Optimised Maximum Power Point Tracking for Non-uniform PV Array*

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Okpoti, F. K., Attachie, J. C., Adjei, P. and Amuzuvi, C. K. (2022), Optimised Maximum Power Point Tracking for Non-uniform PV Array", *Ghana Journal of Technology*, Vol. 6, No. 2, pp. 1 - 8.

Abstract

Installed photovoltaic (PV) array works in difficult conditions or harsh environments, therefore, non-uniform aging will occur and affect unfavourably the performance of a PV system, particularly at the centre during their life span. Because of the high cost of supplanting matured PV modules by new modules, it is important to enhance the energy efficiency of matured PV system. For this reason, this project displays a PV module reconfiguration methodology to accomplish the maximum power generation from non-consistently matured PV system without critical investment. At a point when PV systems are influenced by aging, a Global Maximum Power Point Tracking (GMPPT) algorithm is needed to build the energy reaping capacity of the system. A new GMPPT algorithm is proposed using a Perturb and Observe (P&O) algorithm, which is incorporated into a Genetic Algorithm (GA) function to create a single algorithm. By embedding a simple P&O into a GA algorithm, the population size and the number of iterations are decreased, thus finding the Maximum Power Point (MPP) in a shorter time. The algorithm parameters (population size, number of genes, and number of iterations) are Optimised and the final solution is provided. The control part and the GMPPT algorithm were tested and analysed in MATLAB for a small-scale photovoltaic system. A description of this algorithm and its performance is detailed and verified through simulation.

Keywords: Global Maximum Power Point Tracking, Photovoltaic, Genetic Algorithm

1 Introduction

Energy from conventional sources is limited because of their finite nature. The world is shifting from the use of conventional sources to non-conventional sources due to its adverse effect on the environment. Solar PV is one of the non-conventional source of energy being considered aggressively by the world today. Others, such as biomass and wind technology are augmenting the realisation of this vision. The integration of these and many other renewable energy sources is giving rise to the use of micro-grid system for power generation (Vasquez *et al.*, 2009). The micro-grid operation, which consists of distributed energy resources and loads can be employed in both grid-connected and stand-alone modes and has service reliability and environmental friendliness as its major advantages (Balaguer *et al.*, 2011).

However, this technology has a disadvantage of a mismatch between its output voltage and current when the condition of partial shading is encountered by the PV module (Lijun *et al.*, 2009). During this condition of partial shading of the PV module, the tracker (MPPT) will fail in realising the Global Maximum Point (GMP) needed for an efficient power output (Ahmed *et al.*, 2011).

An investigation of partial shadowing conditions in Noguchi *et al.* (2002) demonstrates that, utilising a traditional MPPT amid partial shadowing lowers the PV's power output. By this, a considerable measure of inquiries has been directed to help decide how this setback can be improved for a superior and efficient output.

Patel and Agarwal (2008) proposed an MPPT, which is short-circuit based with a quick sweep in light of the power and voltage curve to recognise the relative component that is ordinarily utilised as part of an MPPT, which is current based. When the GMP is located, an extra switch, which is connected to the source of the photovoltaic in parallel is needed to process the short circuit current at regular intervals (Masoum *et al.*, 2002). Along these lines, this technique if allowed causes momentary power losses and requires additional cost to fix. To abstain from utilising an additional switch, Kazmi *et al.* (2009) proposed a controller that has the ability to swing the duty cycle of the converter from 0 to 1 in order to gauge the open circuit voltage (V_{oc}) and short circuit current (I_{sc}) and thereafter, determine the ideal current and voltage. Considering the values calculated, the working point is moved in one stage to the ideal working point. The traditional hill-climbing technique is utilised to keep up the maximum point close to the operating point (Alajmi *et al.*, 2013).

Liu (2009), noted that several MPPT tracking methods proposed to solve the issue of power loss have failed, since none was able to identify effectively the occurrence of partial shading. Considering a test of partially shaded PV system, Liu (2009) did not consider the observation made by

**Manuscript received October 20, 2021*
Revised version accepted March 20, 2022

Patel and Agarwal (2008), but maximum power point tracking in light of a partial shadowing identifier and traditional hill climbing has been advanced by Ismail *et al.* (2013). Additionally, Ismail *et al.* (2013) saw that, the GMP of a PV system under non-uniform condition is constantly situated to one side of the GMP at ordinary climate conditions.

