Differential Evolution-based MPPT with Dual Mutation for PV Array under Partial Shading Condition

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***Abstract*— The performance of the photovoltaic system heavily depends on solar irradiance and temperature conditions. A condition where photovoltaic received non-uniform solar irradiance is called partial shading condition. Partial shading can affect the power-voltage characteristics of the photovoltaic system resulting in more than one maximum power points. This reason can be one of the leading causes of some energy losses for many photovoltaic systems. In order to overcome the mentioned problem, this paper proposes a differential evolution (DE) based MPPT algorithm with dual mutation factors to track the global maximum power point of photovoltaic systems under partial shading. The mutation step is modified by using two mutation factors to enlarge the search space and optimize the convergence speed in the tracking process. The photovoltaic system in this paper uses two 100 Wp photovoltaic modules configured in series and a DC-DC boost converter. The performance of the proposed algorithm is validated in PSIM simulation and compared to the PSO algorithm. The proposed MPPT is tested with a rapid change of solar irradiation on both two modules. The result shows that the MPPT is able to track the GMPP under fluctuating partial shading conditions fast, with no oscillation and accurate. The average tracking speed of the proposed algorithm is 0.309 s, and the MPPT accuracy is 99.9%.**

Keywords—dc-dc boost converter, differential evolution, MPPT, partial shading photovoltaic system.

I. INTRODUCTION

The need for clean energy sources nowadays has increased because of the depletion of conventional energy sources and the pollution that affects the surrounding environment. One of the most promising options for clean energy production is solar photovoltaic technology [1]. This technology converts solar irradiation to produce electricity through the use of photovoltaic modules. The usage of the solar photovoltaic system has been increasing in recent years and expected to reach 800 GW in the near of the year 2030. The growth of the photovoltaic system market is because solar energy is available almost every time, emission-free, no noise, and the electricity continuity is mostly granted. However, there are three significant drawbacks to this system. First, the efficiency is relatively low, which is around 20%. Second, the performance of the photovoltaic module sometimes affected by the weather condition. When the weather is bad, the energy produced can go below specification. Third, the nonlinear characteristic of the electrical aspect is because the photovoltaic cell mostly depends on the level of solar irradiance and the atmospheric temperature. Therefore, the photovoltaic system must be operated at its maximum power point to extract the highest power possible so that the best efficiency value can be achieved. This maximum power point can be obtained by the use of MPPT [2].

The primary function of the MPPT is to regulate the photovoltaic array output power to supply the maximum possible power to the load or grid [3]. MPPT control has advantages in terms of simple implementation, easy to build, and does not need large components. Because the photovoltaic panel is highly dependent on solar irradiation, the MPPT must be able to adapt to dynamic change in solar irradiation quickly and must be able to acquire the maximum optimal power of the photovoltaic arrays [4]. In recent years, there are a number of experiments on the MPPT control methods, including ones based on P&O [5], fuzzy logic [6], and artificial neural network (ANN) [4][7]. However, these methods are only proven to be able to track the maximum power point (MPP) under normal solar irradiation, where the maximum power peak that occurs in the power-voltage (P-V) curve is only one peak. If some of the photovoltaic modules are under partial shading, the P-V curve has more than one peaks, which consist of a global maximum power point (GMPP) and a local maximum power point (LMPP). The methods mentioned above have a high chance of failing to find the GMPP because their searching process for the MPP is suited for local space only [8]. To mitigate the problem above, several Differential Evolution-based MPPT have been proposed in recent years. In [8], they proposed an improved DE algorithm that could track GMPP during partial shading conditions. It was validated from simulation and experimental results that the proposed algorithm was able to track the GMPP accurately within 2 s and also able to respond during load variation rapidly. The approach in [9] uses a hybrid combination of PSO and DE called DEPSO algorithm to track the actual MPP of the PV system under partial shading conditions. The verified results show the proposed MPPT has a very high tracking power efficiency, high tracking speed, no oscillation, and good reliability.

This paper proposes a differential evolution (DE)-based MPPT with dual mutation to track the maximum photovoltaic power under partial shading condition. The conventional DE algorithm generally uses one mutation factor while in this work the mutation strategy uses two mutation factors. The mutation strategy used is DE/Best/1 where the perturbed vector is the best individual with the best fitness in the current population [10]. This strategy is chosen so that the direction of the tracking process is directed towards the best solution. The dual mutation mechanism is two process of mutation that work alternately based on the comparison of a randomly selected vector and the best vector in the current population.

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II. PV SYSTEM MODEL

A. Photovoltaic Module

The Photovoltaic (PV) module is usually built with series and parallel configurations of photovoltaic cells. This can be modeled with a single light-generated current source, single diode, parallel resistor, and a series resistor. A general equivalent circuit model of the photovoltaic cell is pictured in Figure 1.

