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HARDWARE DESIGN FOR MAXIMUM POWER POINT TRACKING (MPPT) BASED ON METAHEURISTIC ALGORITHM IN PHOTOVOLTAIC (PV) SYSTEMS

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PSO and ABC algorithms with Arduino microcontrollers are focused on developing efficient solutions for control systems, energy optimization, and signal processing. These algorithms are generally for platforms with large resources, making them difficult to implement directly on Arduino. Adjustments are needed so that the algorithm can work efficiently without sacrificing the quality of the results. Both are implemented for partially shaded conditions in photovoltaic (PV) systems. The MPPT hardware development method with this meta algorithm can be a solution in dealing with the constraints of partially shaded disturbances. Meanwhile, other studies of the two concepts of the PSO and ABC algorithms have also been developed through software simulations for both MPPT applications and other fields. Evaluation criteria and methods for optimizing MPPT performance have been proposed by implementing a DC-DC Boost Converter. Testing was conducted with a PV with of 47.6 V and Isc of 11.6 A under two conditions to assess the performance of the PSO and ABC. The test resulted in the average power generated by the system with PSO algorithm on three unshaded PV with irradiation of 801 W/m² and a temperature of 84.5 °C with load variations of 50 Ω, 100 Ω, 200 Ω, and 400 Ω was 49.06 W, while the irradiation on one shaded PV at 198 W/m² resulted in an average power of 46.13 W. The system using the ABC algorithm on three unshaded PV generated an average power of 48.35 W, and with irradiation on one shaded solar panel at 198 W/m², it generated an average power of 45.03 W. Overall, the study demonstrates that both PSO and ABC algorithms effectively improve power generation in partially shaded conditions, with PSO showing better performance. These findings suggest that implementing these algorithms can enhance the efficiency of PV systems in practical applications

Keywords: algorithm, partial shading, particle swarm optimization, artificial bee colony, MPPT

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1. Introduction

The rapid development of technology and economy has caused an increase in carbon emissions and the use of fossil fuels. Concerns about both of these things are felt globally, including in Indonesia [1]. To address these challenges, 195 countries through the Paris Agreement in the United Nations Framework Convention on Climate Change (UNFCC) in 2015 [2]. Indonesia is one of the countries crossed by the equator. This causes most areas in Indonesia to receive abundant exposure to sunlight because it is available throughout the year. As a result, solar energy is one of the best potentials in terms of utilizing new renewable energy sources [3, 4]. In 2019, Indonesia had a solar energy potential worth more than 200 GW with the efficiency of available photovoltaic (PV) technology [5].

The Indonesian government expects the process of transforming fossil energy into renewable energy by accelerating the end of the operational period of fossil fuel-based power plants with the utilization of new renewable energy through PV systems [6]. The process of harvesting electrical energy through the PV system is not without obstacles. One of the factors that can affect the efficiency of the output power of a PV system is fluctuating weather conditions. The output power of a PV system is greatly impaired by the partial shading conditions (PSC) [7]. The impact of PSC can also cause a decrease in the current and voltage values of solar panels [8]. The difference in voltage in the system due to PSC causes many peaks to appear on the PV system P-V curve, creating obstacles in terms of peak tracking [9]. This phenomenon can be overcome by implementing a Maximum Power Point Tracking (MPPT) in the PV systems [10]. MPPT is a control system with an algorithm application that can track the maximum power point of a PV under PSC [11]. The MPPT system uses artificial intelligence-based methods, such as Particle Swarm Optimization (PSO) and Artificial Bee Colony (ABC) which have been proven effective in optimizing PLTS performance [12].

The use of Particle Swarm Optimization (PSO) and Artificial Bee Colony (ABC) algorithms in MPPT is still very relevant in modern conditions, especially to handle challenges such as partial shading, dynamic conditions, and multi-input systems. With the support of increasingly sophisticated hardware and innovation in algorithm variants, PSO and ABC remain effective and competitive choices for maximum power optimization in renewable energy systems.

2. Literature review and problem statement

This paper [13] provides a comprehensive review of maximum power point tracking (MPPT) techniques applied to photovoltaic (PV) power systems. MPPT is an essential part of PV systems, extensive research has been revealed in recent years in this field and many new techniques have been reported. Confusion arises while selecting MPPT as each technique has its own advantages and disadvantages. Hence, a detailed description and then classification of MPPT techniques has been made based on features such as number of control variables involved, type of control strategy used, type of circuit used appropriately for PV systems and practical/commercial applications. In order to further improve the control accuracy and adaptability of MPPT in complex environments, related scholars have proposed several new MPPT algorithms, such as fuzzy algorithm and neural network algorithm based on the principle of intelligence, particle swarm optimization algorithm based on the principle of optimization, gray wolf algorithm, and hybrid optimization algorithm based on multiple algorithms [14]. This paper provides a comprehensive overview of the topology, hardware architecture, mathematical models, and some DC-DC circuits of the maximum power tracking PV system; and reviews and summarizes the classical, intelligent, optimization, and hybrid types of maximum power point tracking methods, respectively explaining the principles, advantages, disadvantages, and applications of various methods. MPPT is a system control part that is generally embedded in a microcontroller. The microcontroller produces a signal output in the form of pulse width modulation (PWM). The PWM signal is used to trigger the MOSFET in the converter circuit.

This paper [15] presents research results highlighting the robustness of GWO-optimized PSO MPPT algorithm under various conditions, emphasizing its potential for PV technology by optimizing the MPPT controller. Simulation results show the progress of Grey Wolf Optimizer (GWO)-optimized PSO algorithm in improving MPPT performance. GWO-optimized PSO algorithm in scenario 1 shows a generation increase of 19.8 % higher than PSO MPPT. This research focuses on improving the operation of power converters affected by environmental and load conditions by applying meta-optimization which is increasingly being considered in current research.

The main disadvantage of photovoltaic (PV) systems is the mismatch between load and generation profiles. This paper [16] proposes a segmented structure of electrical thermal loads with a control algorithm that can achieve the MPPT goal without requiring an inverter. The results show that accurate MPPT is achieved according to the number of load segments. To improve the accuracy, the number of load segments should be increased. This shows the role of MPPT algorithms for photovoltaic systems.