In Alajmi *et al.* (2013), a line search technique with Fibonacci sequence has been utilised to monitor the GPP under partial shadowing conditions. This strategy, however, can fail to recognise the Global Maximum Power Point GMPP in some partial shadowing conditions. An optimisation algorithm known as the Particle swarm has been inferred to monitor the maximum global working point under anomalous climate conditions. A vast time delay is needed to enable specialists to process the GMP, bringing about a long calculation time to achieve the greatest working point.

A two-level maximum power point tracking utilising tracking cells was initiated in Kobayashi *et al*. (2003), where at the principal stage, the operating point moves to the maximum power point by accepting that, the power-voltage curve is uniform. In stage two, the strategy known as increment resistor is utilised to find the real maximum power point. It could ignore the global maximum power point in some partial shadowing conditions, and furthermore, V_{oc} and I_{sc} estimations are needed. A versatile PV array is proposed to help lessen the impact of the partial shadowing.

In the proposed power topology, maximum power point tracking (MPPT) technique and the control structure impact on the dependability and effectiveness of the system. With a single MPP, Perturb and Observe (P&O) method can obtain great outcomes for a photovoltaic module.

The proposed calculation is committed to PV systems influenced by aging. A Perturb and Observe technique is incorporated into the Genetic Algorithm structure, in this way forming a solitary algorithm. This technique can find the GMPP on a P-V characteristic with a number of LMPP that is not known on any type of solar panel without any configuration.

2 Resources and Methods Used

The method used is geared towards optimising a non-uniform PV array using P&O technique, which is integrated into a genetic algorithm structure. The processes followed includes: system design, mathematical modelling of healthy PV array and aged or non-uniform PV array, software implementation and simulation using MATLAB/Simulink software version r2010a.

2.1 System Design of the PV Array

Fig. 1 shows the block diagram of the system design for the simulation utilising MATLAB/Simulink. It consists of non-uniform PV arrays arranged in series and connected to a converter (DC-DC). Another converter (DC-AC) is also connected to the design to consider grid connection of the system. A P&O method is developed and integrated into a Genetic Algorithm, which is fed into the system to optimise the efficiency of the system's output.

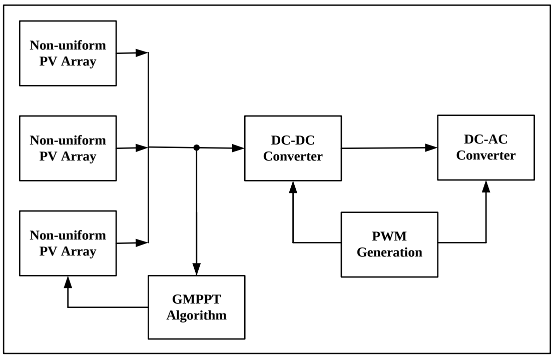


Fig. 1 Block Diagram of the System Design

2.2 Mathematical Modelling

Modelling of both non-uniform aging cell and healthy PV cells are considered in sections 2.2.1 and 2.2.2.

2.2.1 Healthy PV Cell Modelling

Illumination and temperature are the two main electrical attributes that influence PV cells as corroborated by Hu *et al.* (2016). The modelling of the PV cell electrically is given by Equation 1:

$$I = I_L - I_O \left[\exp\left(\frac{\varepsilon V}{T_m} \right) - 1 \right] \quad (1)$$

$$\mathcal{E} = \frac{q}{N_S\, KA} \quad (2)$$

Equations 3 and 4 are components in Equation 1.

$$I_L = \frac{G}{G_{ref}} \left[I_{Lref} + K_i (T_m - T_{ref}) \right] \quad (3)$$

$$I_o = I_{oref} \left(\frac{T_m}{T_{ref}} \right) \wedge 3 \exp\left[\frac{q \times E_{BG}}{N_S \times A \times K} \left(\frac{1}{T_{ref}} - \frac{1}{T_m} \right) \right] \quad (4)$$

where I = current yield for the PV module;
I_L = photon current;
q = electric charge;
A = characteristic factor for the diode;
K = constant for Boltzmann;

I_o = saturated current;
T_m = temperature for the PV module;
G = irradiance;
V = voltage yield;
E_{BG} = electromagnetic band gap;
G_{ref} = irradiance level reference (1000 W/m²);
I_{Lref}, I_{oref} = reference values for I_L and I_o;
K_i = Coefficient for current temperature;
T_{ref} = reference temperature;
N_s = quantity of series-connected cells; and
T_m = temperature for PV module.

