV Power generation under Various Irradiation S Values

CASE1: GENERATED PV POWER:

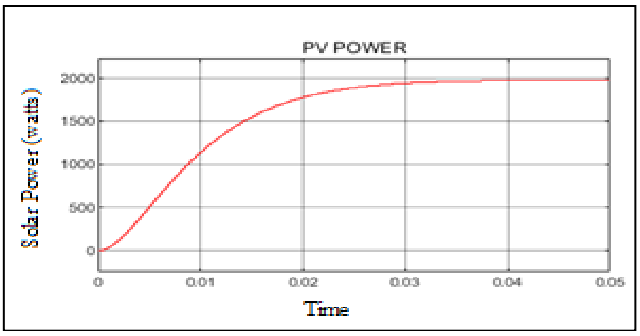

Figure-7. Generated PV Power for Constant Irradiation Level.

CASE 2: GENERATED PV POWER:

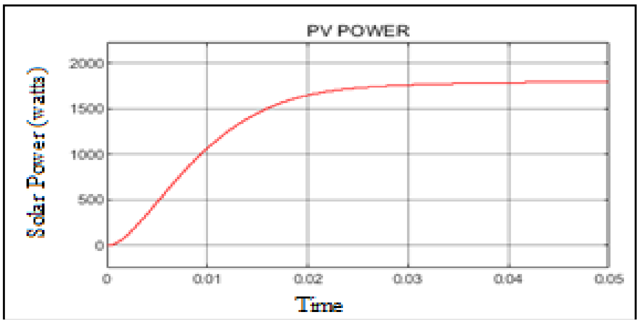

Figure-8. Generated PV Power for Different Irradiation Levels.

CASE 3: GENERATED PV POWER:

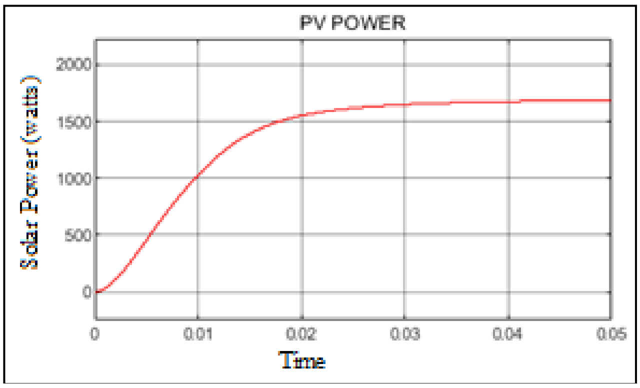

Figure-9. Generated PV power for different irradiation level.

CASE 4 - GENERATED PV POWER DYNAMIC IRRADIANCE

In this case, the irradiance level of Panel P1, P2, and P3 is varied with particular time intervals, the remaining panel maintains a constant irradiance value. According to the dynamic changes in irradiation level, the output waveforms of PV power are measured shown in Fig.10. From this figure the proposed PSO algorithm can successfully detect the shading pattern changes.

Panel 1(P1) - [0.8, 0.9, 0.6, 1, 0.5, 0.7] *1000
Panel 2(P2)- [0.9, 0.9, 0.8, 0.9, 1, 0.7] *1000TIME-[0, 0.2, 0.4, 0.6, 0.8, 1]
Panel 3(P3)- [0.8, 1, 0.6, 1, 0.9, 0.8] *1000
Panel 4(P4)- 1000
Panel 5(P5)- 1000 and Panel 6(P6)- 1000

CASE 4 - GENERATED PV POWER DYNAMIC IRRADIANCE

In this case, the irradiance level of Panel P1, P2, and P3 is varied with particular time intervals, the remaining panel maintains a constant irradiance value. According to the dynamic changes in irradiation level, the output waveforms of PV power are measured shown in Fig.10. From this figure the proposed PSO algorithm can successfully detect the shading pattern changes.

Panel 1(P1)- [0.8, 0.9, 0.6, 1, 0.5, 0.7] *1000
Panel 2(P2)- [0.9, 0.9, 0.8, 0.9, 1, 0.7] *1000TIME- [0, 0.2, 0.4, 0.6, 0.8, 1]
Panel 3(P3)- [0.8, 1, 0.6, 1, 0.9, 0.8] *1000
Panel 4(P4)- 1000
Panel 5(P5)- 1000 and Panel 6(P6)- 1000

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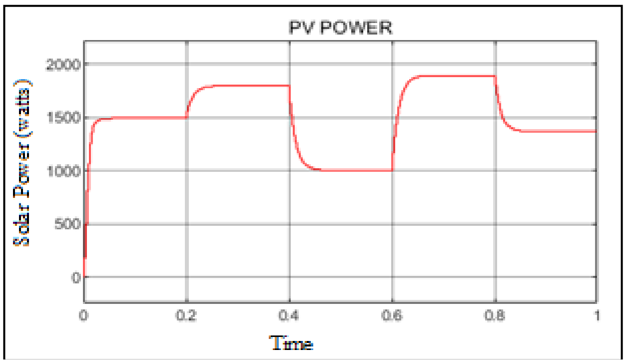

Figure-10. Measured waveforms of dynamic shading pattern.