In addition to the use of modeling and MPPT algorithms above that have been simulated. Several other control modeling and MPPT algorithms have also been researched in the form of software simulations. This provides motivation and stimulation to apply in the form of hardware, so that it can see its performance and capabilities in real terms. This paper [17] proposes a modified coot optimization algorithm (MCOA) to address this problem for tracking the global maximum power point (GMPP) under varying weather conditions. Experimental validation has been carried out to test the efficacy of the proposed approach under variable shading conditions, using a SEPIC converter and a sampling time of 0.1 s. Based on the experimental results obtained, the proposed MCOA has achieved the best performance with an average tracking time of 1.3 s under all weather conditions and an efficiency of 99.87 %.

Still related to MPPT, an efficient approach involves combining PV cells with thermoelectric generators (TEGs) to form a hybrid PV-TEG system. Simultaneously improving the energy conversion efficiency of the PV system by reducing the operating temperature of the PV modules and increasing the output power by utilizing the waste heat generated from the PV system to generate electricity through the TEG. Based on a thorough examination of the literature, this study comprehensively reviews 14 maximum power point tracking (MPPT) algorithms currently applied to hybrid PV-TEG systems and classifies them into five main categories for further discussion, namely conventional, mathematical, metaheuristic, artificial intelligence, and other algorithms. This review aims to inspire further ideas and research on MPPT algorithms for hybrid PV-TEG systems [18].

The use of MPPT techniques is the main focus. This paper discusses two MPPT techniques: perturb and observe (P&) and sliding mode control (SMC), which are applied to standalone photovoltaic (PV) systems under various climatic conditions [19]. Next, this paper [20] explains the research that focuses on improving the performance of MPPT in solar systems using Fuzzy Logic control methods and simulations are run in MATLAB. The main primary circuit with DC-DC Boost architecture and single MOSFET. The simulation model is combining Perturb & Observe with Fuzzy Logic. The simulation results show that it can reduce output power fluctuations, and increase system efficiency up to 97 %.

From the review of previous research literature, most of the algorithms used in MPPT focus on software-based simulations. The large number of algorithms creates confusion in choosing the appropriate algorithm that can be implemented well, including the PSO and ABC algorithms. PSO itself has been widely applied. This hardware implementation is to validate the theoretical model and also overcome the practical challenges associated with MPPT in PV applications. It is necessary to synchronize between simulation and practical applications in the development of MPPT technology in the future.

Review of existing references [11–20] is more on the emphasis of advantages (utilization) in increasing efficiency compared to traditional methods. While for the shortcomings there is no detailed discussion or not discussed. PSO and ABC algorithms can improve tracking efficiency in photovoltaic systems by adapting to changes in environmental conditions and optimizing maximum power point (MPP) tracking. Likewise, when these two algorithms are combined with other algorithms, they still show good performance and increase efficiency even though the computational complexity also increases. In general, capturing global maximum power point (GMPP) tracking is more dynamic than traditional methods such as Perturb and Observe (P&O) and Incremental Conductance (INC). PSO and ABC algorithms require more computing resources than classical methods such as P&O or Incremental Conductance. This is a challenge if applied with microcontroller-based hardware such as Arduino or the like, because when simulated with a computer, computational complexity is not a problem.

3. The aim and objectives of the study

The aim of the study is to develop and implement meta algorithms on microcontroller-based MPPT. This will allow the practical part to show that the implementation of PSO and ABC is not only theoretically relevant but can provide real solutions in the real world. The practical hope of implementing these algorithms in microcontroller-based MPPT hardware will help achieve better and more optimal results.

To achieve this aim, the following objectives are accomplished:

– to develop the Implementation of the Particle Swarm Optimization (PSO) Algorithm on an Arduino Uno Microcontroller-Based MPPT;

– to develop the Implementation of the Artificial Bee Colony (ABC) Algorithm on an Arduino Uno Microcontroller-Based MPPT;

– to analyze the performance of the solar power generation system (PLTS) that has been optimized using the PSO and ABC algorithms based on the Arduino Uno microcontroller integrated with MOSFET on the boost converter circuit.

4. Materials and methods

4. 1. Object and hypothesis of the study

The algorithms implemented are Particle Swarm Optimization (PSO) and Artificial Bee Colony (ABC). Both are implemented for disturbance conditions such as partial shading in photovoltaic (PV) systems. The task of the MPPT hardware is to increase and stabilize the DC electrical output of the PV system caused by disturbances. As is known, the performance of the PV DC electrical output is affected by reduced current and voltage.

The object of this study is the photovoltaic (PV) system, especially the hardware design aspect for maximum power point tracking (MPPT) based on metaheuristic algorithms (PSO and ABC). The MPPT hardware components are designed to optimize the power generated by solar panels. This research focuses on the integration of hardware technology with metaheuristic algorithm approaches to maintain and improve the performance of the PV system.

The hypothesis of this research emphasizes the design of MPPT hardware based on PSO and ABC algorithms. Then comparing the two methods whether they are able to increase efficiency and maintain the stability of PV system performance under environmental conditions.

The assumptions related to the PV module used have characteristics in accordance with standard technical specifications. The intensity of sunlight and ambient temperature in the test reflects real conditions that occur in the field. The MPPT hardware is designed to be able to run PSO and ABC algorithms and is able to process data in real time. The power consumption of the MPPT hardware does not affect the overall system efficiency. The applied algorithm can achieve optimal results in tracking maximum power. The algorithm can also adapt to environmental conditions and parameters have been optimized for the PV system so that it can provide optimal performance.

The hardware design is simplified by using basic components, such as microcontrollers, MOSFETs. MPPT hardware testing is carried out on a laboratory-scale prototype and components such as inverters or batteries are not integrated in this test to simplify the analysis. The PV module used is 400 Wp with the application of sunlight intensity and temperature according to field/real conditions.