The constant dependence of q, N_s, K, A, is ε, which can be calculated using Equation 5:

$$I_{scref} - I_{mpp_{ref}} = \frac{I_{scref}}{\exp\left(\frac{\varepsilon \times Voc_{ref}}{T_{ref}}\right) - 1}\left[\exp\left(\frac{\varepsilon \times V_{mpp_{ref}}}{T_{ref}}\right) - 1\right] \quad (5)$$

where $I_{mpp_{ref}}$= the maximum power point current; I_{scref} = short circuit current, $V_{mpp_{ref}}$ = maximum power point voltage; and Voc_{ref} = open circuit voltage.

2.2.2 Non-uniformly Aged Cell Modelling

Aging of PV array can occur diversely at the level of the cell, module and string. For a cell unit with *m* arrangement PV cells, the connection between the i_{cu} (output current) and the terminal V_{cu} (output voltage) depends on the PV's working points. Hu *et al.* (2016) observed that the short circuit current magnitude for *m* cells is given by the inequality

$$I_{sci1} \leq I_{sci2} \cdots \leq I_{scim}$$

where i_{cell} is the actual current flowing through the PV cells. At a point when i_{cell} increases to I_{sci1} from 0 position, every one of the cells produce power. At a point when i_{cell} surpasses I_{sci1} yet under I_{sci2}, cell i_1 does not produce power: it is transformed into a resistor as a result of the bucket effect. The photovoltaic string comprises of s PV modules, with i_{string} and V_{string} as current and terminal voltage respectively.

2.3 Software Implementation

The software implementation considered both P&O and Genetic Algorithm, which is enacted using MATLAB/Simulink for design and coding.

Perturb and Observe (P&O) Technique

P&O is the most generally utilised MPPT technique. In this instance, the voltage of the module is occasionally given an annoyance and the relating yield control is contrasted and that of the past irritating cycle. In this calculation, a slight irritation is acquainted with the system. This irritation increases the PV module's energy. In the event that there is an increase in power due to the bother, then the annoyance proceeds in a similar way. After the pinnacle power is achieved, the power at the MPP winds up noticeably to zero and the next moment diminishes.

2.4 Proposed Genetic Algorithm

An arbitrary number is utilised to make a single child, like one parent to a limited degree while the remaining indistinguishable to the next parent. For this method, there is coding done with a solitary bit of every quality and also a rearrangement at an irregular position of bits by the change operator. Two parents are picked with the determination operator. These parents deliver an arrangement of posterity by applying the transformation and traditional Genetic administrator hybrid (mutation and crossover). Parents with similar nature are utilised together with the P&O technique to get a new arrangement of people. Another usefulness was then added to the calculation, the best people from the populace guardians utilise hybrid and change to make posterity. The best posterity and parents make the newest populace. This strategy has a superior opportunity to maintain the best people when the cycle is complete.

2.4.1 Individual Iteration

In the wake of experiencing the above procedure for the GA, the fittest individual is picked from both the modified guardians and offspring. The original thought for the global maximum power point tracking strategy is the incorporation of the P&O technique inside the GA. The genetic calculation forsakes its originality, however, carries on as a P&O, that pursuits the GMPPT in a system influenced by partial shading.

The proposed GMPPT calculation which utilises an Optimised GA for tracking in PV systems is often influenced by incomplete shading. The capacities rely on the system to be advanced. The drawback is that, it will lose its generality but become specialised in the Global Maximum Power Point.
The solitary individual's structure for the Genetic Algorithm proposed is introduced. The working point is set by the main chromosome and is given by the controller (Maximum Power Point Tracking) to the power. The rest of the chromosomes (second and third) are utilised by the inserted P&O technique.

Different Genetic Algorithm parameters are: probability of crossover (0.8); probability of mutation (0.1) and size of population (10).

