Simulation and Analysis of Boost Converter with MPPT for PV System using Chaos PSO Algorithm

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Abstract –This paper presents the simulation and analysis of boost converter with maximum power point tracking (MPPT) for photovoltaic (PV) system using chaos particle swarm optimization (PSO) algorithm. The ultimate aim of the paper is, a hybrid intelligent algorithm by combining PSO with chaos searching technique to improve the maximum power point tracking capability for PV system under partial shading condition. A PV power generation system under partial shaded conditions exhibits multiple power peaks in the power-voltage characteristic curve and traditional optimization methods fail to detect the global maximum power point. The effectiveness of the proposed system is proved with the help of simulation. The simulation is performed in MATLAB/Simulink. From the simulation results, it shows that the proposed method outperforms others method in terms of global peak tracking speed and accuracy under various partial shading conditions, it is tested using data of a tropical cloudy day, which includes rapid movement of the passing clouds and partial shading.

Index Terms –Photovoltaic (PV) Systems, DC-DC Converters, Maximum Power Point Tracking (MPPT), Particle Swarm Optimization (PSO)

1. INTRODUCTION

Solar energy is popularly used to provide heat, light and electricity. One of the important technologies of solar energy is photovoltaic (PV) which converts irradiation directly to electricity by the photovoltaic effect [1-5]. However, the solar PV generation panels have two main problems. Firstly, the conversion efficiency of solar PV cells is very low (9% to 17%), especially under low irradiation conditions. Secondly, the amount of electric power which is generated by solar PV panels changes continuously with various weather conditions. In addition, the V-I characteristic of the solar cell is non-linear and varies with irradiation and temperature [6-8].

Various maximum power point tracking (MPPT) algorithms were discussed in literature [9-15] about the occurrence of mismatched non uniform isolation resulting in decrease in photovoltaic (PV) output power, the hot-spot generated damages the PV cells. Since the dynamics of the PV system under partial shading is time varying, MPPT design for PV power system should be equipped with features such as tracking global maximum power point at different conditions, e.g., shading, degradation of PV cell, and adaptability to PV characteristics change in PV array, smooth, and steady tracking behavior. There is number of MPPT techniques such as hill climbing, perturb and observe, and incremental conductance has been proposed for improving the efficiency of the PV system [16-25]. The HC method uses a perturbation in the duty ratio of the power converter and the P&O method uses a perturbation in the operating voltage of the PV system [26-30]. Both these methods yield oscillations at maximum power point (MPP) owing to the fact that the perturbation continuously changes in both directions to maintain the MPP resulting in power loss.

The two influencing parameters in P&O algorithm, namely perturbation rate and perturbation size, are discussed. To reduce these oscillations and improve the module efficiency, the IC method was proposed which reduced the oscillations but not completely. Both P&O and IC methods fail during those time intervals characterized by changing atmospheric conditions. A few improved IC algorithms were also proposed to improve the MPP tracking capability during fast-changing irradiance level and load. To achieve a fast MPP tracking response, a simple trigonometric rule has been presented and to establish relationship between the load line and I–V curve. A dynamic MPPT controller for PV systems under fast-varying insolation and PSCs is proposed, which uses a scanning technique to determine the maximum power-delivering capacity of the panel at a given operating conditions [31-40].

Metaheuristic optimization methodologies such as particles swarm optimization (PSO) and fire-fly have been extensively used for various engineering applications. Recently, developed a metaheuristic algorithm known as Grey Wolf Optimization and this algorithm is inspired by grey wolves to attack preys for hunting purpose. Further, several works are reported in literature on an alternative soft computing method known as grey wolf optimization which is attracting considerable interests from the research community compared to other optimization techniques because it is more robust and exhibits faster convergence. Furthermore, it requires fewer parameters for adjustment and less operators compared to other evolutionary approaches, which advantage when the rapid design process is considered. After a thorough literature survey, it is observed that Grey Wolf Optimization has not been exploited for designing an MPPT. Hence, this work attempts to exploit the Grey Wolf Optimization for designing an MPPT to obtain efficient tracking performance under PSCs [41-45].