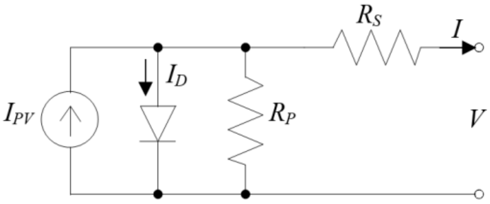

Fig. 1. An equivalent model of photovoltaic cell.

The current value of the PV cell is derived from (1):

$$I = I_{pv} - I_0\left[e^{\left(\frac{V+R_sI}{V_ta}\right)}-1\right]-\frac{V+R_sI}{R_p} \quad (1)$$

where:

- V (volt) = PV output voltage
- I (Ampere) = PV output current
- Ipv (Ampere) = PV current
- Io (Ampere) = saturation current
- Rs (Ω) = series resistance
- Rp (Ω) = parallel resistance
- Vt (volt) = voltage of thermal
- a = quality factor of diode

The photovoltaic modules used in this work are from the ICA Solar product. This module contains 36 series-connected polycrystalline cells that can produce the amount of power of 100 W Peak [11]. The electrical specifications of this module can be seen in Table 1.

Based on the parameters in Table 1, Fig. 2, and Fig. 3 show the result of simulation to determine the photovoltaic characteristics for photovoltaic current-voltage (I-V) curve and power-voltage (P-V) curve based on different solar irradiation applied. The simulation is done using MATLAB software.

TABLE I. ELECTRICAL PARAMETER OF THE ICA-SOLAR MODULE

ICA-Solar	
Polycrystalline	
Rated Maximum Power (Pmp)	100 W
Voltage at Mpp (Vmp)	17,6 V
Current at Mpp (Imp)	5,69 A
Open-Circuit Voltage (Voc)	22,6 V
Short-Circuit Current (Isc)	6,09 A
Maximum System Voltage	1000 V
Maximum Series Fuse	11 A
Standart Test Condition	1000 W/m², 25°C

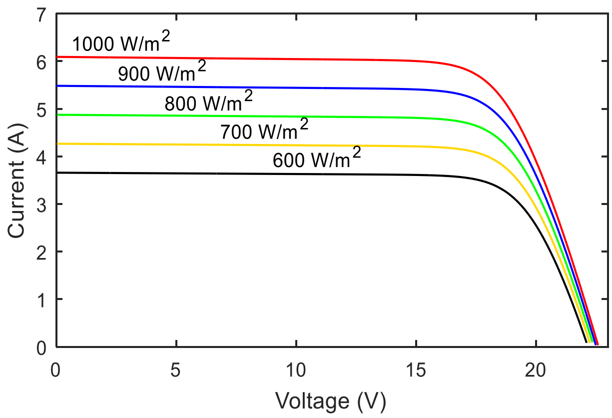

Fig. 2. I-V characteristic curve of the photovoltaic module based on different irradiations.

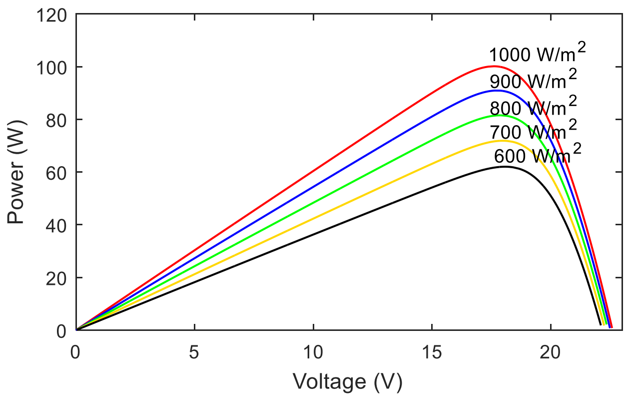

Fig. 3. P-V characteristic curve of the photovoltaic module based on different irradiations.

B. Partial Shading on PV Array

It is known that the partial shading phenomenon causes a significant drop in photovoltaic system efficiency and performance. The power loss can be up to 50% on series or parallel photovoltaic module configuration [12]. When a cell is under partial shading condition, the total amount of the current of the module becomes limited to the decreased current of the shaded cell. Then the shaded cell turns into a power consumer instead of the current generating source for the module [13]. This can cause an increase in solar cell temperature and hot spot trouble. To avoid the losses due to hot spot problem, a bypass diode is connected in parallel to the photovoltaic module, as shown in Fig. 4. This will protect the partially shaded photovoltaic module because the current flows through the less resistive conduction path, which has the bypass diode. Most of the commercial photovoltaic modules manufacturers usually put bypass diodes in their designs.

However, there is a drawback from the bypass diode. The connection of bypass diode will affect the shape of the I-V curve and the P-V characteristic curve of the photovoltaic module [14]. There are multiple maximum power points that occur in the P-V curve during partial shading conditions. The highest power point is called the global maximum power point (GMPP), while the lower ones are called the local maximum power point (LMPP) [15]. This phenomenon can be shown by the power-voltage (P-V) curve of a partially shaded photovoltaic string, as shown in Fig. 5 and Fig. 6.