2.4.2 Optimising the Individual Structure

The aim of optimising the individual structure is to limit the time of search of the global maximum power point tracking without modifying the sample time. This implies the quantity of emphasis and populace estimate must diminish. The aggregate execution time of the proposed Global Maximum Power Point tracking calculation is given by Equation 6:

$$T_{alg} = 2.N_{Iteration}.N_{Population}.T_{MPPT} \qquad (6)$$

where $N_{Iteration}$ is the quantity of emphasis of the GA calculation, N is the populace size and T_{MPPT} is the time difference between two voltage references. The objective of the optimisation is to be able to decrease the number of cycles and populace measure as reasonably as can be expected with a specific end goal to diminish the asset utilisation of the processor and still discover the global maximum power point.

Each prepared individual contains data about its working point. As a result of the voltage circle, the data about the person's position on the PV characteristics is put away in the primary chromosome. For every person, the estimation of the primary chromosome is given as a source of perspective to the voltage circle of the system of control. After the system achieves consistent state, it peruses the current and voltage information and processes the power. The level of power is the wellness estimation of the tried person.

2.4.3 Flow Chart

Fig. 2 shows the flow chart of the embedded P&O into GA algorithm to achieve optimisation.

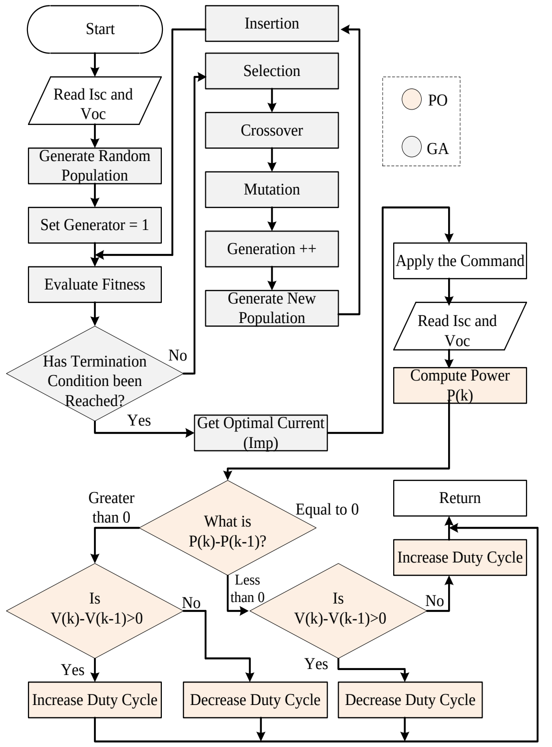


Fig. 2 Flow Chart of P&O Embedded into GA Algorithm

2.5 System Simulation

Fig. 3 shows a diagram of the simulation design. The development of the various blocks is done using Simulink. The P&O method is a subsystem created under one of the blocks, which is integrated into the PV array connection. The codes are written using MATLAB and same for the genetic algorithm.

The codes for the main system is run and graphs representing the voltage, power and current output are displayed. Case 1 and 2 indicate the performance or output without rearrangement and Cases 3 to 5 show better output of the parameters under consideration after optimisation.