4. 2. System Design

The design of the MPPT system consists of two main components, namely software and hardware. The hardware design includes a DC-DC boost converter that implements the MPPT algorithm to increase the voltage from the PV system. The general schematic of the proposed system is presented in Fig. 1.

The system uses voltage and current sensors to measure input and output parameters. On the input side, voltage and current are detected by sensors that provide real-time data for the MPPT algorithm to track the Maximum Power Point (MPP), especially under partial shading conditions. On the output side, similar sensors measure the voltage and current values to ensure accurate tracking and adjustment.

The MPPT algorithm processes the sensor data to determine the optimal operating point. This processed information generates a Pulse Width Modulation (PWM) signal, which is sent to the TLP350 MOSFET driver. The MOSFET driver controls the switching of the MOSFET, enabling the DC-DC boost converter to adjust the voltage based on the calculations performed by the MPPT algorithm.

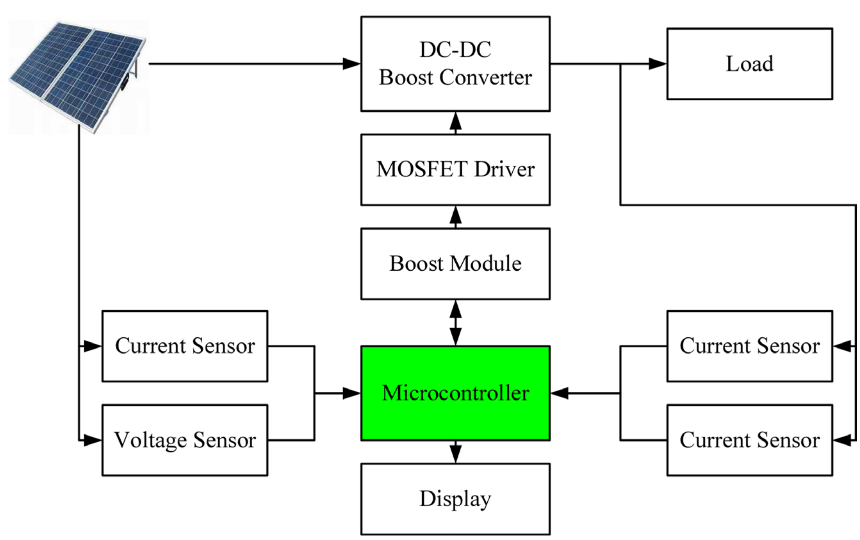

Fig. 1. General system schematic

The system utilizes an Arduino Uno microcontroller, which is powered by a 12 V battery suitable for the microcontroller's operating voltage [21]. The MOSFET driver provides isolation between the power circuit and the control circuit, ensuring safe operation. System parameters such as duty cycle, input voltage, input current, output voltage, and output current are displayed on the Display, providing real-time monitoring and feedback.

4. 3. PV systems design

The solar panels that used in the system consists of three 410 Wp polycrystalline panels. The specification of the solar panels is presented in Table 1.

Table 1

Solar panel specification

Description	Value
Open-circuit voltage (V_{OC})	47.6 V
Short-circuit current (I_{SC})	11.06 A
Maximum power (P_{MAX})	410 Wp
Maximum voltage (V_{MP})	39.1 V
Maximum current (I_{MP})	10.49 A

Table 1 above shows the specifications of the solar panels used in this study. This study used three solar panels with 410 WP.

4. 4. Control circuit design

The proposed MPPT system requires a control circuit that consists of three main components specifically Arduino Uno minimum system, current sensor design, and voltage sensor design.

4. 4. 1. Microcontroller systems

In this proposed system, Arduino Uno is used as control circuit. It receives sensor data from both the PV panels and the DC-DC boost converter. The Arduino processes this data to implement the MPPT algorithms. The microcontroller is programmed to operate using both the PSO and ABC algorithms. PWM output is generated via Pin 9 on the Arduino Uno.

4. 4. 2. Current sensor

The current sensor used in this system is the ACS712-30A module. This module operates based on an integrated Hall Effect sensor, which generates a magnetic field when current flows through a copper conduction path. The magnetic field is then converted into a proportional voltage [22]. The ACS712-30A sensor can measure currents up to 30 A, sufficient for both the input and output sides of the system. For the current sensor used as shown in Fig. 2.

The module in Fig. 2 is a current sensor module that is available on the market and easy to obtain.

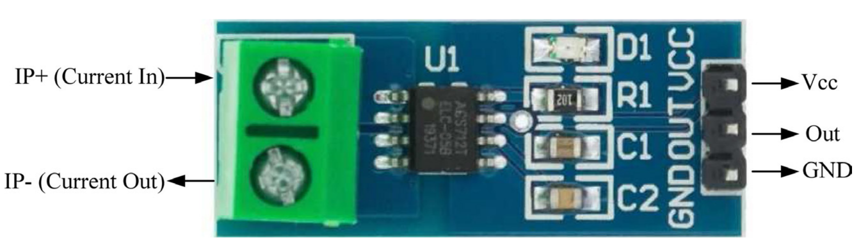

Fig. 2. ACS712-30 pinout

4. 4. 3. Voltage sensor

A voltage divider circuit is employed as the voltage sensor in this system. For the input side, the voltage divider is configured to measure voltages ranging from 0 V to 50 V, while for the output side, it measures voltages from 0 V to 100 V.

As depicted in Fig. 3, the resistance values for the voltage dividers are as follows:

Input Side: R1=500 kΩ, R2=10 kΩ;

Output Side: R1=500 kΩ, R2=12 kΩ.

The voltage divider sensor in Fig. 3 is placed at the input (after the solar panel) and output of the Boost Converter. The output of the sensor is integrated into the Arduino Uno microcontroller.