6. MPPT TRACKING TECHNIQUES - TYPE P&O

A. MPPT Controller type P&O Algorithm

The different methods used for MPPT can be classified into a direct method and an indirect method and are more recent techniques used which are based on soft computing techniques. To maximize the power from the PV system, an MPP tracker is to ensure that the operating point of the system is adjusted to be located on MPP. When the radiation distribution over PV panels is uniform, many traditional MPPT techniques can effectively observe the MPP. When the PV modules in a system receive a non-uniform solar irradiation, the PV system is considered to operate under partial shade condition (PSC). However, when the PV arrays are partially shaded, more MPPs are exhibited [12].

To mitigate the effect of PSC on the PV arrays many evolutionary optimization algorithms have been proposed. Furthermore, it can be utilized to detect the GMPP of the PV panels where the conventional methods fail to converge. For instance, the genetic algorithm (GA), and artificial intelligence methods using fuzzy logic and neural networks have been applied to find the GMMP.

B. Implementation P&O MPPT Control Algorithm

Maximum Power Point (MPP) tracking is the automatic control algorithm to adjust the power interfaces and achieve the greatest possible power extraction, regardless of the changes in insolation and temperature or the effects of the shading.

There are different techniques used to track the maximum power point. Among these algorithms called "P & O" is an MPPT command whose operation is based on the disturbance of the voltage Vpv, by increasing or decreasing it by a small amplitude around its initial value. This disturbance has the effect of acting directly on the duty cycle of the signal controlling the DC-DC converter. The disturbance is followed by the observation of its impact on the power output of the PV panel, with a view to a possible correction of this duty cycle.

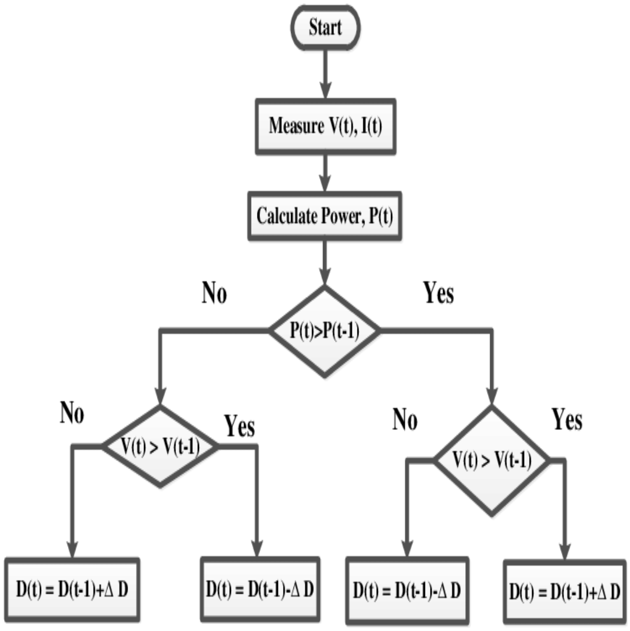

Figure-11. Flow chart for the P&O algorithm.

The "P & O" method is widely used today because of its simplicity of implementation. However, this method has some problems related to oscillations around the maximum power that it generates in a steady state. The search procedure of the Maximum PowerPoint must be repeated periodically, driving the system to oscillate permanently around the PowerPoint. These oscillations can be minimized by reducing the value of the disturbance variable. The Figure-11 shows the flow chart for the P&O algorithm.

Complete or partial shading can occur on the photovoltaic module under many conditions like dirt, dust, and shading due to nearby objects. Under such conditions, the output power of the PV module decreases significantly. The Simulation results of MPPT based on the P&O algorithm for the partially shaded conditions of different shading pattern is listed in the following Table-4.

Table-4. Tracked power under various irradiation s values for the P&O algorithm.

CASE (W/m^2)	P1	P2	P3	P4	P5	P6	PV Power
1	1000	1000	1000	1000	1000	1000	1955
2	900	900	1000	1000	1000	800	1828
3	1000	900	800	700	1000	1000	1741

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The above Table-4 shows the variation of output power for the PV systems concerning different irradiance levels. It can be observed that the power obtained is higher than that obtained at lower irradiations.

CASE 1: GENERATED PV POWER:

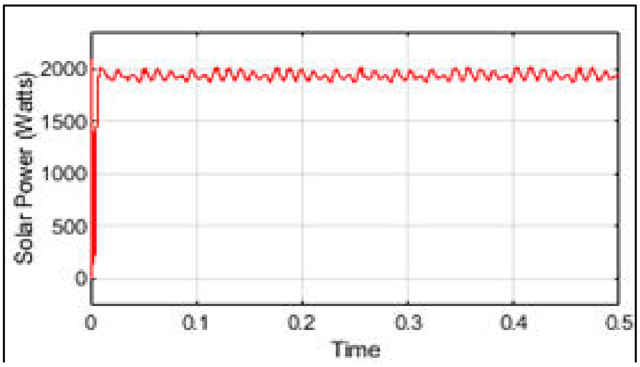

Figure-12. Generated PV power for Constant Irradiance Level.