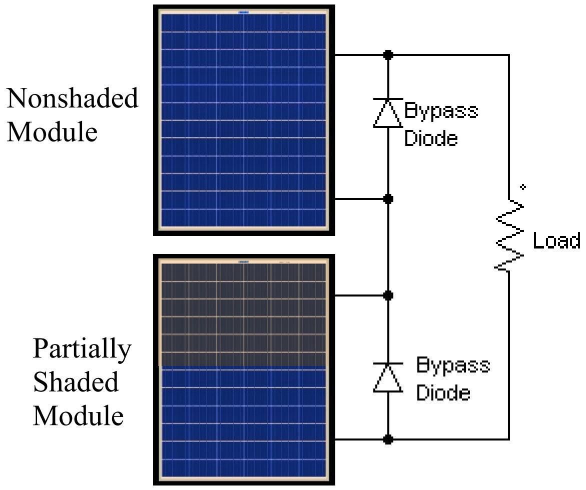

Fig. 4. Photovoltaic string under partial shading condition.

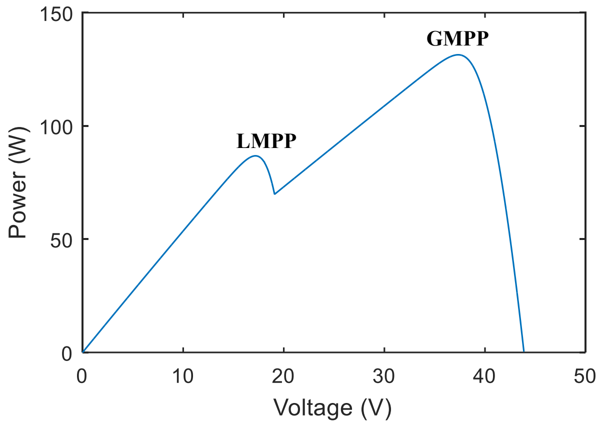

Fig. 5. P-V characteristic curve for partially shaded photovoltaic string, solar irradiation are 900 W/m^2 and 600 W/m^2.

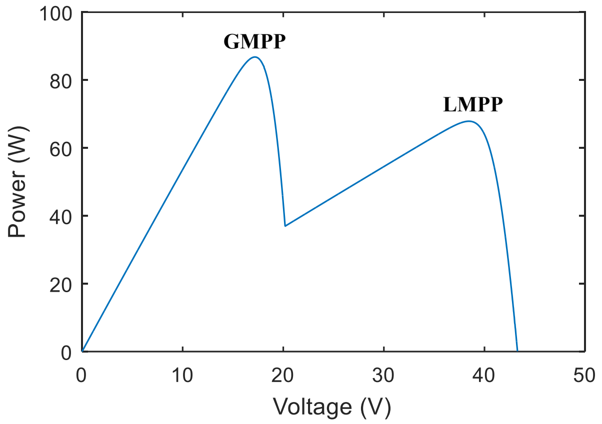

Fig. 6. P-V characteristic curve for partially shaded photovoltaic string, solar irradiation are 900 W/m^2 and 300 W/m^2.

It can be seen in Fig. 5 that the power peak has two peaks, which is LMPP and GMPP. The global MPP in Fig.5 is 131.4 Watt and the local MPP is 86.8 Watt. In Fig. 6 is shown that the global peak power moved to the left side. This is because the solar irradiation applied is shaded photovoltaic module is very low, which is 300 W/m2. The global MPP of Fig. 6 is 86.79 Watt and the local MPP is 67.8 Watt. Because of these multiple peaks, the system without MPPT may absorb the power on the LMPP. This condition may decrease the photovoltaic system efficiency.

C. DC-DC Boost Converter

The DC-DC converter is an essential component in the photovoltaic system because its function is to deliver the maximum power from the photovoltaic array to the load or grid. The duty cycle of the DC-DC converter is changed by the MPPT control during tracking process to ensure that the photovoltaic array power obtained is the maximum power. The proposed MPPT system is shown in Fig. 7, where two pieces of 100 Wp photovoltaic modules are series-connected. The MPPT controller uses two inputs from the voltage and current sensor as a feedback. The converter used in this work is a DC-DC boost converter, which is a non-isolated converter that can increase the voltage while decreasing current from its input supply to its output [16]. Based on [17], the efficiency of the boost converter is better than the buck converter in a photovoltaic system. Therefore, this converter is chosen for this work. The boost converter specification and designs are shown in Table II.