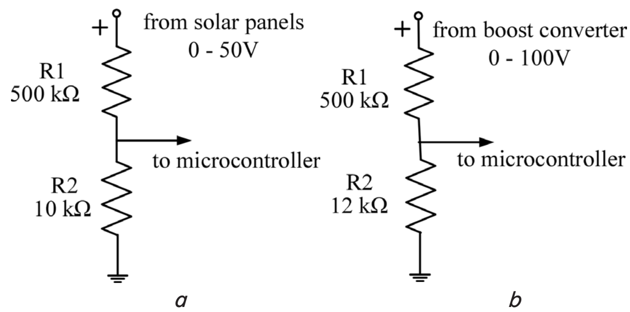

Fig. 3. Voltage divider schematic: *a* — voltage sensor on the input side; *b* — voltage sensor on the output side

4. 5. MPPT algorithms design

The MPPT algorithms are designed to track the global maximum power point (MPP) of the shaded PV system. This study aims to determine the true maximum power point through testing [15].

4. 5. 1. Particle swarm optimization

The PSO algorithm is widely used in MPPT due to the simplicity of its mathematical structure and implementation [23]. Particle Swarm Optimization (PSO) algorithm is inspired by the behavior of particle flock in search of resources [24]. In PSO, potential solutions are represented as particles moving in a search space, adjusting their positions and velocities to find the optimal solution. Each particle keeps track of its best solution (Pbest), while the group shares information about the best solution found (Gbest). The algorithm combines personal and collective experiences to approach the optimal solution.

In optimizing the DC-DC boost converter, PSO algorithm is used to find the operating point that produces maximum output power. The optimized parameters include input voltage and current as well as electronic components in the converter. PSO iterates to find the combination of parameters that optimize the output power of the converter, improving the efficiency of the boost type DC converter. With the adaptive and collaborative nature of PSO, this study can improve the performance of DC converters through automatic parameter adjustment according to changing operational conditions.

In order to implement the PSO method for MPPT, the position (x) are taken as the current references (idc,ref), whilst the velocity (v) variables are the correction terms for the current references (Φ). The aim of the PSO algorithm is to maximize the converter input power.

As depicted in Fig. 4, the particle position and the velocity are updated iteratively based on the following two equations:

$$\Phi_i^{k+1} = \omega\Phi_i^k + c_1 r_1 \left\{ I_{Pbest}^k - I_{dc,i}^k \right\} + c_2 r_2 \left\{ I_{Gbest}^k - I_{dc,i}^k \right\}, \quad (1)$$

$$I_{dc,i}^{k+1} = \Phi_i^{k+1} + I_{dc,i}^k, \quad (2)$$

where $I_{dc,i}^k$ is the input reference, $I_{dc,i}^{k+1}$ is the modified input current reference, and I_{Pbest}^k is the local best input current; I_{Gbest}^k is global best input current, Φ_i^k is the current perturbation, and Φ_i^{k+1} is the modified perturbation.

For the search point concept, let's use the PSO algorithm as shown in Fig. 4.

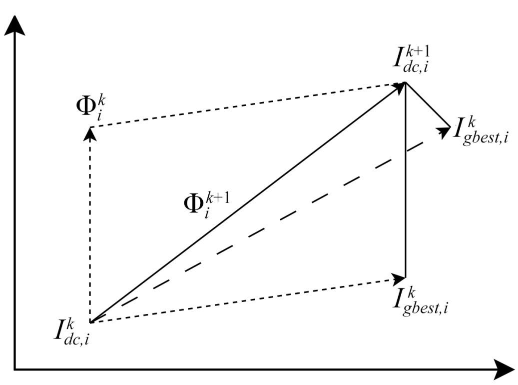

Fig. 4. Searching point concept by PSO [25]

The program flow below is the PSO algorithm used in the MPPT method, as shown in Fig. 5. This PSO algorithm is then entered into the Arduino Uno microcontroller to regulate the PWM signal. The PWM signal is used to drive the MOSFET on the Boost Converter.

The implementation of the PSO algorithm can be seen in Fig. 5 [25].

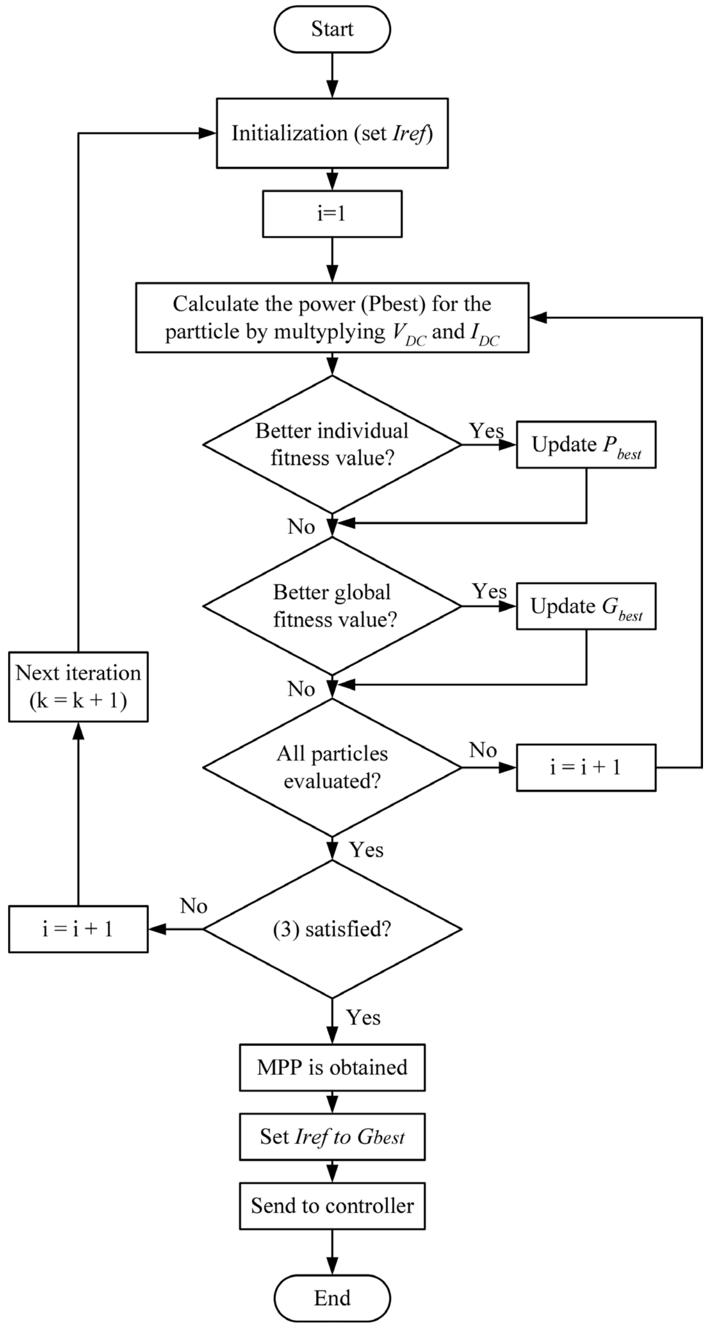

Fig. 5. PSO algorithm flowchart [25]

Based on the flowchart above, to start the optimization, PSO algorithm sends initial values of the DC reference to the converter controller and senses the produced power.