A global mode is activated during partial shading and subsequently the direct algorithm tries to track the global point (GP). Once the stopping condition is achieved, it activates the P&O method to maintain the operating point at GP. Although, this method has been proven to be effective for most of the times, the algorithm is very complex; it increases the computation burden of the overall MPPT system significantly. Recently, several works are carried out to employ artificial intelligence technique, in particular the fuzzy logic control for MPPT. Although FLC MPP tracking is effective, it requires extensive processes which include fuzzification, rule base storage, inference mechanism and defuzzification operations. Consequently, compromise has to be made between tracking speed and computational cost. An alternative approach is to treat the MPP tracking as an optimization problem and thereafter applying the evolutionary algorithms to search for the global maxima. Due to its ability to handle multi-modal objective functions, EA are envisaged to be well suited for a problem of such nature. Recognizing these advantages, various authors have employed PSO to track the GP during the partial shading [51-55].

However, in all these PSO methods, random numbers are used. The main disadvantage of this approach is that the randomness tends to reduce the searching efficiency significantly. For example, during the exploration process, if a low valued random number is multiplied with the present information of control variable, only a small change in the velocity term of the PSO equation is obtained. This small perturbation may be insufficient to bring the operating point to near the desired value. Consequently, further iterations need to be carried out. However, there is no guarantee that the random number in the subsequent iteration will close the gap towards the GP. On the other hand, if the perturbation is too large, it may cause the control variable to escape from the GP region and possibly being trapped into the vicinity of a local peak. Furthermore, the unpredictability of solution due to randomness is more severe if the number of particles is small. Increasing the number of particles will improve the chances of converging to a feasible solution. However, this can only be achieved at the expense of computation time. If the time taken to locate the GP is too long, practical implementation of the algorithm may not be possible. In view of these drawbacks, this paper introduces a chaos PSO algorithm to improve the tracking capability of the conventional PSO algorithm. The main idea is to remove the random number in the accelerations factor of the PSO velocity equation.

From all the above analysis, conclude that, the proposed technique is designed based on the following steps: the algorithm is implemented on a boost converter and compared to the conventional MPPT methods. The proposed approach offers several advantages: due to the absence of random values, the particles follow a deterministic behavior; for each independent run, the solution is consistent even with a small number of particles, only one parameter i.e. the inertia weight, need to be tuned, the optimization structure is much simpler compared to conventional PSO and by limiting V_{max}, the algorithm can be very useful in frequently changing environmental conditions.

2. NON-LINEAR CHARACTERISTICS OF PV ARRAY UNDER PARTIAL SHADED CONDITIONS

Fig.1 shows the model of a generalized S-P configuration of a PV array. The output current equation of this topology using two diode model [56]. I_{PV} is the current generated by the incidence of light; Io is the equivalent reverse saturation currents of diode1 and diode2, respectively. Other variables are defined as follows: V_T (Ns kT/q) is the thermal voltages of the PV module having Ns cells connected in series, q is the electron charge (1.60217646×10^{-19} C), k is the Boltzmann constant (1.3806503×10^{-23} J/K) and T is the temperature of the p-n junction in Kelvin. Variable a2 represents the diode ideality constant. N_{ss} and N_{pp} are the series and parallel PV modules, respectively.

The practical arrangement of a PV array, in which, two additional diodes are connected. First is the bypass diode that is connected in parallel with each PV module to protect modules from hot-spot. This problem usually occurs when a number of the series PV cells modules are less illuminated and behave as a load instead of a generator. In literature, this is known as partial shading. The second is the blocking diode connected at the end of each PV string. It protects the array from being affected by the current imbalance between the strings.