CASE 2: GENERATED PV POWER:

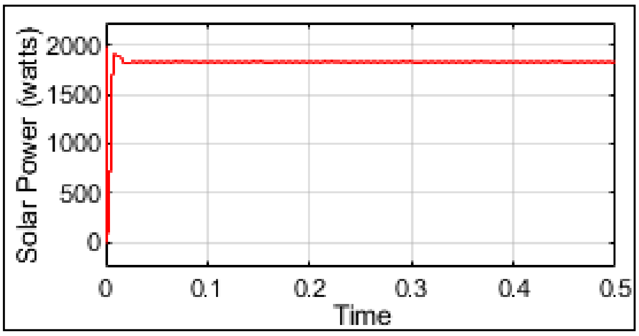

Figure-13. Generated PV power for Different Irradiance Level.

CASE 3: GENERATED PV POWER:

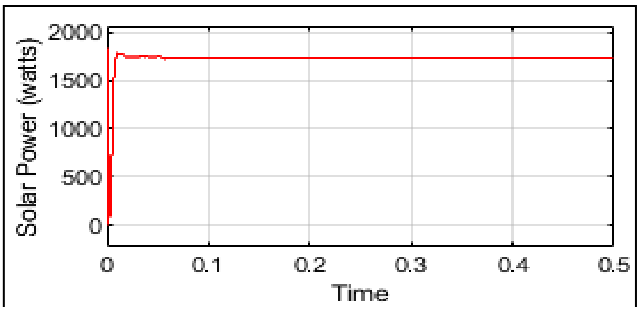

Figure-14. Generated PV power for Different Irradiance Level.

7. MPPT TRACKING TECHNIQUES – TYPE PSO

A. MPPT Controller Type PSO Algorithm

Particle Swarm Optimization (PSO) is one of the swarm intelligence techniques that uses stochastic variables based on population for solving optimization problems. This technique was first introduced by Eberhart and Kennedy (1995). The study of the use of PSO in the MPPT of photovoltaic systems was carried out by Miyatake *et al.* in 2004. in 2004. There are several methods are available for MPP tracking to increase the production of photovoltaic systems. Depending upon the implementation, required accuracy, and application a specific algorithm can be used. PSO is a population-based stochastic optimization method. It is modeled according to the social behaviour of bird flocking or fish schooling. It has fast convergence and is accurate in tracking MPP when the PV array has a single power peak. However, if some part of the PV array is shaded, the PV array exhibits multiple power peaks in power-voltage characteristics. The new velocity equation for PSO is given by,

$$V_i^{t+1} = w^t . V_i^t + C_1 R_1 \left(P_i^t - S_i^t\right) + C_2 R_2 \left(G_i^t - G_i^t\right) \quad (2)$$

$$S_i^{t+1} = S_i^t + V_i^{t+1} \quad (3)$$

Where W can be expressed by the inertia weights and often decreases from W_{max} to W_{min}. In general, to achieve high convergence speed of PSO the value of inertia weight W is set according to the following equation.

$$W^t = W_{max} - \left[\frac{\left(W_{max} - W_{min}\right)}{Iter_{max}}\right].iter \quad (4)$$

Where *intermix* represents the maximum number of iterations, and *iter* is the number of current iterations or generations. Also, *c*1 and *c*2 are the acceleration constants that influence the convergence speed of each particle, and *r*1 and *r*2 are random numbers in the range of (0, 1), respectively.

The position of each particle is updated with each generation. When a particle determines a value that is better than any that it has found earlier, it will track the better position by updating Equations 2 and 3. Under this shading condition, inertia weights (w) in PSO must be readjusted accordingly. The movement of particles depends on two variables, namely, Particle best (Pbest) and Global Best (Gbest). The Pbest is used to store the best position of each particle as an individual best position and the Gbest is used to store the best position among all the particles. The particle swarm uses this process to move to the best position and continually review its direction and velocity, in this way, each particle quickly converges to an optimal or close to a global optimum.

B. Steps for Type PSO Algorithm

The steps for the general algorithm used for PSO are as follows:

Step 1: Start the process.
Step 2: Generate the initial population randomly by using random initialization of variables. Set the population, iterations, etc.
Step 3: Evaluate the fitness value of every particle.
Step 4: Determine the best positions of the particle and also the global best.
Step 5: Update the velocity and position of each particle according to the above-given equation.
Step 6: Continue until maximum iterations or convergence conditions.
Step 7: The result obtained in this step is the optimum solution.

C. Application of PSO Algorithm in MPPT

To realize the MPPT algorithm for the photovoltaic system under PSC, the particle swarm optimization algorithm is applied. The presented system consists of a series and parallel connected PV module, a dc–dc converter, and a digital controller in which the proposed MPPT algorithm is implemented. The step procedure for the proposed PSO-based MPPT technique is as follows:

a) **Selection of parameters**: In the proposed system, the position of the particles is defined as the value of the duty cycle d of the dc-dc converter.

b) **PSO Initialization:** The location of the GMPP in the search space that initializes the particle around it. Here Wmax and Wmin are the maximum and minimum duty cycles of the utilized DC-DC converter respectively.

c) **Fitness evaluation:** The goal of the proposed MPPT algorithm is to maximize the power generated. The photovoltaic voltage and current can be measured based on the position of the particle i. These values can be used to calculate the fitness value, here the maximum generated power.

d) **Update individual and global best data:** If the fitness value of particle i is better than the best fitness value in P_{best},i, set the current value as the new P_{best},i.

e) **Update velocity and position of each particle:** After all the particles are evaluated, the velocity and position of each particle in the swarm should be updated.

f) **Convergence and re-initialization:** If the maximum number of iterations is reached, the proposed MPPT algorithm will stop and return the best solution obtained. Re-initialize the PSO algorithm if the constraint is not met.

