# DIFFERENTIAL EVOLUTION BASED MAXIMUM POWER POINT TRACKER FOR PHOTOVOLTAIC ARRAY UNDER NON-UNIFORM ILLUMINATION CONDITION

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#### Abstract

Photovoltaic system (PV) is an important technological asset for renewable energy production. It works by converting solar cell energy from the sun into electrical direct current. In reality, the photovoltaic module usually receives non-uniform solar irradiance at different light intensity due to non-atmospheric hindrance. Under such conditions, the PV system exhibits multiple peaks on the energy characteristic curve, generally known as the partial shading condition (PSC). Therefore, in order to maximize the energy harvested by the photovoltaic system (PV), maximum power point tracking (MPPT) method is suggested to extract all possible maxima that have been produced by the PV system under various circumstances through the non-uniform irradiance of the sunlight. Based on previous researches, it is found that conventional method such as perturb and observed (P&O) method failed to track the maximum power and was trapped at the local maximum power (LMPP). This paper focuses on exploring a metaheuristic method which is the differential evolution (DE) algorithm in optimizing the energy harvested by the PV system. The platform chosen for modelling in this paper is a 3×3 PV array. The PV array is tested with different conditions of partial shading where random irradiance values are set. Comparing the performance of PV between P&O and DE based MPPT controller, the DE based MPPT controller is inferred to have a higher success rate to escape from being trapped in LMPP and thus produce more total energy.

#### Keywords:

Photovoltaic system, Maximum Power Point Tracking, Partial Shading Condition, Perturb and Observed, Differential Evolution

### **1. INTRODUCTION**

As the years go by, the demand for power/electricity is increasing. Electricity is an important resource for the society to live. Generally, most of the electricity is produced by burning fossil fuel, which is a non-renewable energy source that would deplete in the future [1]. It is foreseeable that non-renewable energy sources like fossil fuels will become too expensive for consumption, let alone the damages done to the environment in order to obtain the resource [2].

Hence, the demand for renewable energy has increased rapidly in this era of globalization [3]-[5]. Renewable energy gives a positive impact to the environment as the energy is generated through the natural resource such as sunlight, wind, rain, etc. Therefore, renewable resources could sustain continual energy supply as they are constantly replenished.

Among all types of renewable sources, solar power is popular in Malaysia due to several advantages, such as its comparatively ready availability and relatively low maintenance [6] [7], besides the minimal impact on the environment. Photovoltaic system (PV) is used to convert solar energy into electric energy [8]. Solar PV

produces direct current by converting the solar cell energy directly from the sun into stream of electrons [9].

The power output of the PV array may reduce as the PV panels are connected close to each other and lead to the occurrence of partials shading condition (PSC). Under PSC, the unshaded modules of PV array receive solar irradiation at a higher level, while the shaded modules of PV array receive lower irradiation [10]. Therefore, the multiple maximum power points occur under the PSC [11].

The conventional technique such as perturb and observed (P&O) are normally unable to track the maximum power point. Nevertheless, this conventional technique requires oscillating power output around the maximum power point. However, it will potentially trap at the local maximum power point (LMPP) instead of global maximum power point (GMPP) [12]. Besides, under a fixed perturb size it will affect the tracking time duration to track the power point and the size of fluctuation. As the perturb size becomes larger, the tracking time is faster but the fluctuation is bigger. Meanwhile, the smaller the perturb size, the slower the tracking time although smaller fluctuation can be obtained [13].

Therefore, to balance the fluctuation with the tracking time to track the power point, differential evolution (DE) is proposed. In fact, P&O has been used to track the maximum power point. Hence, this paper would explore the potential of DE to enhance the performance of energy harvested by the PV system. The proposed algorithm is tested in a PV system under non-uniform irradiance condition. This is because the PV array will exhibit several maximum power points (MPP) when the array is illuminated with different levels of irradiance values. DE is implemented to optimize the MPPT and to examine its performance in comparison to P&O under PSC.

### 2. REVIEW OF MPPT METHODS

Various studies on tracking the maximum power of PV system show that it has become important in PV development [14]. Scholars have researched extensively for improving the efficiency of MPPT by implementing various algorithms. Several techniques for MPPT have been proposed, including the ones based on perturbation and observation (P&O), [15] [16] rule-based algorithm, and evolutionary algorithm (EA) [17] [18]. These techniques basically search for the maximum power point (MPP) within a local search space.

The clouds, objects or buildings that are located near the PV array could create shadows on its surface [19]. Besides, there could be mismatch in the power generation of the PV due to the dirtiness and the different orientation of the parts of the PV. Hence, the characteristic of the PV array which encounters the mismatch in operating conditions will produce more than one

peak [20]. Various techniques have been developed to optimize the maximum power point based on previous researches [21] [22]. The conventional methods include P&O [23] and rule-based algorithm [24].