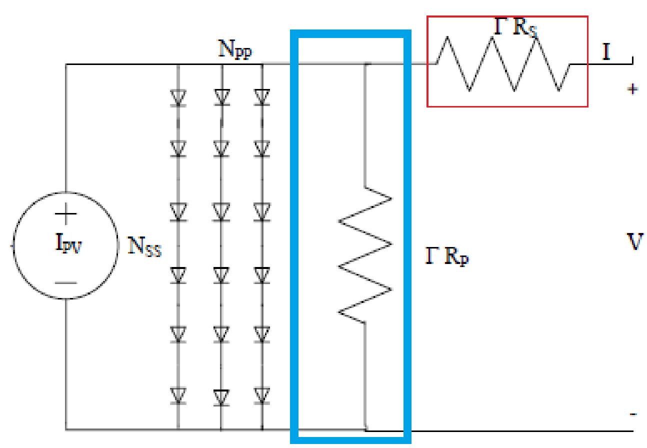
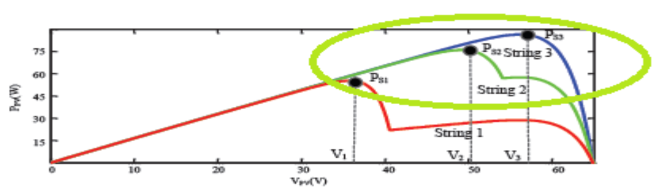


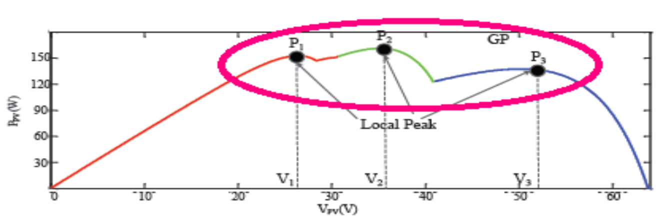
Fig. 1 PV array structure.

When the PV array is operating under uniform insolation, the resulting P–V characteristics curve of the array exhibit a single MPP. However, during partial shading, these additional diodes transform the P–V curves into more complicated shape–characterized by several local and one global peak. This effect can be visualized by an SP configuration comprises of three strings, each having three set of PV modules. In this figure, each module has a nominal rating of 25W at standard testing conditions (STC). When the PV array receives a uniform insolation of 1000W/m^2 (string 3), the parallel diodes are reverse biased; consequently the PV current flows due to the series PV modules. However, when PV array is subjected to partial shading (string 1 and 2), the shaded modules receives a reduced solar irradiance of 500W/m2.

The voltage difference between the two unequally irradiated modules activates the bypass diode of the lower irradiated string. As a result, the resulting P–V curve for each shaded string is characterized by two peaks, namely PS_2 (60W) for string 2 and PS_1 (40W) for string 1. In Fig. 2 (a), it can be noted that the peaks PS_1, PS_2 and PS_3 occur at V_1=24 V, V_2=35 V, and V_3=52 V, respectively. The key point to note here is that each string exhibits its maximum peak at 80% of open circuit voltage (Voc) of the unshaded modules. The resulting P–V curve for the entire array is shown in Fig. 2 (b). It can be observed that the position of PS_1, PS_2, and PS_3 govern the position of the peaks P_1, P_2 and P_3, correspondingly.



(a)



(b)

Fig.2. (a) P–V curves for each string. (b) The resultant P–V curve for entire array

Moreover, these Peaks occur nearly at the voltages V_1, V_2 and V_3 respectively. Furthermore, it can be deduced that all the local peaks are displaced to each other by an integral multiple of 80% of Voc (n×0.8×Voc) of a single PV module, where "n" is an integer. Since the minimum integral difference in the number of shaded modules between the series modules of two strings is one, the minimum possible displacement between two successive peaks is $0.8 \times V_{ocmodule}$.

These important observations of partially shaded PV array and they will be used later in the implementation stage of the proposed MPPT method.

3. STANDARD PARTICLE SWARM OPTIMIZATION

The particle swarm optimization is a simulating algorithm, evolutionary, and a population-based stochastic optimization method that originates in animal behaviors such as the schooling of fish and the flocking of bird, as well as human behaviors. It has best position memory of all optimization methods and a few adjustable parameters and is easy to implement. The standard PSO does not use the gradient of an objective function and mutation.