D. Circuit Simulation

To determine the robustness and effectiveness of the proposed MPPT algorithm, the significant Matlab/Simulink tool is used. The modelling of the PV system with an MPPT algorithm and converter was done in Matlab. The solar PV system is simulated such that the PV module charges the battery through the controller and the battery also delivers the power to the load when the solar radiation is insufficient. To determine the robustness and effectiveness of the proposed MPPT algorithm, the significant Matlab/Simulink tool is used. The modelling of the PV system with an MPPT algorithm and converter was done in Matlab. To verify the correctness of the proposed MPPT method, a 2000-W prototyping circuit is implemented from which simulations and experiments are carried out accordingly. The parameter settings of the implemented PSO-based MPPT algorithm are listed in Table-5. The effect of PSC on the PV module characteristic curve is simulated by randomly setting the insolation values.

Table-5. Parameter settings of the implemented PSO algorithm.

Number of Generation	6
Population size	10
Variation of duty cycle	0.3 to 0.8
C1=C2	1.5

Matlab/Simulink is one of the significant tools that are used to determine the performance (robustness and effectiveness) of the recommended MPPT algorithm. The modelling of the PV system with a DC-DC power converter and MPPT algorithms was done in Matlab, which is shown in Figure-15.

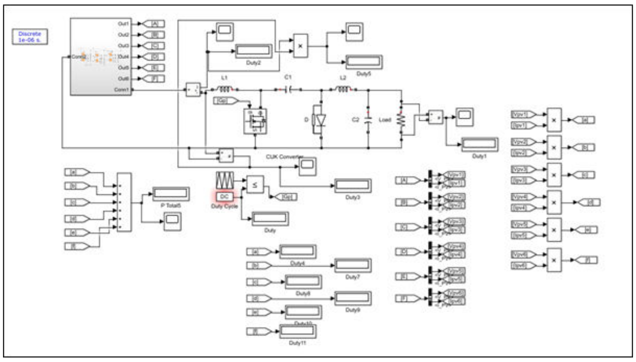

Figure-15. Matlab/ Simulink for a PSC PV system with a CUK converter.

E. Assessment of Simulation of PSC PV System with PSO MPPT Controller

All PV modules were exposed under full radiation for Case 1; hence, there was only one MPP generated at 1956W, while another three cases of PV modules were exposed under the PSC for Cases 2 and 3.

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The PV arrays were partially shaded by three different solar irradiance values, where the global MPP for cases 2 and 3 are (1838W and 1754 Watts respectively).

Table-6. Application of PSO in MPPT under partial shading patterns.

CASE	P1	P2	P3	P4	P5	P6	PV Power
1	1000	1000	1000	1000	1000	1000	1956
2	900	900	1000	1000	1000	800	1838
3	1000	900	800	700	1000	1000	1754

In case 1, the PV system is exposed to the same levels of irradiation and under uniform radiation conditions (1000 W/m^2) and one constant temperature (25 °C) as presented in Figure-16.

CASE 1: GENERATED PV POWER:

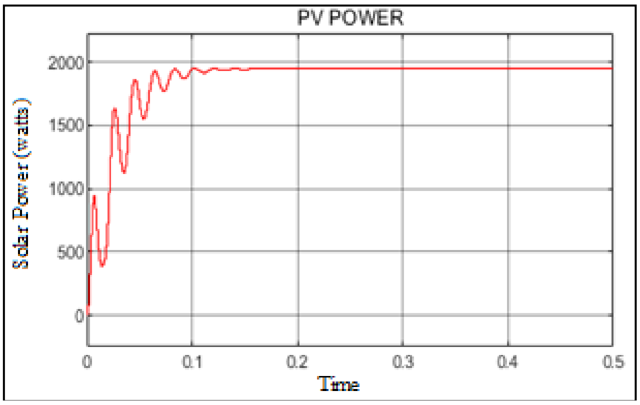

Figure-16. Generated PV power for constant irradiation level.

CASE 2: GENERATED PV POWER

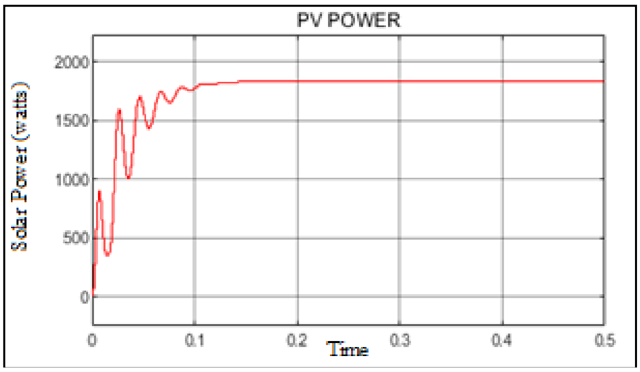

Figure-17. Generated PV power for different irradiation level.