TABLE II. BOOST CONVERTER PARAMETERS

Parameter	Designed Value
Output power	200 W
Inductor	335 µH
Capacitor	1000 µF
Switching Frequency	70 kHz
Voltage ripple	±1%
Mode of operation	CCM

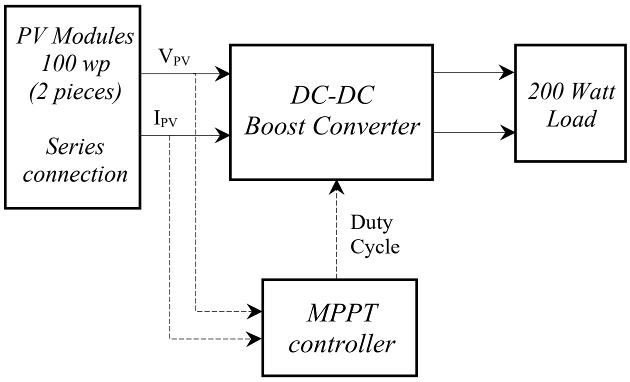

Fig. 7. The proposed PV system with MPPT controller.

III. THE PROPOSED DE ALGORITHM

Differential evolution (DE) is one of the evolutionary algorithms (EA) proposed by Storn and Price in 1995 [18]. It is an algorithm that optimizes the problem by iteratively improving the candidate solution in the population until the best solution is obtained. DE is one of the most used algorithms that is based on population because it has simple structure, fast convergence, good robustness and easy to be implemented [10]. The P-V curve of photovoltaic array can consist of multiple maximum power point under partial shading. This can confuse conventional MPPT algorithm to find the true GMPP. DE is able to track the GMPP because it relies on wide search space on P-V curve, its stochastic perturbation also helps the algorithm to explore the search space better. DE algorithm is easy to implement because only few parameters required to be set like *Np* – the population size, *F* – the mutation factor and *Cr* – the crossover rate. These parameters are required to be tuned in the initial system design to give good results on the optimization process. The DE optimization process can be explained as follows:

A. Initialization

DE starts with the initialization of random individuals in a population and distributes them in the search space thoroughly. DE algorithm utilizes 2D vectors, with x as the individual and i as the vector index. G denotes the generation number and Np is the population of the individuals as shown in (2):

$$x_{i,G}\ ; \quad i = 1,2,\ldots,Np \tag{2}$$

In the proposed algorithm, the perturbed vector is the duty cycle, therefore the variable $x_{i,G}$ is equal to $D_{i,G}$ to which is the variable to save the duty cycle value. Therefore (2) becomes (3). The initial duty cycle is distributed through the range of 5%-90% and divided by *Np* which is the population number.

$$D_{i,G}\ ; \quad i = 1,2,\ldots,Np \tag{3}$$

B. Mutation

There are some mutation strategies proposed by R.Storn and K. Price that is used in creating a mutant vector with respect to each individual vector in the population [19]. One of the most used mutation strategies is DE/Best/1 [10] as shown in (4):

$$v_{i,G} = x_{best,G} + F \cdot |x_{r1,G} - x_{r2,G}| \tag{4}$$

The index r_1 and r_2 are random integers selected from the population, should not be the same from one another and also different from current index, i. While F is the mutation factor that is used to calculate the difference between two of the chosen random vectors. F is chosen in the range of 0 to 1. $x_{best,G}$ is the best vector in the population that generate the best fitness function at current generation G.

Generally, the mutation process in conventional DE uses one mutation factor to create mutant vector. In the proposed algorithm, the mutant vector $D_{(mutant),i,G}$ is generated by mutation process using (5). The target vector $D_{best,G}$ is perturbed by two mutation process that work alternately based on the comparison between random vector and best vector. If random vector $D_{r1,G}$ has smaller duty cycle value than $D_{best,G}$, the mutation factor will use F_1= 0.7, otherwise the mutation factor will use F_2= 0.2. These values are chosen from optimal parameter tuning. The formula is shown below:

$$D_{(mutant),i,G}=\begin{cases} D_{best,G}+ F_1 \cdot |D_{r1,G}-D_{r2,G}|; & if \;\; D_{r1,G}<D_{best,G} \\ D_{best,G}+ F_2 \cdot |D_{r1,G}-D_{r2,G}|; & else \end{cases} \tag{5}$$

C. Crossover

After the mutant vectors generated, the mutant vectors are crossed with the target vectors through a crossover process, as shown in (6) where a random value variable "*rand*" in the range of [0, 1] is compared to the crossover rate *Cr*. The value of *Cr* is chosen in the range of [0, 1]. The *Cr* value in the proposed algorithm is set to 0.5. Crossover process will generate the trial vector as follows:

$$D_{(trial),i,G}=\begin{cases} D_{(mutant),i,G}; & if \quad rand < Cr \\ D_{best,G} \quad ; & else \end{cases} \tag{6}$$