Then, based on (1), (2), the algorithm updates the DC references and sends the new currents to the controller. The process of generating new references and calculating the corresponding power continues until the convergence criterion defined in (3) is obtained. This is to ensure that all particles converge to the MPP.

$$\left(P_{Gbest} - P_{new,i}\right) < P_t h, \quad i = 1, \dots, n, \quad (3)$$

where P_{Gbest} is the global best fitness and P_{th} is a threshold value [2].

4. 5. 2. Artificial bee colony

Artificial Bee Colony (ABC) algorithm is an optimization algorithm inspired by the behavior of bees in searching for optimal food sources. The basic concept of ABC involves an artificial bee colony working collectively to find the best solution in the search space. In ABC, there are two main types of bees that play a role in the optimization process: worker bees and onlooker bees [26].

Worker bees are responsible for exploring the search environment and generating potential solutions. Each worker bee tries various solutions and updates their position based on the quality of the solutions they find. Onlooker bees follow the information about the quality of solutions found by worker bees and choose to follow promising solutions in updating their own positions. Meanwhile, foragers are tasked with finding new solutions around the search space if the existing solutions do not improve in quality. The implementation of the ABC algorithm can be seen in Fig. 6 [27].

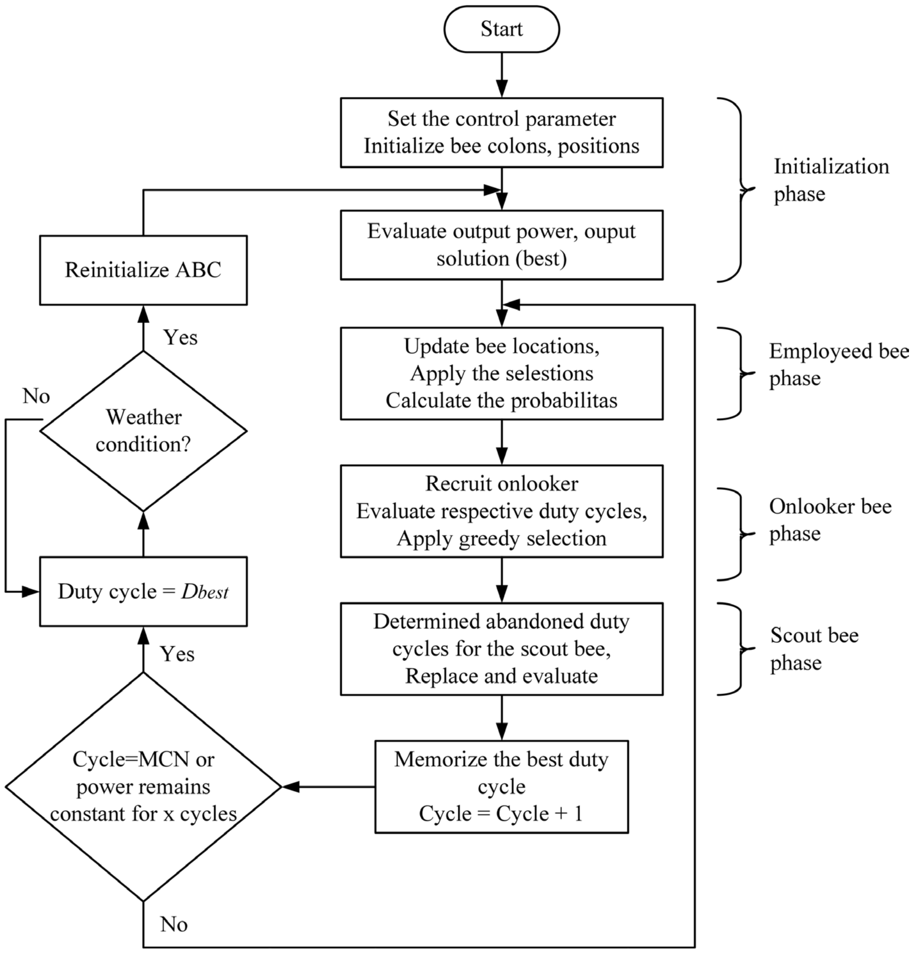

Fig. 6. ABC algorithm flowchart

The program flow above is the ABC algorithm used in the MPPT method, as shown in Fig. 6. This ABC algorithm is then entered into the Arduino Uno microcontroller to regulate the PWM signal. The PWM signal is used to drive the MOSFET on the Boost Converter.

4. 6. DC-DC boost converter

DC-DC boost converter system is designed as MPPT implementation based on metaheuristic algorithms to achieve maximum PV system power output under PSC. The schematic of DC-DC boost converter is shown in Fig. 7.

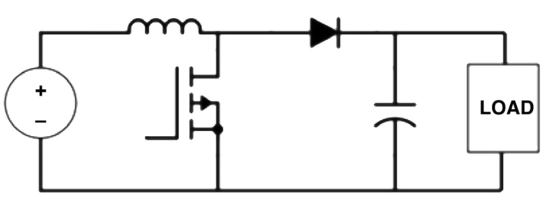

Fig. 7. DC-DC boost converter schematic

Generally, DC-DC boost converters formed from some electronics component, such as inductor (L), switch (Q), diode (D), capacitor (C), and load [28]. The proposed DC-DC boost converter specification is given in Table 2.