CASE 3: GENERATED PV POWER

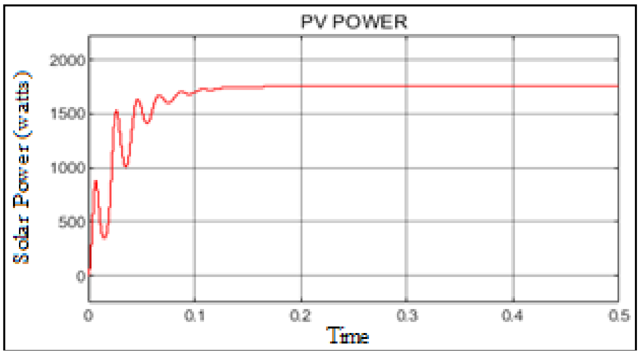

Figure-18. Generated PV power for different irradiation level.

F. Simulation Result Analysis

The simulation results of MPPT based on the PSO algorithm for the partially shaded conditions of different shading pattern is listed in Table-6. In case 1, all the panels are having a constant maximum irradiance (1000 W/m^2). Hence the solar panel will deliver maximum power. When the solar PV panel is not connected to the MPPT controller, at that time it has to produce a power of 1953W. But in the shading pattern is changed from case 1 to case 2 and 3 the irradiance level is changed. Then the corresponding power production was also reduced to 1794W and 1685W.

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Table-7. Comparison of controller without, with P&O, and with PSO MPPT controller.

CASE (Irradiance Level W/m^2	PV Power - Without MPPT Controller	PV Power - P&O MPPT Controller	PV Power - PSO MPPT Controller
1	1953	1955	1956
2	1794	1828	1838
3	1685	1741	1754

The same shading pattern is applied to the PV system when it is connected to a Perturb and Observation (P&O), PSO-based MPPT controller. From Table-7, when the PSO algorithm is implemented to track the maximum power, the power delivered from the PV system is considerably increased. In the first case, all the modules have a uniform solar irradiance level. At this time the PV system generates a power of 1956 watts which is higher than without PSO and P&O algorithm. When the irradiance level is decreased in cases 2 and 3, the power generation by the solar panel based on the P&O method will also decrease having a value of 1828W and 1741 Watts.

When the irradiance level is decreased in cases 2 and 3 for a PSO-based MPPT controller, the power generation by the solar panel will also be decreased having a value of 1838W and 1754 Watts. From Figure-17 and Figure-18, it can also be observed that as the value of irradiance changed, the solar panel output power also changed. The simulation is performed with PSO algorithms using a CUK converter.

The DC load is employed with a DC-DC converter with a single power switch. The duty cycle of the gate triggering pulse to the power switch decides the power drawn from the partially shaded solar panel. Therefore, the duty cycle is determined for GMPP using the Particle Swarm Optimization algorithm which can track the GMPP fast concerning changing irradiances. The power transferred to the load under different shading patterns is analyzed.

8. RESULTS AND DISCUSSIONS OF SIMULATION

The variations of output power with different irradiance levels are shown in the various graphs for P&O and PSO-based MPPT controllers. Thus, a direct effect on the output power concerning change in irradiance can be observed. It is observed from the graph that the variations are non-linear and are rather exponential. The simulation results showed that the PSO algorithm can promise a good performance compared to the classical P&O control when the shading pattern is applied.

9. EXPERIMENTAL IMPLEMENTATION OF PSO BASED MPPT

For experimental implementation, we use six panels. These panels are connected in series and parallel. The solar panels are mounted on the ground surface. The PV experimental platform for the proposed system is shown in Figure-19.

Figure-19. Experimental setup for 2KW solar PV system.

10. EXPERIMENTAL RESULTS

Photovoltaic systems are highly susceptible to partial shading. The maximum power generation of a photovoltaic system can be reduced when partial shading takes place. The susceptibility of partial shading can vary based on the partial shading patterns. The solar PV power generation on 09.06.2022 in unshaded conditions is tabulated. Also, the PV power generation on different shading patterns is analyzed and readings are tabulated. With the implementation of the PSO algorithm, the tracking of maximum power is possible even during the different partial shading conditions shown in Table-4 (Appendix). The developed MPPT controller is connected between the panel and load concerning their polarities and the output power is observed. Experimental results show that the proposed MPPT technique can track the maximum power which is close (reaching) to power generated during the unshaded conditions.

In partially shaded conditions, the power generated in the proposed PV system should be close to the power generation when all the PV arrays are in unshaded conditions. The voltage and current of a PV panel change concerning the temperature and irradiance.

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During partial shading or reduced irradiance, the value of solar-generated power is varied. The proposed PSO-based MPPT controller which is implemented here can track the maximum power generation even in partial shading conditions. From these experimental results, the proposed method can successfully deal with PSC and can track the actual maximum power regardless of the shading conditions. For all considered shading cases, it was observed that the proposed method can easily track the maximum power.