D. Selection

The last process in DE algorithm is called selection. This process determines whether the trial vector or the target vector survives to the next generation by evaluating the fitness function. The evaluation is done by measuring the photovoltaic power from the trial vector duty cycle $P_{(trial),i,G}$. Then it is compared to the photovoltaic power from the target vector $P_{best,i,G}$. If $P_{(trial),i,G}$ has higher power value than $P_{best,i,G}$ or the same, then trial vector $D_{(trial),i,G}$ will be the next target vector and replace the current best vector $D_{best,G}$. The selection operation is shown in (7):

$$D_{i+1,G}=\begin{cases} D_{(trial),i,G}; & if\, P_{(trial),i,G} \geq P_{best,i,G} \\ D_{best,G} \quad ; & else \end{cases} \tag{7}$$

Then, the process is back to mutation process until the best solution met or the GMPP is tracked. However, solar irradiation is not always constant [12]. The change on solar irradiation may affect the production of the photovoltaic modules power as well. Therefore, the algorithm will add a checking stage at the end of the program by calculating the difference (ΔP) between the new measured power and the current best power. If the difference of the new power and the current best power is more than 5 watts, the searching process will be repeated from the initialization step. Flowchart of the proposed DE algorithm is shown Fig. 8.

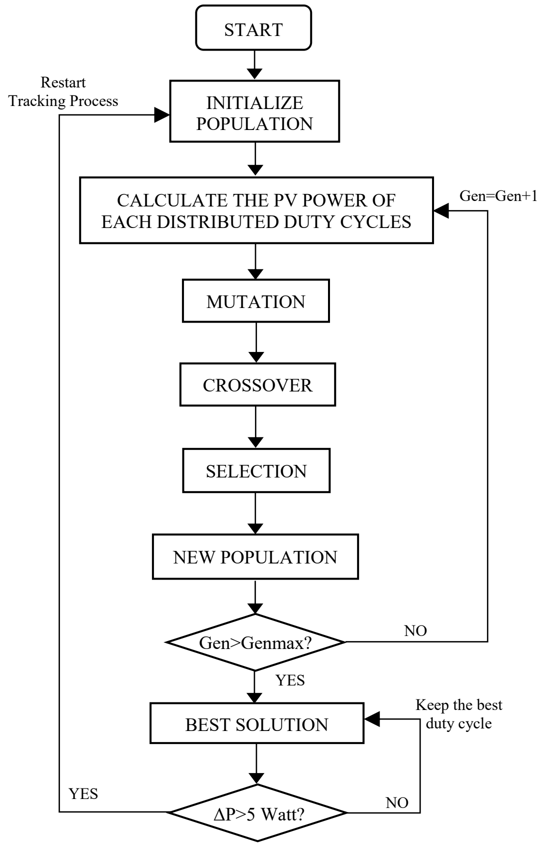

Fig. 8. The flowchart of proposed MPPT DE algorithm.

IV. Simulation Result

The simulation is validated by the use of PSIM software. To test the proposed algorithm performance, the irradiance is set to fluctuate rapidly during 4 seconds on both modules. The irradiance condition is arranged on 4 partial shading patterns as shown in Table III. The P-V characteristic curve of the 4 partial shading pattern is shown in Fig. 9 where each of the patterns has the global maximum power point (GMPP). The value of the GMPP on pattern 1 is 170 Watt. The value of the GMPP on pattern 2 is 88 Watt. The value of the GMPP on pattern 3 is 152 Watt. The value of the GMPP on pattern 4 is 131 Watt. The simulation circuit is shown in Fig. 10. The comparison is made with the PSO algorithm.

TABLE III. PARTIAL SHADING PATTERNS

Module Number	Solar Irradiance (W/m^2)			
	Pattern 1	*Pattern 2*	*Pattern 3*	*Pattern 4*
1	1000	700	700	900
2	800	400	1000	600
Time (s)	1	2	3	4