In recent years, the MPP techniques for tracking the maximum power have been proposed under the conventional methods which are quite useful and popular due to its simplicity [25]. A wellknown P&O that works satisfactorily when the irradiance fluctuates very slowly is proved. However, it has often failed to track global MPP when the irradiance changes suddenly [26]. Unfortunately, another problem of P&O is the time-consuming issue in getting the MPP [27]. This is due to the dependency on the initial condition of the system. P&O algorithm was found to have many drawbacks that are overcome by the fuzzy-logic controller (FLC). The previous research has found that the optimum point is tracked after the slope changed [28].

In FLC, the slope of the power and current will also change. Since the duty cycle is neglected, this limits the exploration of the algorithm to seek the optimum solution, because every control decision is precisely calculated based on the predefined rules and membership functions [29].

Remarks Method Advantages Disadvantages Conventional Failed to track the Quite useful and GMPP Method popular to be used Works satisfactorily Perturb and Time consuming for the when the irradiance Observed P&O to get the MPP fluctuates very slowly The duty cycle is Optimum point will neglected and limiting be tracked after the Fuzzy-logic the exploration of the slope changed algorithm Few issues such as the Optimizes the problem by iteratively dynamic problems, pass Particle trying to improve a up stagnation, handle-Swarm candidate solution constraint and multiple Optimization based on a given objective are still being measure of quality conducted to overcome Do not require Low speed and Genetic derivative information degradation for highly Algorithm and deals with large interactive fitness number of variables function Able to locate accurate global optimum regardless of Differential the initial parameter Evolution values, rapid convergence and utilizing few control parameters

Table.1. Summary for Review of MPPT in PV system

Conventional methods have failed to track the GMPP as it can be trapped at the LMPP. Metaheuristics methods, such as Differential Evolution (DE), Particle Swarm Optimization (PSO), and Genetic Algorithm (GA) have been developed and experimented. Some of these algorithms are intended for social behaviour simulation. For instance, the original purpose of PSO is to represent the movement of organisms in a school of fish or a flock of bird. This approach could optimize the problem by iteratively trying to improve a candidate solution based on a given measure of quality [30]. However, few issues are yet to be resolved including the dynamic problems, pass up stagnation, handle-constraint and multiple objectives [31].

GA has been proposed in the optimization problem as it does not require derivative information and deals with a large number of variables [32]. Unfortunately, GA faced a problem of low speed and degradation for the highly interactive fitness function.

Therefore, this paper would explore the potential of DE for optimization. Previous research found that DE can locate the accurate global optimum regardless of the initial parameter values. Moreover, DE could converge faster to the global point, utilizing a few of the control parameters. DE is easy to be implemented [33]. Unlike PSO, there are only two parameters that are required to be set in DE, thereby reducing the complexity in tuning the required parameters to achieve accurate MPPT [34]. DE is well suited to solve problems that are non-differentiable, non-continuous, nonlinear, noisy, flat, multidimensional, have many local minima or maxima, constraints, and stochastic.

### **3. METHODOLOGY**

This section will discuss the methodology for the paper where it is separated into two subsections. The first subsection will discuss the modelling of the PV system. The platform of this modelling is a  $3\times3$  PV array. Then, the methodology of maximum power point tracking based on the differential evolution will be discussed in the second subsection.

#### 3.1 PLATFORM MODELLING

As mentioned above, the modelling platform is a  $3\times3$  PV array but in order to build a PV array, the main PV cell is discussed. The Fig.1 shows a single-diode of a PV cell. The single-diode circuit consists of PV array, controller unit, and AC/DC loads as shown in the Fig.1, which is the block diagram of a PV cell. The Fig.2 shows the PV-cell equivalent circuit models. A single-diode is a model where it has four components namely a photo-current source, a diode located parallel with the source, a series resistor,  $R_s$  and a shunt resistor,  $R_{sh}$ .

Therefore, the PV cell is represented by a single diode model where it consists of light generated current source,  $I_L$ , diode and current diode flows from positive to negative, equivalents to shunt resistor,  $R_{sh}$  and the equivalent series resistor,  $R_s$ . The shunt resistance,  $R_{sh}$  is neglected as the value is larger. The relation of the voltage with the current is described as below:

$$I = I_L - I_D = I_L - I_o \left[ e^{\frac{q(V + IR_S)}{\alpha}} - 1 \right] - \frac{V + IR_S}{R_{sh}}$$
(1)

where,  $I_L$  is light-generated current of the cell,  $I_O$  is diode saturation current, I is terminal current, V is the output voltage,  $R_s$  is series impedance,  $R_{sh}$  is the shunt resistance, q is electron charge (1.602×10<sup>-19°</sup>C), and  $\alpha$  is the thermal voltage timing completion factor.