Each particle randomly moves throughout the problem space, updating its position and velocity with the best values. Each particle represents a candidate solution to the problem and searches for the local or global optimum. Every particle retains a memory of the best position achieved so far, and it travels through the problem space adaptively. Every generation, the velocity of individuals in the swarm is computed and which adjusted velocity is used to compute the next position of the particle. To determine whether the best solution is achieved and to evaluate the performance of each particle, the fitness function is included. The best position of each particle is relayed to all particles in the neighborhood. The velocity and the position of each particle are repeatedly adjusted until the halting criteria are satisfied or convergence is obtained.

4. CHAOS-ENHANCED PSO WITH ADAPTIVE PARAMETERS

This section demonstrates that the proposed variant of particle swarm optimization improves upon the performance of the standard particle swarm optimization. The novel scheme improves upon the performance of other population-based algorithms in solving high-dimensional or multimodal problems. Chaos operates in a nonlinear fashion and is associated with complex behavior, unpredictability, determinism, and high sensitivity to initial conditions. In chaos, a small perturbation in the initial conditions can produce dramatically different results [57-58]. In 1963, Lorenz [59] presented an autonomous nonlinear differential equation that generated the first chaotic system.

In recent years, the scientific community has paid increasing attention to the chaotic systems and their applications in various areas of science and engineering. Such systems have been investigated in such fields as parameter identifications, optimizations, electronic circuits, electric motor drives, power electronics, communications, robotics [59-65] and many others. Feng et al. [66] introduced two means of modifying the inertia weight of a PSO using chaos.

The first type is the chaotic decreasing inertia weight and the second type is the chaotic random inertia weight. In this paper, the latter is considered intensifying the inertia weight parameter of the PSO. The dynamic chaos random inertia weight is used to ensure a balance between exploitation and exploration. A low inertia weight favors exploitation while a high inertia weight favors exploration.

A static inertia weight influences the convergence rate of the algorithm and often leads to premature convergence. Chaotic search optimization in all instances was used herein because of its highly dynamic property, which ensures the diversity of the particles and escape from local optimum in the process of searching for the global optimum is shown in Fig. 3. The logistic map is a very common chaotic map, which is found in much of the literature on chaotic inertia weight; it does not guarantee chaos on initial values of that may arise during the initial generation process.

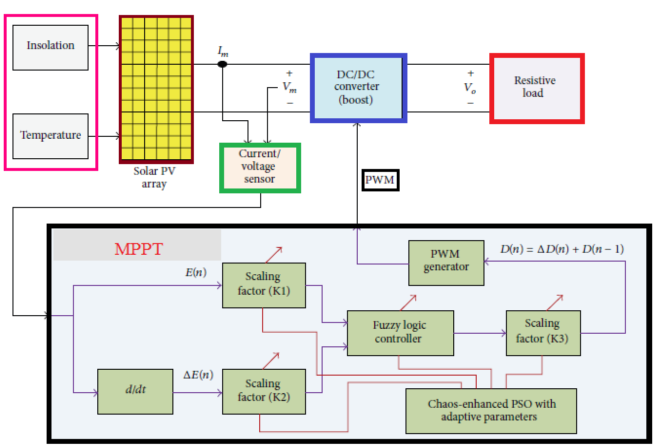


Fig 3: Block diagram of maximum power point tracking for standalone PV system.

5. PROPOSED CHAOS PSO ALGORITHM

A basic problem with the conventional PSO for the MPPT system can be traced to its random nature. It can be seen that the last two terms, totally dependent on random numbers. Two potential problems can be readily observed by investigating. First, during the exploring phase of algorithm (searching towards the GP), the particles change their positions (in this case duty cycle) based on the perturbation in the velocity. Therefore, if the change in duty cycle in two successive iterations is very low, the corresponding change in array operating voltage will also be very low. Thus, more iteration is needed to reach the final solution. Second, the farther the particle from the best position (based on its own experience and its neighbor), a larger change in the velocity is required to follow the best position. However, too large change in the velocity might cause the particle to escape from the vicinity of the GP. This opens up the probability of converging to a local peak instead of the GP. However, both problems can be resolved by carefully observing the trends in P–V curves under partial shading and taking advantages of their properties.