Table 2 above is the specification and realization of Boost Converter hardware design. The hardware design utilizes commercially available components.

Table 2

DC-DC boost converter specification

Description	Value
Minimum input voltage	47.6 V
Maximum output voltage	100 V
Output current	0–10 A
Duty cycle	51 %
Voltage ripple	0.01 V
Switching frequencies	32 Hz
Inductor	100 μH
Capacitor	100 μF

4. 6. 1. Inductor

Determining the inductance in a DC-DC boost converter power circuit uses the calculation of the minimum inductance value $L_{\min}$ in the circuit, as in (4) below [28]:

$$L_{\min} = \frac{D(1-D)^2 R}{2f}, \tag{4}$$

where $L_{\min}$ is the minimum inductance (H) for the converter to remain in CCM; D is the duty cycle; R is the resistive load (Ω); F is the switching frequency (Hz).

This is a formula for calculating the minimum inductance ($L_{\min}$) in a buck-boost converter or similar DC-DC power converter to maintain operation in continuous conduction mode (CCM).

4. 6. 2. MOSFET

Metal Oxide Semi Field Effect Transistor or MOSFET in a DC-DC boost converter used for switching process based on duty cycle value settings. In this design, MOSFET IRFP260N chosen due to its rating that can handle drain-source voltage (V_{DS}) up to 200 V with drain current (I_D) maximum value of 50 A [29].

4. 6. 3. Diode

Choosing the diode in a DC-DC boost converter system takes into account the switching frequency and the voltage and current system. In this design, the diode used is the STTH3003CW diode with a peak-reverse voltage (V_{RRM}) of 300 V and an average forward current (I_F) of 30 A [30].

4. 6. 4. Capacitor

In a DC-DC boost converter system, the capacitor acts as a filter that can reduce the voltage ripple due to MOSFET switching.

The capacitance value required by the system can be determined through (5), below [28].

$$c_{\min} = \frac{D}{RfV_r} C_m in = D/(RfV_r), \tag{5}$$

is a formula for calculating the minimum capacitance value ($C_{\min}$) in a DC-DC power converter circuit to keep the output voltage (V_r) within certain limits.

Where $C_{\min}$ is the minimum capacitance (F) required for stable output voltage; D is the duty cycle; R is the resistive load (Ω); f is the switching frequency (Hz); V_r is the allowable output voltage ripple (V).

With the desired system voltage ripple of 0.01 V and a load of 50 Ω, the calculation of the minimum capacitance value is as follows.

The minimum capacitance value obtained based on the calculation above is 85 μF. The design proposed uses a capacitor with a capacitance of 100 μF with a voltage rating of 450 V. The realization of the circuit is shown in Fig. 8.

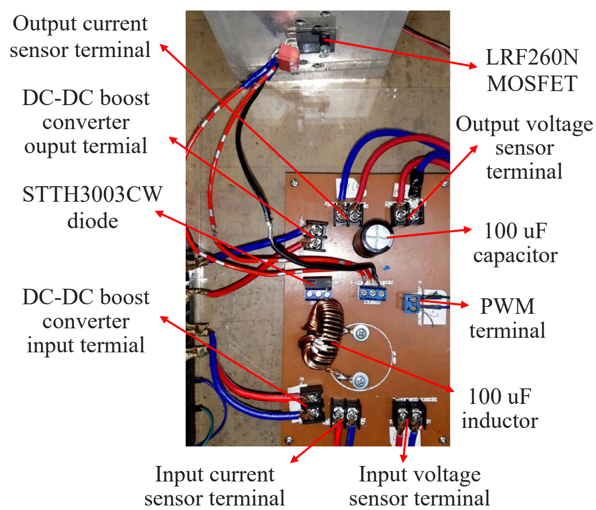

Fig. 8. DC-DC boost converter hardware

The realization of proposed DC-DC boost converter design is presented by Fig. 12. From Fig. 12, it can be observed that there is a heat sink on the MOSFET to help lower the temperature of the MOSFET when working.

5. Results of applying the PSO and ABC algorithms to MPPT

5. 1. Results of testing the implementation of PSO MPPT based on Arduino

The proposed MPPT system design is validated through direct testing. Testing will be carried out in July 2024, from 9 am to 4 pm. The testing activities in this study are shown in Fig. 9.

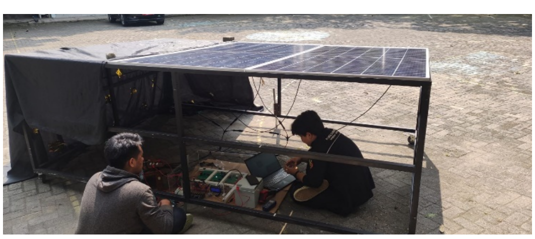

Fig. 9. MPPT system testing

The purpose of testing the MPPT algorithms was to verify their ability to successfully track the MPP of the PV system. The testing involved two conditions: the first with a 400 Wp panel fully exposed to sunlight, and the second with one panel shaded. The irradiation levels were 801 W/m^2 for unshaded and 198 W/m^2 for shaded, with a constant temperature of 54.8 °C. The loads tested were 50 Ω, 100 Ω, 200 Ω, and 400 Ω.

The first set of tests with the PSO algorithm was conducted under full solar irradiation of 801 W/m^2 and a temperature of 54.8 °C, with no shading. The results are shown in Fig. 10, which shows the MPPT performance under these conditions.