In order to obtain the characteristic graph of current versus voltage,  $I_L$ ,  $I_O$ ,  $R_S$  and  $\alpha$  must be determined. Therefore,  $I_L$  can be calculated as:

$$I_{L} = \frac{\emptyset}{\emptyset_{REF}} \left[ I_{L,REF} + \mu_{I,SC} \left( T_{C} - T_{C,REF} \right) \right]$$
(2)

where,  $\emptyset$  is the irradiance value,  $\emptyset_{ref}$  is 1000W/m<sup>2</sup> known as reference irradiance  $I_{Lref}$  is light at references and  $\mu_{I,SC}$  is short circuit temperature coefficient,  $T_c$  is the temperature of the PV cell and  $T_{C,REF}$  is 25°C which is the reference temperature.

Consequently, the saturation current can be expressed as:

$$I_{o} = I_{o,REF} \frac{T_{C,REF} + 273}{T_{C} + 273} e^{\left[\frac{e_{gap}N_{S}}{q\alpha_{REF}} \left(1 - \frac{T_{C,REF} + 273}{T_{C} + 273}\right)\right]}$$
(3)

where,  $I_{O,REF}$  is the reference of saturation current which can be calculated as  $I_{O,REF} = (I_{L,REF} e(-V_{OC,REF}/e_{gap}\alpha_{REF}), e_{gap}$  is the band gap which commonly use 1.17eV for Si materials,  $N_S$  is the number of cells in series of PV module and  $\alpha$  is thermal voltage timing completion factor at reference. Meanwhile,  $\alpha_{REF}$  can be calculated as:

$$\alpha_{REF} = \frac{2V_{mp,ref} + V_{OC,REF}}{\frac{I_{SC,REF}}{I_{SC,REF} - I_{MP,REF}} + \ln\left(1 - \frac{I_{MP,REF}}{I_{SC,REF}}\right)}$$
(4)

where,  $V_{mp,ref}$  is the maximum power point voltage at reference,  $I_{mp,ref}$  is the maximum power point current at reference, and  $I_{sc,ref}$  is the short circuit current at references. Then, the function of temperature and series resistance can be expressed as:

$$\alpha = \frac{T_C + 273}{T_{C,REF} + 273} \alpha_{REF} \tag{5}$$

$$R_{S} = \frac{\alpha_{REF} \left( \frac{I_{SC,REF}}{I_{SC,REF} - I_{MP,REF}} \right) V_{OC,REF} - V_{MP,REF}}{I_{MP,REF}}$$
(6)

In order to form a photovoltaic panel as shown in Fig.3, the photovoltaic cells are connected in series and parallel with suitable parameters. The number of cells that connected in series and parallel are being considered and Eq.(1) becomes:



Fig.1. Block diagram of photovoltaic cell



Fig.2. Equivalent circuit of a photovoltaic cell

Fig.3. Photovoltaic Platform

#### 3.2 PROPOSED DIFFERENTIAL EVOLUTION

This subsection discusses the development of the proposed differential evolution based MPPT. The first algorithm that is introduced for optimization and searching is differential evolution (Ref Parameter). This method is based on the optimization which is practically used to treasure the best optimal solution concerning some conditions. As the differential evolution is quite effective and efficient in optimization, differential evolution has gained popularity in recent years.

Differential evolution works when there is an agent which consists of a population of candidate solution. Then, a mathematical formula is used for the candidate solution to move around the search-space. This process is to make existing agents combine with the population.

After that, the candidate solution will be evaluated and compared. A comparison will be made, wherein, if the new position of the agents is an improvement, the new agents will be accepted as a part of the population. Otherwise, the new population will simply be discarded and will not be counted into the population.

In differential evolution, there are four basic steps. They are initialization, mutation, recombination and selection as shown in Fig.4. Differential evolution starts with initializing the random population, which is then improved by using mutation, crossover and selection. This process is repeated through a generation until the stopping criteria is reached. The best fitness value is usually selected to combine with the current power to get the maximum power.

Differential evolution works on the population of a candidate solution. The process of differential evolution starts with choosing the size of the population which is basically at least four N number. The parameter vectors are stated as in the following form:

$$X_i G = [x_i G, x_2 i G, \dots, x_D i G]$$
 where  $i = 1, 2, \dots, N$  (8)

where, G is the generation number.