It is noted that the minimum distance between two consecutive peaks are displaced by 80% of the Voc of the unshaded module. Thus, by removing the random factor and limiting the velocity factor (Vmax) according to the distance between two peaks, the conventional PSO is transformed to a more deterministic structure. The key element of this transformation is the possibility of removing the random numbers. Fittingly, the transformed equation is named as chaos searching technique PSO.

It can be seen that proposed modifications offers several advantages: (i) Due to the absence of randomness, the particles follow a deterministic behavior. Subsequently, for each independent run, the obtained final solution is consistent with respect to iteration size. In the conventional PSO, this iteration number (final solution's iteration) changes due to random number. (ii) Tuning effort is greatly reduced; only one parameter i.e. the inertia weight, w, needs to be tuned. (iii) The method significantly simplifies the optimization structure compared to the conventional PSO.

It lessens the computation requirement and can be easily realized by a low cost microprocessor. (iv) The limiting velocity factor, Vmax, can be very useful in the variation of environmental conditions; one such example is in the tropical countries. The occurrences of clouds in tropical region are very common, resulting in frequent alterations in P–V curves. By manipulating the value of Vmax, the values of duty cycles increase or decrease slowly in two successive MPPT cycles. Although, searching capability tends to be slower, the GP tracking is guaranteed.

5.1. Direct Control Method and its Global Mode:

Fig. 4(a) shows a boost converter used in conjunction to a typical MPP controller. Fig. 4(b) depicts the conventional MPP tracking scheme. With regards to the ease of design, inexpensive maintenance and low cost solution, implementation is mostly done using PI controllers.

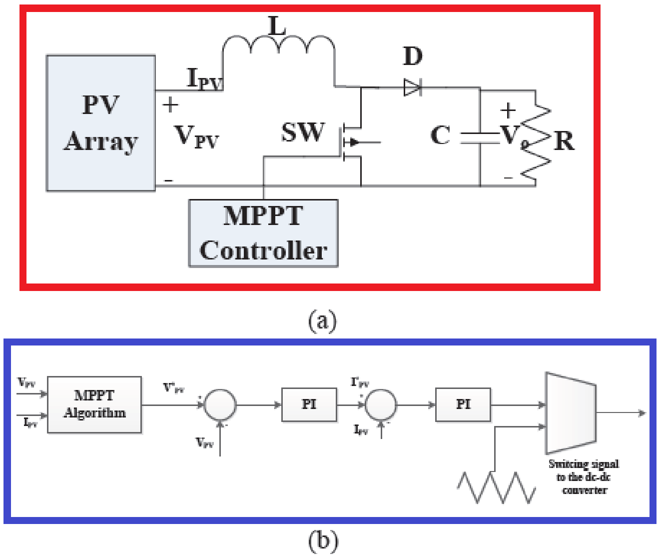


Fig. 4 MPPT boost converter

However, due to the unpredictable environmental conditions and non-linear characteristics of PV system, the PI controllers tend to lose their performance when employed in PV system. Both PI control loops are eliminated and duty cycle is computed directly in the MPP tracking algorithm. This scheme offers number of advantages: (i) it simplifies the hierarchy of the control structure, (ii) reduces the computation time and (iii) eliminates the need to tune the PI gains. In essence, it simplifies the implementation of the conventional PI-based MPPT tracking while maintaining the similar optimal results.