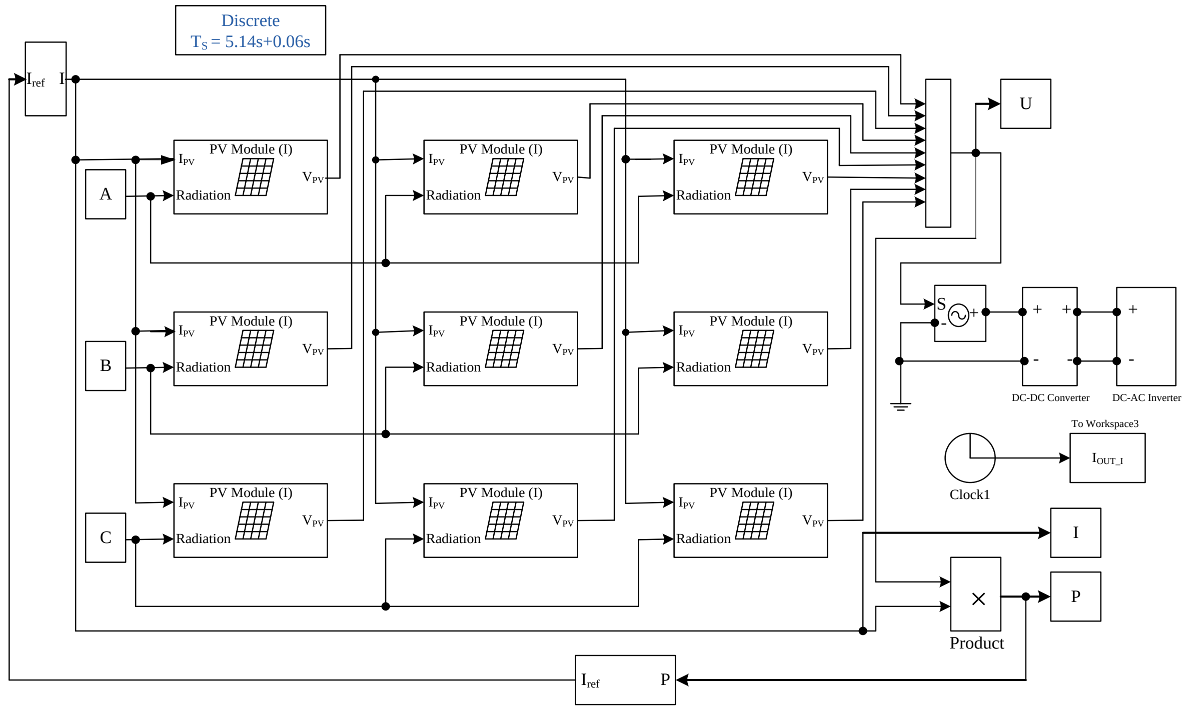


Fig. 3 Simulink Simulation Diagram

3 Results and Discussion

The results arising from the crossover and mutation from Genetic Algorithm and disturbance of the operating point (Perturb and Observe technique) to the point of simulation is discussed in detail. During the simulation with MATLAB of the PV array reconfiguration, a 3×3 PV array is employed. Per unit (pu) is the unit in which the maximum I_{sc} of each photovoltaic module is expressed. Table 1 shows the parameter specification of the PV module. Considering a healthy PV module, for instance, its pu is expressed as 1. The PV array expressed in terms of their per unit can be 0.1 pu, 0.2 pu, 0.5 pu, and 1 pu, which represents a PV array that is aged to one that is healthy. Table 1 is corroborated by Hu *et al.* (2016) as the parameter specification for the module under consideration.

Table 1 Parameter Specification of the PV Cell

Parameter	**Value**
V_{oc}	44.8 V
I_{sc}	5.29 A
Output Power	180 W
Maximum power point Current	5 A
Maximum power point Voltage	36 V
Coefficient of Current Temperature	0.037%/K
Coefficient of Voltage Temperature	-0.34%/K
Coefficient of Power Temperature	-0.48%/K
Cell Operating Temperature	46 ±2˚C

(Source: Hu *et al.*, 2016)

In order to authenticate the strategy proposed in this paper, an 8.5 kW array that is not uniformly aged is used for the test or simulation. Five cases of test were conducted in all; two of the cases considered a PV array before its reconfiguration (Table 2) and three cases considered after reconfiguration (Table 3). Table 2 and Table 3 show the 2×3 PV Array and 3×3 PV before and after reconfiguration respectively.

Table 2 Before Reconfiguration (2×3 Array)

Row (String)	**Column (Module)**
	[0.9 0.8 0.7] [0.9 0.9 0.6] [0.8 0.5 0.4]
	[0.7 0.6 0.6] [0.9 0.5 0.4] [0.6 0.4 0.3]

In this simulation of PV array reconfiguration, in Cases 1, 2, 3, 4 and 5, a 3×3 PV array for simulation using MATLAB is considered. The module's maximum I_{sc} are (0.9 pu, 0.8 pu, 0.7 pu); (0.8 pu, 0.5 pu, 0.4 pu) and (0.6 pu, 0.4 pu, 0.3 pu) respectively. Also, the output voltage and current varies for different condition by replacing maximum short-circuits currents from one position to the other.

For Cases 1 and 2, there is no change provided for maximum short-circuit currents. For Cases 3, 4 and 5, the PV modules are rearranged. Here, the values are given as short-circuit current for a 3×3 PV string. Table 3 shows the aged PV array after rearrangement.

Table 3 After Rearrangement (3×3 Array)

Row (String)	Column (Module)
	[0.9 0.8 0.7] [0.8 0.7 0.5] [0.9 0.5 0.4]
	[0.9 0.9 0.6] [0.7 0.6 0.6] [0.7 0.6 0.3]
	[0.8 0.5 0.4] [0.9 0.5 0.4] [0.6 0.4 0.3]

Case 1: Fig. 4 (a) shows the output curve generated by the simulation of the proposed designed system. This case is one realised before optimisation or before rearrangement of the PV array. The output power observed is 748.7 W.