A. Generation of Solar Power During Maximum Load on 09.06.2022

Tests on solar panel systems are carried out to analyze the power generation of solar panels during the temperature changes per time. The developed MPPT charge controller is connected between the PV module and load. The variable resistive load is directly connected to the output terminal of the charge controller. The connected load to the solar system is 1500 watts and then the PV power generation is observed. The solar power generation of the proposed MPPT controllers at different temperatures for this connected load can be measured from 10.00 AM to 13:30 PM at 30-minute intervals as listed in Table-1 (Appendix).

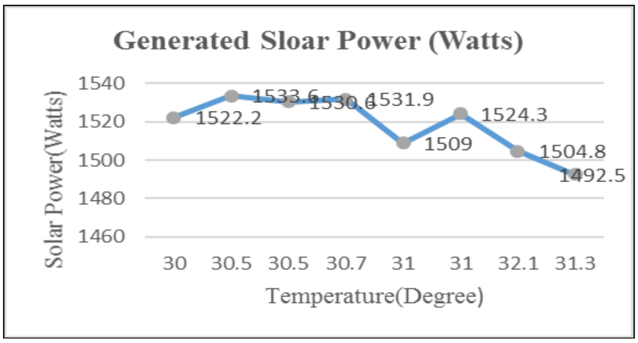

Figure-20. Generated solar power (Table 1-Appendix).

It can also be observed from Fig.20 that as the value of temperature changes, the solar panel output power also Changes. The I-V characteristics of solar power generation in Table-1 (appendix) are shown in Figure-21.

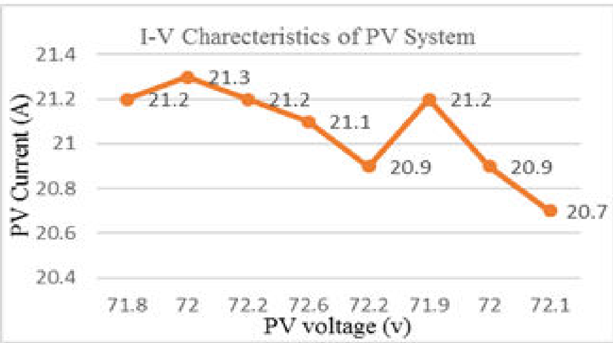

Figure-21. I-V characteristics of the solar power generation (Table 1-Appendix).

The P-V characteristics of solar power generation in Table-1 (appendix) are shown in Figure-22.

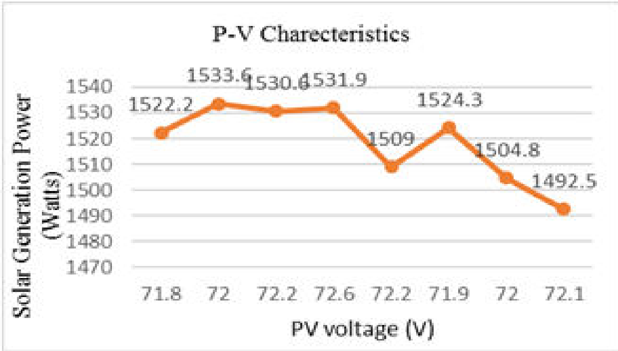

Figure-22. P-V characteristics of the solar power generation (Table 1- Appendix).

B. Solar PV Power Generation in Different Shading Patterns

A hardware implementation of the proposed PV system was built to verify the hardware results. Experimental validation was conducted of all the cases for partial shading. Shading was conducted by hiding the panels from insolation using opaque sheets. The percentage of shading by opaque sheets was converted into respective insolation levels in W/m^2.

At the initial phase of the implementation, the PV panels were unshaded and the produced average power was nearly 821 watts. Several experimental measurements have been done to study the impact of partial shading on the PV system. The experiment was conducted at 11.00 AM dated 16.02.2022. Here the temperature is measured at 30^{0}C but, the irradiation level is changed according to the environmental conditions for the unshaded conditions. Table 2 (Appendix) gives the photo voltaic systems voltage, current, and solar-generated power when dynamic variations happen in temperature and irradiations. The average power developed when the single panel is covered with 50% is 810.63 watts. Similarly, the average power developed when the two panels are covered with 50% and fully covered is 817.43 watts and 760.49 watts. Comparing the power output for both shaded and different unshaded conditions, the proposed PSO-based controller will extract the power in shaded conditions close to the value of power generation in unshaded conditions.

C. Experimental Comparison of PSO and Conventional MPPT Charge Controller

The newly designed PSO algorithm-based MPPT controller is compared with the existing conventional controller with a rating of 48V systems. There are 6 numbers of modules used in a similar configuration setup. The experimental testing was performed for the conventional charge controller and the proposed MPPT charge controller which has the same specifications. To check the behavior of both the controllers at dynamic conditions the results of solar PV output power for both

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systems were noted from 10.30 AM to 13:30 PM at 30-minute intervals. Table-3 (Appendix) shows the solar power generation of the existing available and proposed 2 kW solar PV system.