Subsequently, the upper and the lower bound are initialized for each parameter where the upper bound is commonly two, and lower bound is zero. The initial parameter is randomly selected on the interval. Next, the algorithm reached the mutation stage, where each of the N parameter experiences mutation. Then, there will be a random selection of three numbers to get the vector. The vector of Eq.(9) is as follows:

$$V_{I}G + 1 = [x_{i}G + F(x_{r1}G - x_{r1}G)]$$
 (9)

where, *F* is a mutation factor in interval of zero to two and  $V_iG+1$  is donor vector. After mutation, recombination includes successful solution from the previous generation. Trial vector which is  $u_{i,j}$ , G+1 is formed from the comparison of the random number with a crossover rate, *CR*. If the random number is smaller than the *CR*, the trial vector will be the donor vector. Otherwise, it will be the first population.

Finally, the selection will be the last part of DE. Selection works by comparing the target vector with the trial vector. The one with the lowest function will be the next generation. This DE algorithm will be executed when the stopping criterion is met.



Fig.4. Basic stage of Differential Evolution Algorithm



Fig.5. Flowchart of Differential Evolution Algorithm

The Fig.5 illustrates the flowchart of the proposed algorithm which focused on the differential evolution. The proposed algorithm is tested under two cases for the modelling, as discussed in detail by the result and discussion section. The irradiance values are randomly chosen from 250Wm<sup>-2</sup> until 1000Wm<sup>-2</sup>. The partial shading that happened on the modelling of the PV system in the Matlab simulation is considered for the irradiance values set.

#### 4. RESULT AND DISCUSSION

This section discusses the result of the modelling and the performance of the proposed algorithm in comparison to the conventional method on a PV system under different conditions. Thus, this section is separated into two subsections where the first subsection is the verification of the modelling and the second subsection is the result for the proposed algorithm.

#### 4.1 VERIFICATION OF MODELLING

Based on the description of modelling methodology, this paper modelled a  $3\times3$  PV array as per the datasheet of Mitsubishi Electric Solar Panel 125W PV-AE123MF5N. The parameters of PV module are shown in Table.2. Thus, to verify the modelling, simulation is made in the Matlab and the characteristic result of a photovoltaic module is shown as Fig.6.

Parameter	Symbol	Value
Maximum power	P <sub>max</sub>	125W
Voltage at maximum power	$V_{MP}$	17.3V
Current at maximum power	I <sub>MP</sub>	7.23A
Open circuit voltage	Voc	21.8V
Short circuit current	ISC	7.9A
Temperature coefficient of $V_{oc}$	$\overline{K_V}$	-0.343V/°C
Temperature coefficient of $I_{sc}$	K <sub>I</sub>	0.054A/°C
Temperature coefficient of $P_{max}$	K <sub>P</sub>	-0.452%/°C
Operating temperature	Т	47.5°C
Number of photovoltaic cells	-	36





(a) P-V Characteristic

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(b) I -V Characteristic

Fig.6. Characteristic of a PV Module

Based on the result of simulation for a PV cell, the maximum power is 125W at the operating voltage of 17V. Meanwhile, the open-circuit voltage is 21.8V and short circuit current is 7.9A, as shown in Fig.6. This shows that the simulation result matches the datasheet result as revealed by Table.3.



(b) I-V Characteristic

Fig.7. Characteristic of 3×3 PV Array

Thus, the photovoltaic system is modelled with a  $3\times3$  PV array and the result is shown in Fig.7. The maximum power of the PV array is 1125W at operating voltage of 50.72V. While the open circuit voltage is 65.4V and the short current is 23.7A. This means that the power of PV array is 9 times more than the power of a PV module as it is connected in series and parallel as given by the Eq.(10). The Table.3 shows the summary for the modelling verification, wherein, the PV module simulation is compared with the datasheet of the PV module.

$$_{max} = 125W \times (9 \text{ PV module}) = 1125W$$
(10)

Table.3. Summary for Modelling Verification

Characteristic	PV module datasheet	PV module simulation	PV array simulation
Power maximum, <i>P<sub>max</sub></i>	125W	125W	1125W
Open circuit voltage, V <sub>oc</sub>	21.8V	21.8V	65.4V
Short circuit current, <i>Isc</i>	7.9A	7.9A	23.7A

#### 4.2 PERFORMANCE OF ALGORITHM

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In this subsection, the performance of tracking the maximum power of the PV system based on the proposed algorithm is discussed. The proposed algorithm is tested with three cases where the irradiance values randomly choose from 250Wm<sup>-2</sup> until 1000Wm<sup>-2</sup>. The irradiance values set is considered as the partial shading happened on the modelling of the PV system in the Matlab simulation. Thus, the parameters of differential evolution are set as in Table.4.