The overall MPPT algorithm operates in two modes. Under normal condition, i.e. slow change in the environmental variation, the algorithm operates in local mode where it maintains the existing GP of the PV array. However, if partial shading occurs, the global mode is activated, i.e. the algorithm immediately jumps to the Chaos PSO subroutine where the GP is computed. Once the GP is successfully located, the algorithm switches back to local mode. In this mode, hill climbing with variable step-size perturbation is employed.

To implement the Chaos PSO, the following parameters are used: NP=3 and ω=0.4. During partial shading the PV curves are characterized by multiple peaks which are displaced with each other by an integral multiple of 80% of Voc (n×0.8×Voc). The objective function is defined to be the output array power. Furthermore, V_{max} is chosen to be 0.035; this value ensures that no major peak is missed when the algorithm operates in the global mode. The velocity vector is initialized to zero. Let's assume that initially the algorithm is settled at MPP (point A). Suddenly, a change in environmental condition occurs; it results in the reduction of the tracked power even though the duty cycle is not changed. Since Chaos PSO is based on search optimization, in principle, it should be able to locate the GP for any type of P–V curve regardless of environmental variations. However, to differentiate between the change in uniform insolation and occurrence of partial shading, the following check is performed.

The d_1, d_2 and d_3 are marked by triangular, circular and square points, respectively. These duty cycles are computed and serve as the Pbesti in the first iteration. Among these, d_2 is the Gbest that gives the best fitness value. In the second iteration, the resulting velocity is only due to the Gbest term as the (Pbesti –d (i)) factor is zero. Furthermore, it can be observed that d_1 and d_3 are too far from d_2. This will result in a large change in V_1 and V_3 i.e. more than V_{max}. However, since V_{max} has been set to 0.035, the corresponding velocities are limited to this value. Additionally, the velocity of Gbest for d2 is zero. This is due to the fact that Gbest -d is zero. Hence the duty cycle d_2 is unchanged. As a result, this particle will not contribute in the exploration process. To avoid such situation, a small perturbation in duty cycle is allowed to ensure the change in the fitness value, as depicted. It can be also seen that the change in array voltage does not exceed the minimum possible displacement between the two successive peaks i.e. 80% of V_{oc} module.

Due to the fact that all the duty cycles in the previous iteration attain improved objective function, the velocity direction of these particles is unchanged and subsequently they move towards Gbest in the same direction. In this iteration, the operating power is not improved for the case of d_3 as compared to its previous Pbest3 . Thus, in the next iteration, previous d_3 still serves as the P best3 . In the fourth iteration, d_1 and d_2 arrive at the GP region having a very low value of velocity. In most applications, this velocity is sufficiently small enough such that the corresponding duty cycle can no longer improves the objective function. Thus, if any of the particle (di) does not exhibit further improvement in objective function and the difference between the voltage of this particle to the other particles (dj, where i≠j) is sufficiently small, the GP region is assumed to be found both di and dj lie on the neighborhood of the GP.

Generally, the proposed method exhibits a very good performance by selecting N_P=3 and V_{max}=0.035. However, more accurate results can be achieved either by increasing NP or decreasing V_{max}. Both options yield better results but at the expense of more number of iterations. When the optimization starts, the two extreme Pbest particles (d1 and d3) are too far from Gbest (d2). In order for them to reach closer to d2, a large change in velocity is required. This is more crucial for d3; it changes from 28V to 49V more than 80% of Voc module. It has to be noted that despite the successful tracking of the GP, there exists areas in the PV curve that could not be explored, due to the large change in array voltage.

If this region contains a higher peak than the previously found GP, the consequence would be that the final tracked MPP will be a local instead of the global. This important fact is highlighted by another numerical example, depicted in Fig. 5. Because once the GP is located, the algorithm exits the Chaos PSO and switches to the local mode operation. In this mode, a conventional hill climbing method is employed. To minimize the energy loss due to oscillations in the vicinity of MPP, the variable step-size perturbation technique is applied. The local mode is activated by either of the following conditions: (i) In the case of uniform insolation, the local mode is activated when inequalities are not met.