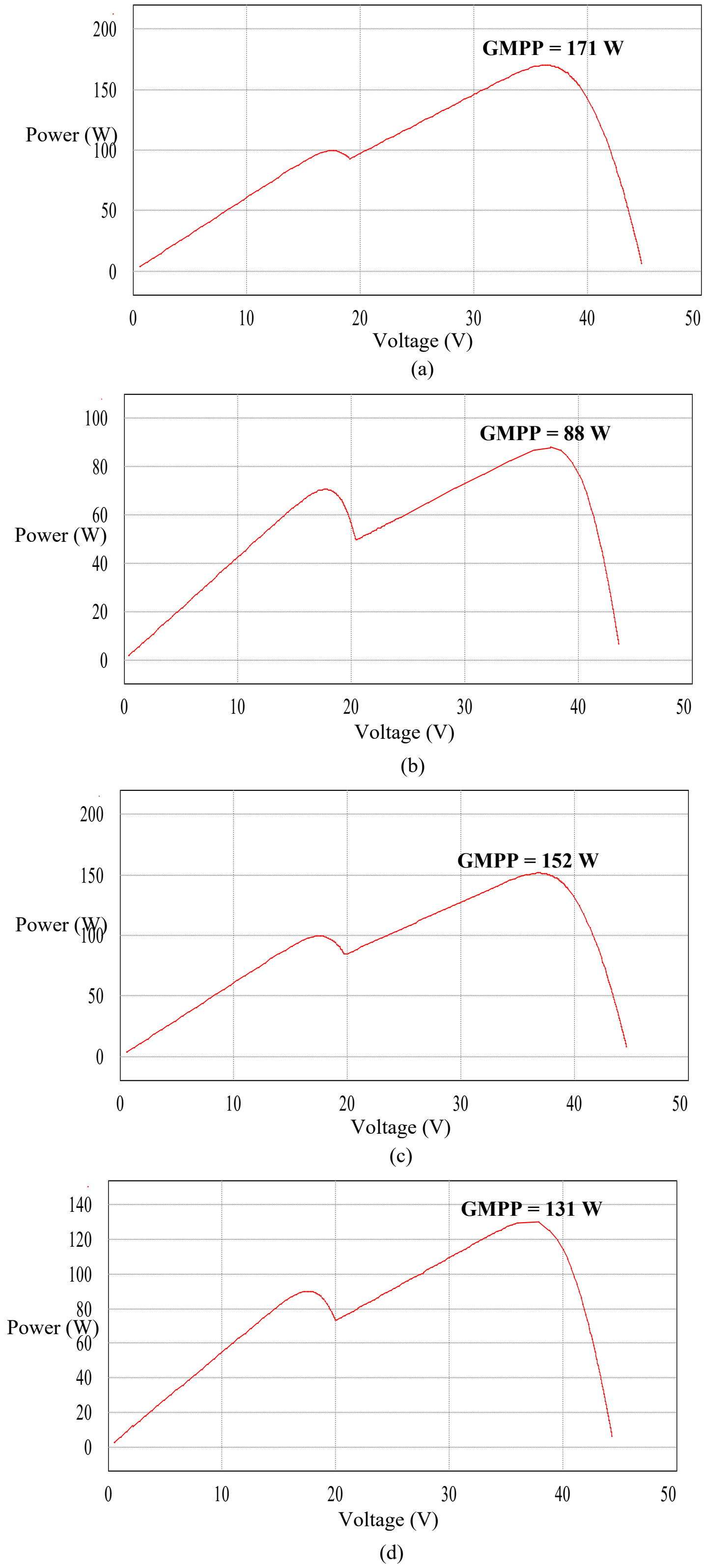

Fig. 9. The P-V characteristic curve for 4 partial shading patterns; (a) patern 1, (b) pattern 2, (c) pattern 3 and (d) pattern 4.

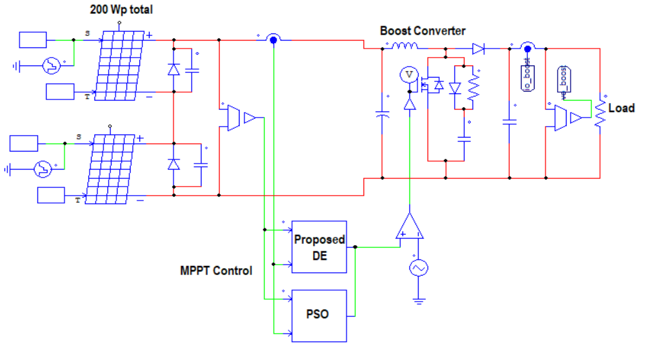

Fig. 10. The simulation circuit in PSIM software.

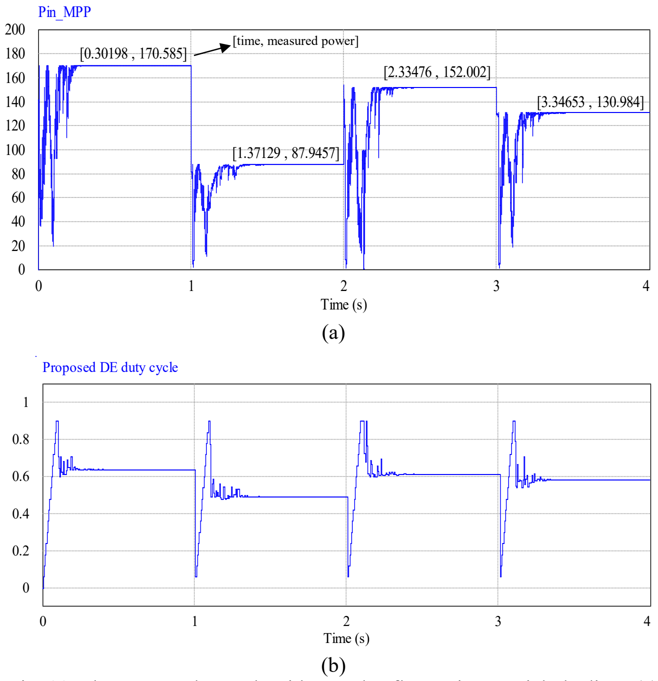

Fig. 11. The proposed DE algorithm under fluctuating partial shading; (a) MPPT tracking process and (b) duty cycle value