To assess the effectiveness of the proposed PSO based MPPT method and test its performance, the proposed system is compared with existing same rating system. For testing the existing and proposed system simultaneously a minimum load of 1000 watts is connected to both the systems. The temperature is varied and generated power, voltage and current are measured with respect to time for both existing MPPT controller and also proposed PSO MPPT controller. The proposed scheme and as existing method were assessed and the total power extracted with both methods are shown in Table 3 (Appendix). It can be seen that as the temperature is varied and hence there is a change in generated solar power. Based on the results, the proposed approach is effective to produce the more power as compared to the existing MPPT controller system.

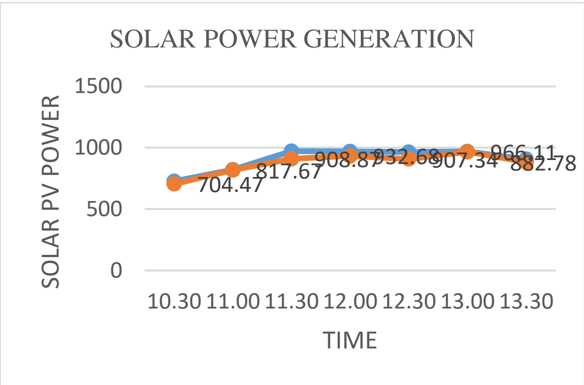

Figure-23. Comparative analysis of PV Power Generation of proposed and conventional method

At time 11.30AM, the power delivered by the existing system is 908.87 Watts and also in proposed system is 971.96 Watts. The difference of power generation between the two system is 63 Watts. Similarly, at 12.30 PM, the difference of power generation between the two system is 56 Watts. The average power developed by the existing controller and proposed charge controller is **874.27 Watts** and **903.48 Watts** respectively. The maximum power developed by the existing controller and proposed charge controller is **966.11 Watts** and **971.96Watts** respectively. By calculating the efficiency of the proposed and existing MPPT solar PV system, the efficiency of proposed system is 92.7% and existing system is 90.47%.

D. Solar Power Generation at Different Shading Patterns at Maximum Load

The solar systems are tested and evaluated under two types of partial shading patterns. The experiment considers a partial shading conditions including Unshaded conditions, Single panel is 50% shaded, two panels are 50% shaded. Table 4 (Appendix) are tabulated based on the data on the P-V characteristics of Fig.24 which show the maximum power and maximum power delivery voltage of all the experimental set ups under the applied conditions.

Figure-24. Single PV panel partially shaded

E. Experimental Result Analysis

The proposed MPPT method is tested and assessed in three conditions. In the first case when solar PV system with MPPT controller is connected to an average maximum load of 1600 watts under real conditions of both unshaded and partial shading conditions. And also the power generation of PSO based MPPT controller system is compared with another existing system with the same rating of system. For comparing these two systems a minimum average load of 1000 watts is applied and hence tested and assessed using real conditions of temperature.

Experimental result data of PSO – MPPT based Solar PV generation with Maximum load applied on 09.06.2022:

Max.Power	-1533.6W
Avg.Power	-1518.6Watts
Power generation in Partial Shaded Conditions:	
Unshaded Conditions	-1527.9W
Single Panel with 50% Shaded	-1511.9W
Two Panels with 50% Shaded	-1497.4W
Maximum power developed by,	
Existing controller	-966.11Watts.
PSO charge controller	-971.96Watts.

In this work it is observed that the implementation of PSO based MPPT controller has considerably improved the tracking of Maximum Power in Partial Shaded Conditions with a power generation of 1511.9W compared to the normal working conditions with 1527.9Watts. When the two PV systems are compared, the PSO controller system produces the power of 971.96 wat

11. RESULTS AND DISCUSSIONS OF IMPLEMENTED PV SYSTEM WITH PSO MPPT

The importance of MPPT methods is that they are primarily used in practice to obtain the maximum power of PV systems and to provide this power to the consumer load. When the PV system is influenced by uniform solar irradiation, the characteristic of the system will be nonlinear with only one MPP, which can be easily obtained using a simple control technique, such as perturb and observe, modified perturb and observe, and incremental conductance (INC). Conversely, in the case of non-uniform solar irradiation conditions, the characteristic curve of the PV system will have multiple MPPs. In this situation, the PSO metaheuristic based MPPT algorithm can be implemented to extract the maximum power. The implementation of the particle swarm optimization based MPPT controller is validated through a 2 kW solar system to extract maximum power. The experimental results are carried out for both unshaded and different shading conditions and are tabulated. The measurement of power generation at unshaded conditions on 09.06.2022 is tabulated and analysed. The average and maximum power generated in the implemented PV systems is 1518.6 Watts and 1533.6 Watts respectively.

In partially shaded conditions, the power generated in the proposed PV system should be reached close to the power generation when all the PV arrays are in unshaded conditions. The PV power generation of three different shading patterns is considered for analysis. Experimental results show that the proposed MPPT technique can track the maximum power which is close (reaching) to power generated during the unshaded conditions. The PSO based MPPT controller is implemented here for tracking the power generation even in partial shading conditions. The implementation of the PSO scheme has considerably improved the tracking performance in terms of extracting the maximum power generation.