Case 2: Case 2 as shown in Fig. 4 (b) also depicts the V-P and V-C relationship before rearrangement. The graph produced a power output of 602.5 W after simulation.

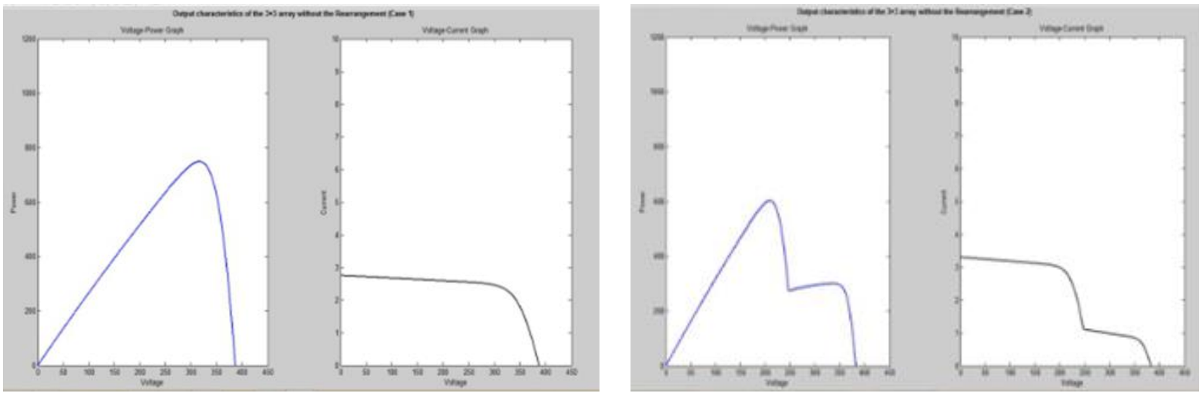
Case 3: The first power output after rearrangement is 624.5 W with Case 3. It is shown in Fig. 5 (a).

Case 4: Case 4 in Fig. 5 (b) shows the second power output curve after rearrangement. The power produced is 959.6 W.

Case 5: Case 5 in Fig. 5 (a) shows the third power output curve after rearrangement. The power produced is 1119 W.

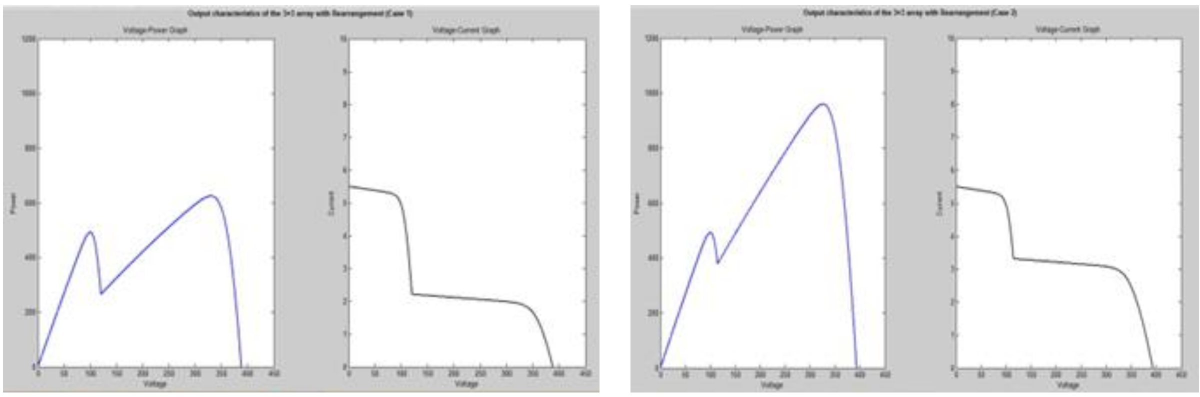
The graph shown in Fig. 6 (b) is the displayed waveform of both PV current and voltage generated when the system is connected to the grid. The first waveform shows the variation in the current when connected to the grid. The second waveform indicates the grid voltage when connected to the grid. Finally, the last waveform depicts the waveform of the output voltage from the converter. Converter output on the DC-DC is 700 V, the inverter above 200 V and Current is 9.8 A

The indications from all the three graphs shows how balanced the load is. This gave credence to the effectiveness of the simulation using the proposed strategy.