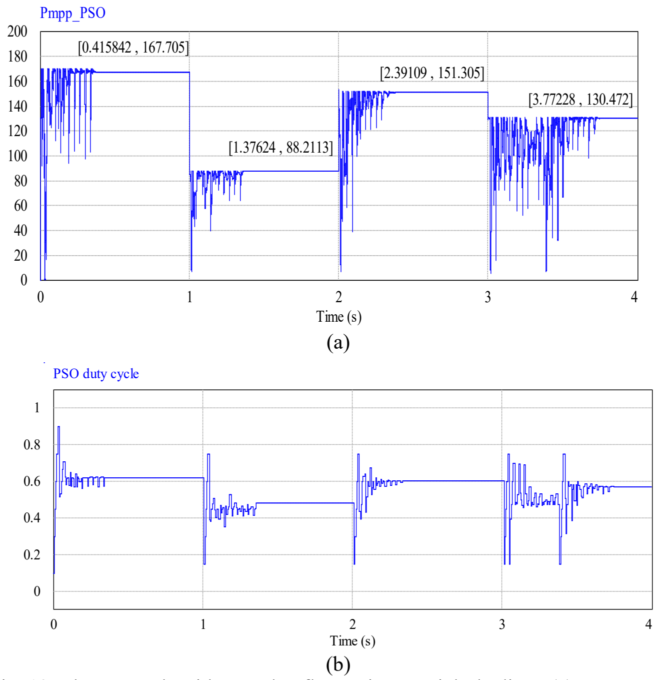

Fig. 12. The PSO algorithm under fluctuating partial shading; (a) MPPT tracking process and (b) duty cycle value

The simulation result for the proposed DE algorithm is shown in Fig. 11 and Fig. 12, where a comparison is made with the PSO algorithm to evaluate the tracking speed and MPPT accuracy. When the first pattern applied to the photovoltaic modules, the proposed DE algorithm is able to track the GMPP with a value of 170.5 Watt after 0.301 s while the PSO algorithm tracked the GMPP value of 167.7 Watt after 0.415 s. Then, the second partial shading pattern is applied, and the proposed algorithm is able to restart the tracking of the GMPP which the new value is 87.9 Watt after 0.371 s while the PSO algorithm tracked the GMPP value of 88.2 Watt after 0.371 s. The third pattern is applied and the GMPP value is reached on 152 Watt after 0.233 s while the PSO algorithm tracked the GMPP value of 151.3 Watt after 0.239. The last pattern is applied and the proposed algorithm succeeds in finding the GMPP value which is 130.9 Watt after 0.334 s while the PSO algorithm tracked the GMPP value of 130.4 Watt after 0.77 s. The average comparison can be seen in Table IV. The duty cycle value of the proposed DE algorithm is shown in Fig. 11 (b) and where each duty cycle value that is related to each MPPT process has converged to the best duty cycle value. The proposed algorithm begins the MPPT process by distributing duty cycle value in the range of 5% to 90% (0,05 to 0,9) in the first iteration. Next, mutation and crossover process begin the tracking process until the GMPP of the photovoltaic system is tracked and the duty cycle is locked to avoid power oscillation. If there is any change in solar irradiation, the algorithm repeats from the beginning. Based on the first partial shading pattern, after the GMPP is tracked, the duty cycle remains at 0.64. Then, the next partial shading pattern is applied and the algorithm detects the drop on photovoltaic power. The duty cycle repeats to distribute again to scan the MPPT search space. Once the GMPP is reached, the duty cycle remains at a new value which is 0.49. This mechanism is used to find the GMPP on the next two partial shading patterns.

TABLE IV. COMPARISON OF THE PROPOSED DE AND PSO

Evaluated parameters	***Proposed DE***	***PSO***
Accuracy	99.9 %	99.2 %
Tracking speed	0.309 s	0.45 s

V. CONCLUSION

In this work, the performance of MPPT using differential evolution (DE) algorithm with dual mutation is tested on fluctuating partial shading condition. The mutation strategy uses DE/Best/1 variant so that the searching process is based on the best vector with the best fitness value. The two mutation factors are tuned to give a better convergence speed. The proposed algorithm demonstrates a fast and accurate response in tracking the GMPP under fluctuating partial shading condition. The GMPP is tracked under 1 second in every change on partial shading pattern and the average tracking time is 0.332 s. The proposed MPPT shows a good result to mitigate the partial shading condition on the photovoltaic array.

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REFERENCES

[1] B. K. Oubbati, M. Boutoubat, M. Belkheiri and A. Rabhi "Global maximum power point tracking of a PV system MPPT control under partial shading," 2018 International Conference on Electrical Sciences and Technologies in Maghreb (CISTEM), Algiers, pp. 1-6, 2018.