When compared to the conventional charge controller, the developed MPPT charge controller significantly improves the solar power generation for each test time. The average power developed by the existing controller and proposed charge controller is 874.27 Watts and 903.48Watts respectively. The maximum power developed by the existing controller and proposed charge controller is 966.11 Watts and 971.96Watts respectively.

12. CONCLUSIONS

In this work we have studied the performance of the photovoltaic solar system with PSO based MPPT controller under partial shading. The PV system simulation was made for a non-uniform irradiance in order to make a comparison between the MPPT control based on the P&O algorithm and the PSO MPPT control and to determine the best control in terms of performance and robustness. According to the simulation results, the PSO is also an intelligent technique that has been employed to find the MPP in all conditions.

The proposed work is implemented with 2KW PV system and also compared with existing same rating system in terms of power extraction. This result shows that the proposed PSO based MPPT technique enhanced the average power generation from 874.27 Watts to 903.48Watts. The average and maximum power generated in the implemented PV systems is 1518.6 Watts and 1533.6 Watts respectively

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APPENDIX

EXPERIMENTAL RESULTS

1. Unshaded Conditions

Table 1. Experimental data of PSO – MPPT based solar PV generation with maximum load applied on 09.06.2022

S. No	Time	Temperature (Celsius)	PV Voltage (Volts)	PV Current (Amps)	Solar PV Generated Power (Watts)	Load Voltage (Volts)	Load Current (Amps)	Load Power (Watts)
1	10.00	30.0	71.8	21.2	1522.2	54.3	22.6	1227.2
2	10.30	30.5	72.0	21.3	1533.6	54.1	22.8	1233.5
3	11.00	30.5	72.2	21.2	1530.6	54.3	23.2	1259.8
4	11.30	30.7	72.6	21.1	1531.9	54.2	23.5	1273.7
5	12.00	31.0	72.2	20.9	1509.0	54.0	24.1	1301.4
6	12.30	31.0	71.9	21.2	1524.3	54.3	24.5	1330.4

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7	13.00	32.1	72.0	20.9	1504.8	54.6	23.8	1299.5
8	13.30	31.3	72.1	20.7	1492.5	53.8	24.0	1291.2

2. Shaded Conditions

Table-2. PV Power generation in different shading patterns for the proposed PSO MPPT system on 16.02.2022.

Case	Shading Pattern	Time	Temperature (Celsius)	Irradiance (w/m^2)	PV Voltage (Volts)	PV Current (Amps)	Solar PV Generated Power (Watts)
1	Unshaded conditions	11.00	30	863	57.48	13.79	792.64
		11.15	30	810	57.90	14.67	849.39
2	Single panel is 50% shaded	11.30	30	874	56.10	13.92	780.91
		11.45	31	833	56.40	14.90	840.36
3	Two panels are 50% shaded	12.00	31	890	55.23	14.92	824.03
		12.15	31	923	54.86	14.78	810.83
4	Two panels are fully shaded	12.30	31	885	53.43	14.21	759.24
		12.45	32	904	53.12	14.34	761.74
5	Three panels are 50% shaded	13.00	32	873	51.9	8.5	441.15
6	Three panels are fully shaded	13.15	33	863	51.0	5.9	300.9
7	Six panels are 50% shaded	13.30	33	895	51.0	5.7	290.7

3. Experimental Comparison of the PSO and Conventional MPPT Charge Controller

Table-3. Experimental data of the PSO- MPPT and existing MPPT based solar power generation on 19.05.2022.

S. No	Time	Temperature (Celsius)	EXISTING MPPT CONTROLLER			PSO MPPT CONTROLLER (PROPOSED)		
			PV Voltage (Volts)	PV Current (Amps)	Solar PV Generated Power (Watts)	PV Voltage (Volts)	PV Current (Amps)	Solar PV Generated Power (Watts)
1	10.30	33	54.61	12.90	704.47	55.73	13.04	726.56
2	11.00	34	59.05	13.85	817.67	59.23	13.84	820.00
3	11.30	35	60.27	15.08	908.87	60.51	16.06	971.96
4	12.00	35	60.95	15.30	932.68	61.35	15.79	968.73
5	12.30	34	62.36	14.55	907.34	62.40	15.44	963.30
6	13.00	33	64.63	14.95	966.11	64.89	14.93	968.98
7	13.30	30	67.75	13.03	882.78	68.97	13.12	904.88

4. Shaded Conditions

Table-4. PV Power generation in different shading patterns for the proposed PSO MPPT system with maximum load.

Case	Shading Pattern	Time	Temperature (Celsius)	PV Voltage (volts)	PV Current (amps)	Solar PV Generated Power (watts)	Average PV Power Generated (watts)
1	Unshaded conditions	10.00	30.2	71.8	21.2	1522.2	1527.9
		10.30	30.5	72.0	21.3	1533.6	
2	Single panel is 50% shaded	11.15	30.5	70.6	21.5	1517.90	1511.9
		11.45	30.6	70.7	21.3	1505.91	
3	Two panels are 50% shaded	12.15	31.0	69.8	21.4	1493.72	1497.46
		12.45	31.2	69.5	21.6	1501.20	

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