When non-uniform irradiance values occur at the PV system, the characteristic of the PV system exhibits multiple peaks. This is due to the presence of diode in the PV module. When the PV system generates the power, bypass diode will be reverse biased under uniform irradiance values [35]. Conversely, under partial shading conditions, the PV module tends to be reverse biased by other PV modules causing bypass conduction [36]. Thus, the bypass diodes will short-circuit the shaded PV module and allow the current to flow through them, thereby reducing the power loss caused by shaded PV modules and consequently avoiding the exhibition of multiple peaks.

The Fig.8 shows the performance of the proposed differential evolution with different irradiance values. They are set with three different cases which gives three different partial shading conditions. From the graph that is displayed in Fig.8, the tested modelling shows the production of multiple peaks as the irradiance value is different. The three cases show different types of peaks, suggesting different performance of DE in tracking the maximum power of the PV system.

For the first case as shown in Fig.9, the maximum power produced by the modelling is 319.3W at 17.55V operating voltage which is indicated with the red line in Fig.8. Then, the PV system is tested under P&O and DE. The maximum tracking for both algorithms is found at 319.3W, which is same as the maximum power of modelling. This is because the first peak of the modelling is the maximum power. Thus, P&O and DE can track easily but with different iteration values where P&O is at 354 iterations while DE is at 352 iterations. This means that DE is slightly faster than P&O in tracking the maximum power as the step size of DE is better than P&O, and DE is rapidly changed.

For the second case, the maximum peak is at the second peak of the modelling result, as indicated by the blue line, at about 489.8W and operating voltage of 35.28V. Then, the second case is tested on the algorithm as explained in Fig.10, and it is found that the P&O is only able to track the first peak of the modelling which is 349.8W. Meanwhile, DE is successfully tracks the global maximum power up to 489.8W. This proves that the conventional method is only able to track the local maximum power as P&O only assumes a single peak of power against voltage characteristic. Thus, it is trapped at the first peak and is unable to proceed to the next peak to produce the maximum power output, unlike the DE algorithm.

Lastly, the third case is slightly similar to the second case but the maximum power for the third case is at the third peak, which is 497.2W as shown in Fig.8 with a magenta line. Then, the PV system is also tested under P&O and DE to compare the performance of both algorithms. The Fig.11 shows the result of the P&O and DE in tracking the maximum power of the third case. Based on the result, P&O tracks a local maximum power, similar to the second case, which is at 317.9W; while, the DE can track until the third peak of the modelling which is 497.2W. This shows that DE is better in optimizing the energy of the PV system.

Thus, this proved that DE is one of the meta-heuristic method in order to utilize the power of the PV system. It can trap the GMPP of the PV array under PSC as it tracks the highest maximum point of the PV system. The Table.5 shows a summary of the power performance for three cases. It concludes that DE has 99.9% efficiency under three cases that have different conditions. This shows that DE is able to track the maximum power point at any condition with the efficiency of approximately 99%.

Table.4. Parameter of	Differential	Evolution
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Fig.8. Performance of the modelling under partial shading



Fig.9. Performance of the P&O and proposed DE for Case 1



Fig.10. Performance of the P&O and proposed DE for Case 2



Fig.11. Performance of the P&O and proposed DE for Case 3

Table.5. Summary of the Power Performance

Case	Modelling	P&O	DE
	319.3W		
1	229.2W	319.3W	319.3W
	240.3W		
	349.8W		
2	489.8W	349.8W	489.3W
	148.4W		
3	317.9W		
	484.9W	317.9W	497.2W
	497.2W		

# 5. CONCLUSION

In conclusion, as the PV system undergoes non-uniform irradiance values that are commonly known as partial shading, the PV system exhibits multiple peaks. Based on the PV modelling, it is seen that the more the PV module is used, the higher the power that is produced. The performance of the PV system is tested under different conditions with a mainly focus on the PSC. MPPT controller plays an important role in tracking the maximum power. Conventionally, it is found that the P&O method is unable to track the maximum power when the PV system exhibits multiple peaks. P&O is only successful in tracking the maximum power when the irradiance values are uniform.

Thus, this work presents a differential evolution based MPPT to prevent maximum power point from being trapped at the local optimum and to track the MPPT accurately. Simulation in MATLAB model used different partial shading conditions. The performance of the MPPT is compared between the conventional and meta-heuristic method, which are P&O and DE. It concludes that DE is able to track the maximum power of PV system better than the P&O, thereby optimizing the energy harvested by a PV system with DE.

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