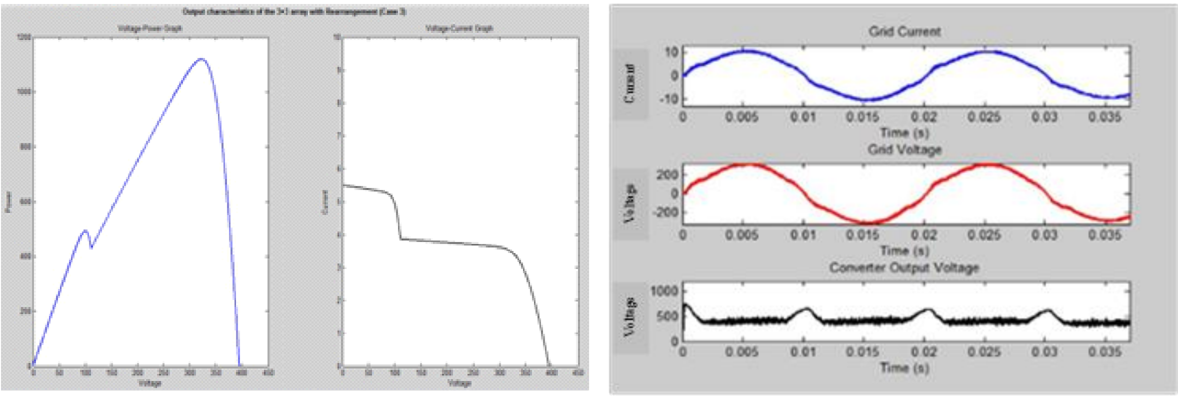
(a) (b)

Fig. 4 (a) Output Power Curve for Case 1 before Rearrangement and (b) Power Output Curve for Case 2 before Rearrangement



(a) (b)

Fig. 5 (a) Power Output Curve for Case 3 after Rearrangement and (b) Power Output Curve for Case 4 after Rearrangement



(a) (b)

Fig. 6 (a)Power Output Curve for Case 5 after Rearrangement and (b) Output Curve for Grid Current and Voltage

3.1 Summary of Results

Before rearrangement, the PV array is still operating under its aging condition and therefore produces lower power as its output. As mentioned earlier, five cases were considered in the simulation, the first two cases showed the output graph of the power realised before the application of the algorithm. The last three depicts the power obtained after the rearrangement or optimisation. Discussions for power improvement and efficiency is made subsequently. Case 1 produced a power of 748.7 W without rearrangement. The minimum power produced before rearrangement in Case 2 was 602.5 W. Cases 3, 4 and 5 produced output power values of 624.5 W, 959.6 W and 1119 W respectively. Between Case 1 and 4, there was a 210.9 W power saved and 28.17% improved efficiency after the reconfiguration. Between Case 2, which was the minimum power realised and Case 3, there was a saving of 22 W and 3.65% increased efficiency. Between cases 1 and 5, there was a power gain of 370.3 W and 49.46% improved efficiency. It can be concluded that, the proposed optimisation strategy has effectively improved the power yield or output of the non-uniform aged PV array.

4 Conclusion and Recommendation

4.1 Conclusion

Reduced efficiency of PV modules, which is often as a result of the non-uniform aging of the modules under unfavourable environmental conditions is a common development. When this condition is not resolved, it can cause greater damage to the PV module and the output power. The MPPT schemes or techniques available and with its limitation cannot track the potential maximum power of the array without rearrangement of the non-uniformly aged PV arrays. The new GMPPT developed which is a P&O method integrated into a modified genetic algorithm to create a single algorithm, have proven to have a better tracking ability and lesser time of convergence with superior results when compared to other strategies. This is evident in the power output values realised. Ultimately, the values obtained in terms of the system's efficiency also showed an average of 27.09% improvement as compared to other techniques used by Hu *et al*. (2016).

4.2 Recommendation

Further research should be conducted to discuss how to compute a function to help generate numbers in a random manner. Chaos theory can be used for such a function. Also, in converting wind to electrical energy, such an algorithm can be employed since the speed of the wind varies more.

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