[2] C. Hua and Y. Chen, "Modified perturb and observe MPPT with zero oscillation in steady-state for PV systems under partial shaded conditions," 2017 IEEE Conference on Energy Conversion (CENCON), Kuala Lumpur, pp. 5-9, 2017.

[3] M. H. Rashid, "Chapter 27 : Photovoltaic System Conversion," in *Power electronics handbook: devices, circuits, and applications*, 3rd ed., Amsterdam, Netherland: Butterworth-Heinemann, pp. 711–716, 2011.

[4] A. Hidayat, A. B. Muhammad, N. Ayub Windarko and M. Z. Efendi, "Short Circuit Current Based ANN MPPT For Battery Charging," 2019 International Electronics Symposium (IES), Surabaya, Indonesia, pp. 422-427, 2019.

[5] K. Harini and Syama S., "Simulation and analysis of incremental conductance and Perturb and Observe MPPT with DC-DC converter topology for PV array," 2015 IEEE International Conference on Electrical, Computer and Communication Technologies (ICECCT), Coimbatore, pp. 1-5, 2015.

[6] A. Musafa, P. W. Purnawan, A. S. Tri Yulianto, A. Priyadi, M. Pujiantara and M. H. Purnomo, "Fuzzy Logic Based MPPT with Feedback Control for Photovoltaic Application," 2018 International Seminar on Intelligent Technology and Its Applications (ISITIA), Bali, Indonesia, pp. 169-174, 2018.

[7] M. N. Habibi, N. Ayub Windarko and A. Tjahjono, "Hybrid Maximum Power Point Tracking Using Artificial Neural Network-Incremental Conduction With Short Circuit Current of Solar Panel," 2019 International Electronics Symposium (IES), Surabaya, Indonesia, pp. 63-69, 2019.

[8] K. S. Tey, S. Mekhilef, M. Seyedmahmoudian, B. Horan, A. T. Oo and A. Stojcevski, "Improved Differential Evolution-Based MPPT Algorithm Using SEPIC for PV Systems Under Partial Shading Conditions and Load Variation," in IEEE Transactions on Industrial Informatics, vol. 14, no. 10, pp. 4322-4333, Oct. 2018.

[9] M. Seyedmahmoudian et al., "Simulation and Hardware Implementation of New Maximum Power Point Tracking Technique for Partially Shaded PV System Using Hybrid DEPSO Method," in IEEE Transactions on Sustainable Energy, vol. 6, no. 3, pp. 850-862, July 2015.

[10] S. Das and P. N. Suganthan, "Differential Evolution: A Survey of the State-of-the-Art," in IEEE Transactions on Evolutionary Computation, vol. 15, no. 1, pp. 4-31, Feb. 2011.

[11] ICA Solar, "PV Module: polycrystalline," 50-310 Wp datasheet, 2019.

[12] R. S. Magdaleno, P. A. Sánchez-Pérez, J. L. Z. Ramírez Cruz, D. M. Escobar and A. Sánchez-Juárez, "Influence of partial shading on the power output of a solar cell and a PV module," 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC), Waikoloa Village, HI, pp. 1324-1327, 2018.

[13] H. Ibrahim and N. Anani, "Variation of the performance of a PV panel with the number of bypass diodes and partial shading patterns," 2019 International Conference on Power Generation Systems and Renewable Energy Technologies (PGSRET), Istanbul, Turkey, pp. 1-4, 2019.

[14] J.C. Teo, R.H.G. Tan, V.H. Mok, V.K Ramachandaramurthy, C. Tan, "Impact of Partial Shading on the P-V Characteristics and the Maximum Power of a Photovoltaic String," Energies, 2018.

[15] X. Yuan, D. Yang and H. Liu, "MPPT of PV system under partial shading condition based on adaptive inertia weight particle swarm optimization algorithm," 2015 IEEE International Conference on Cyber Technology in Automation, Control, and Intelligent Systems (CYBER), Shenyang, pp. 729-733, 2015.

[16] D. W. Hart, "Chapter 6 : DC-DC Converters," in *Power Electronics*, New York, USA: McGraw-Hill, pp. 211–216, 2011.

[17] R. Patil and H. Anantwar, "Comparative analysis of fuzzy based MPPT for buck and boost converter topologies for PV application," 2017 International Conference On Smart Technologies For Smart Nation (SmartTechCon), Bangalore, pp. 1479-1484, 2017.

[18] R. Storn and K. Price, "Minimizing the real functions of the ICEC'96 contest by differential evolution," Proceedings of IEEE International Conference on Evolutionary Computation, Nagoya, Japan, pp. 842-844, 1996.

[19] K. V. Price, R. M. Storn, and J. A. Lampinen, *Differential Evolution: a Practical Approach to Global Optimization*. Dordrecht, Germany: Springer-Verlag Berlin and Heidelberg & Co. KG, 2006.