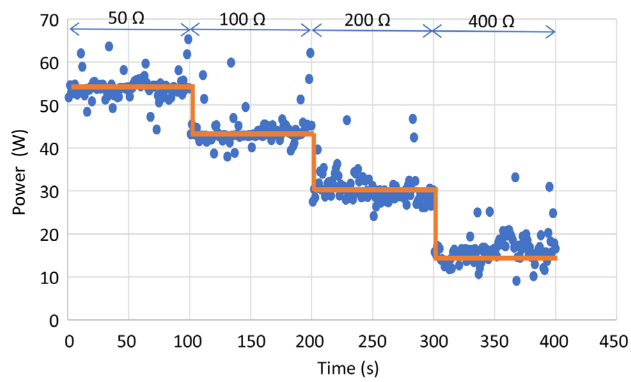

Fig. 10. PSO algorithm on unshaded condition

The second MPPT test with the PSO algorithm was carried out on three solar panels connected in parallel. One of the panels was shaded with an irradiation of 198 W/m^2, while the other two panels were exposed to irradiation of 801 W/m^2 at a temperature of 54.8 °C. The load variations used were 50 Ω, 100 Ω, 200 Ω, and 400 Ω. The results of this test are shown in Fig. 11, which shows the MPPT performance graph under these conditions.

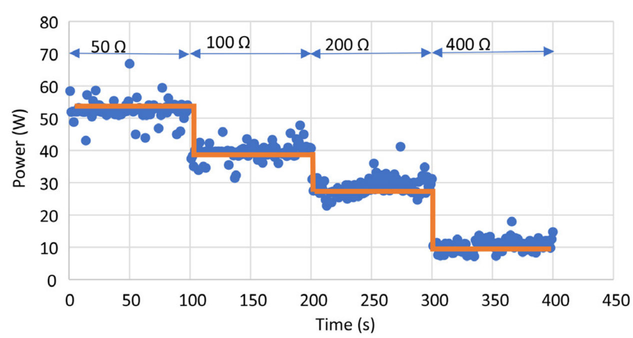

Fig. 11. PSO algorithm on shaded condition

The graph in Fig. 11 shows the output power based on the variation of the load used. The load variation uses a variable resistor so that its switching can be done easily.

5. 2. Results of testing the implementation of ABC MPPT based on Arduino

The first MPPT test with the ABC algorithm was carried out at an irradiance of 801 W/m^2 and a temperature of 54.8 °C without any shadow on the panel. The resistance variations used were 50 Ω, 100 Ω, 200 Ω, and 400 Ω. The results of this test are shown in Fig. 12, which shows the MPPT performance graph under these conditions.

The second MPPT test with the ABC algorithm was conducted with three solar panels connected in parallel. One panel was shaded with an irradiation of 198 W/m^2, while the other two panels were exposed to irradiation of 801 W/m^2 at a temperature of 54.8 °C. The load variations used were 50 Ω, 100 Ω, 200 Ω, and 400 Ω. The results of this test are shown in Fig. 13, which shows the MPPT performance graph under these conditions.

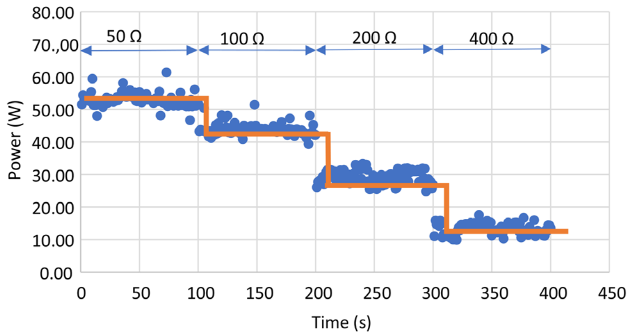

Fig. 12. ABC algorithm on unshaded condition

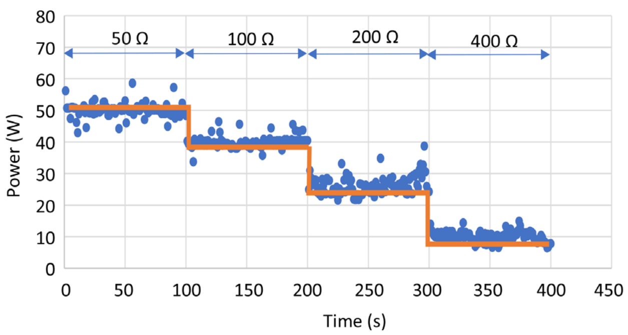

Fig. 13. ABC algorithm on shaded condition

The graph in Fig. 11 shows the output power based on the variation of the load used. The load variation uses a variable resistor so that its switching can be done easily.

5. 3. Comparison of PSO and ABC MPPT for unshaded and shaded solar panels

The comparison of the output power of the system using the PSO and the ABC algorithm was tested by varying the conditions of the PV arranged in parallel and the load value. The variations in the conditions of the solar panels are as follows: the first condition, the 400 Wp panel is unshaded, so that it receives the same irradiation value of 801 W/m^2 with a temperature value of 54.8 °C. The second condition, one panel is shaded, with an irradiation value of 198 W/m^2 at a temperature of 54.8 °C. The load variations used in this test are 50 Ω, 100 Ω, 200 Ω, and 400 Ω.

Comparison of the output power produced by MPPT in the first condition is shown in Fig. 14 below.

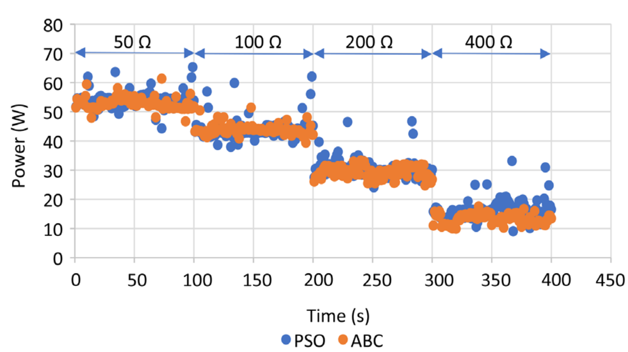

Fig. 14. Comparison between PSO and ABC algorithm on unshaded condition

Comparison of the output power generated by MPPT in the second condition with one shaded panel receiving irradiation of 198 W/m^2 at a temperature of 54.8 °C, and other solar panel not covered by shade receiving irradiation of 801 W/m^2 at a temperature of 54.8 °C, as shown in Fig. 15.

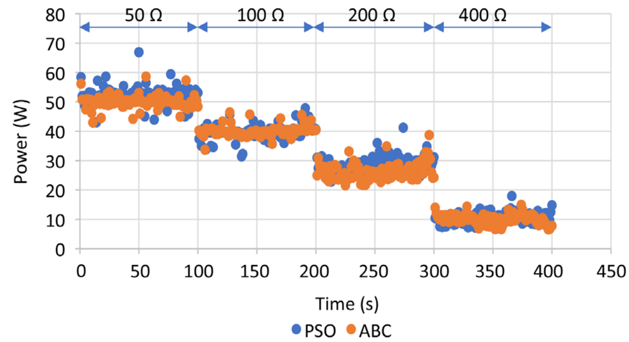

Fig. 15. Comparison between PSO and ABC algorithm on shaded condition

The comparative value of the power generated by the two MPPT systems in the first condition can be seen in Table 3 below.

Table 3

Comparison between PSO and ABC algorithm on unshaded condition

Load (Ω)	PSO (W)	ABC (W)	Deviation (W)
50	54.06	52.80	1.26
100	44.07	43.90	0.17
200	30.49	29.28	1.21
400	16.47	13.26	3.21
Average			1.46

The comparative value of the power generated by the two MPPT systems in the second condition can be seen in Table 4 below.

Table 4

Comparison between PSO and ABC algorithm on shaded condition

Load (Ω)	PSO (W)	ABC (W)	Deviation (W)
50	52.57	50.06	2.51
100	39.69	40.01	0.32
200	28.86	26.31	2.55
400	10.57	10.09	0.48
Average			1.31

The comparison of disturbances between the unshaded conditions in Table 2 and the shaded conditions in Table 3 is based on the loads used in this study.

6. Discussion of the results of the MPPT hardware implementation with the PSO and ABC algorithms

This study presents a significant advancement in the field of MPPT systems by transitioning from software simulations to the hardware realization of MPPT using PSO and ABC algorithms. While previous research has predominantly focused on software-based simulations, our work demonstrates the practical implementation and effectiveness of these algorithms in a real-world hardware environment. The successful integration of PSO and ABC algorithms into the MPPT system highlights the potential for improved energy efficiency in solar power systems. This hardware realization not only validates the theoretical models but also addresses the practical challenges associated with deploying MPPT systems in actual PV applications. By bridging the gap between simulation and practical application, this study provides a robust foundation for future developments in MPPT technology.

This research focuses on the development of MPPT hardware implementation with the implementation of metaheuristic algorithms based on Arduino Uno microcontroller. The algorithms implemented are PSO and ABC. The PSO algorithm is very suitable for solving multi-extreme optimization problems [31]. Meanwhile, according to the paper [32], the ABC algorithm has several characteristics that make it more attractive than other methods inspired by biology. In particular, this method is simple, uses fewer control parameters, and its convergence does not depend on initial conditions. Several previous PSO and ABC studies generally show the implementation of software applications in the form of simulations.

This study develops a hardware MPPT by implementing PSO and ABC algorithms and compares their performance for shaded and unshaded conditions. It is also based on the research [32], describing the co-simulation methodology, combining Matlab/SimulinkTM and Cadence/PspiceTM, used to verify the effectiveness of the proposed method and compare its performance, under dynamic weather conditions, with the performance of the PSO-based MPPT algorithm. Simulation and experimental results have shown satisfactory performance of the proposed approach. The PSO and ABC algorithms are intended to overcome disturbances that occur in PV such as partial shading. It is expected that this hardware MPPT can optimize the output power performance of the PV system.

Based on Table 4, it can be seen that the system using MPPT on solar panels that are partially shaded with the application of the PSO and ABC algorithms. Both are able to maintain power at its maximum point according to the load given. At the same load variation, the power generated by the two algorithms shows a difference in output power. The difference in power measurements with the average load variation is 1.31. The difference in power generated by the two MPPT systems in partially shaded conditions is not too large.

The measurement results also show that the PSO algorithm is better than the ABC algorithm because the power obtained is greater with the difference in power given not too large. This is in line with one of the previous studies involving the PSO algorithm [33], the study showed good performance when applied to MPPT.

The results of this study indicate that the implementation of the two MPPT algorithms can be used as a microcontroller-based MPPT hardware solution. The MPPT hardware implementation that has been made still has shortcomings in the boost converter device. The designed boost converter only has a good and safe duty cycle at 51 % for an output current of 0–10 A (Table 1). There needs to be improvement in the MOSFET component so that it can maximize the output current up to 10 A or can be increased even higher than that. The shortcomings of this research are the limitations of hardware, accuracy, and flexibility in handling problems. However, development directions such as hybrid algorithms, distributed computing, and adaptive optimization can provide better solutions. This development is important because it allows research to be applied in more real contexts, with more accurate and efficient results.

7. Conclusions

1. The development of the implementation of two MPPT algorithms, namely PSO and ABC, has been proposed in this study. From the results of the study, both algorithms can be implemented on Arduino Uno microcontroller-based hardware. Testing was carried out on a 400 Wp solar panel with an irradiation level of 801 W/m^2 for unshaded and 198 W/m^2 for shaded, a constant temperature of 54.8 °C, and the tested loads were 50 Ω, 100 Ω, 200 Ω, and 400 Ω.

2. The results of the development test of the implementation of the PSO and ABC algorithms on microcontroller hardware indicate that there is output power optimization. Output power optimization can be seen from the measurement results when there is no interference (unshaded condition) and interference occurs (shaded condition). The first condition, the 400 Wp panel is not shaded at 801 W/m^2 irradiation and the second condition is 198 W/m^2 irradiation at the same temperature of 54.8 °C with load variations of 50 Ω, 100 Ω, 200 Ω, and 400 Ω. For example, for the shaded condition of PSO and ABC at a load of 50 Ω, the output power is 52.57 and 50.06 Watts, while for the unshaded condition, it is 54.06 and 52.80 Watts.

3. Based on the performance measurements and analysis that have been carried out, it can be seen that the PSO algorithm is better than the ABC algorithm because the power obtained is greater than the ABC algorithm, but the difference in power provided is not too large, namely an average of 1.46 for conditions without shade and 1.31 for shade.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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