In the local mode, the best duty cycle (D_{ref}), which produces the maximum power, is used as a reference for the subsequent perturbation process. (ii) The local mode is also activated once the stopping condition in the global mode is reached. The algorithm stops exploring the P–V curve and switches to local mode. The stopping condition occurs when the change in the velocity of any particle di, reaches a small value and the difference between the voltages of di particle to the other particle (dj, where i ≠ j) is sufficiently small. The difference could be selected between 30–60 percent of Voc module. The resulting voltage due to di and dj is relatively small which implies that both particles have successfully reached at the GP region.

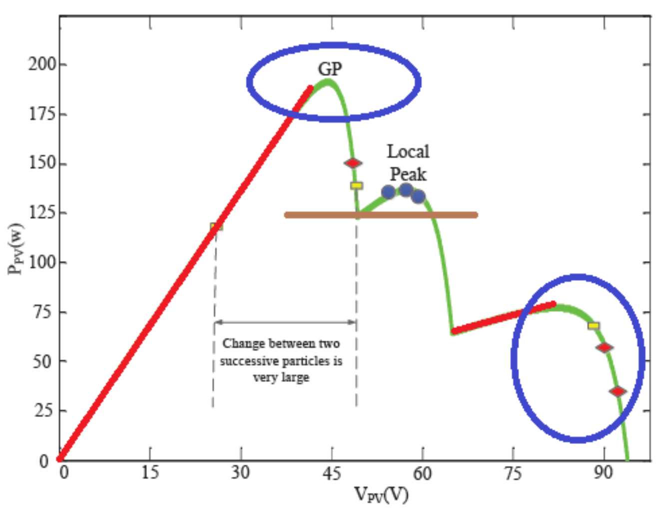


Fig. 5 GP lies at the extreme P–V curve.

If ΔP is greater than a certain threshold value (P_{thr}), then the tracking process starts to search for the new GP (in the main program). To determine ΔP, the array's output power at two different sampling instants, 0.05 s apart, is considered. The sudden variations in insolation are usually small in magnitude (smaller than G=0.027kW/m^2) and occurs within 1s. Based on this fact, ($\Delta G < 0.027$ kW/m^2), P_{thr} can be fine-tuned accordingly. Moreover, the initial duty cycles (in this case three) for the power converter are selected between d_{min} and d_{max}. However, as stated earlier, the position of the duty cycle signals should be able to detect the staircase P–V curves during partial shading.

6. SIMULATION OF PROPOSED MPPT METHOD

The following specifications for the boost converter are used: C_1=470µF, C_2=220µF and L=1mH. The converter switching frequency is set to 50 kHz. Furthermore, to ensure the system attains steady state before another MPPT cycle is initiated, the sampling interval is chosen as 0.05s. To evaluate the effectiveness of the tracking algorithm, the Chaos PSO is compared with the conventional P&O method. The P&O periodically updates the duty cycle d(k) by a fixed step-size with the direction of increasing power. Since, it was clear in section V that three particles can effectively track the GP; accordingly, this value will be used for simulation and hardware implementation.

The PV array is connected in S-P configuration, which consists of five strings with ten modules per string. Each block in the figure represents a PV module, rated (at STC) at P_{MAX} = 20W, I_{MPP}=1.21 A, V_{MPP}=16.8 V, I_{SC} =1.29 A, and V_{OC} =21V at STC. For the non shaded module, the full insolation is defined to be at 1000W/m^2 while the shaded receives 600W/m^2 (60% of insolation).

In Partial Shading simulation, Fig. 6 shows the resulting I–V and P–V curves for the two cases: (i) when the whole PV array attains full insolation, i.e. non presence of Partial shading and (ii) when the array is being partially shaded with the pattern. It can be seen that the P–V curve for partial shading condition exhibits five local peaks labeled by A–E. Clearly, Peak E is the desired global maxima. These curves (cases 1 and 2) will be imposed on the Chaos PSO (in simulation) to evaluate their respective Performances. The transition rate, i.e. the changes of one insolation level to another is set to 2s.

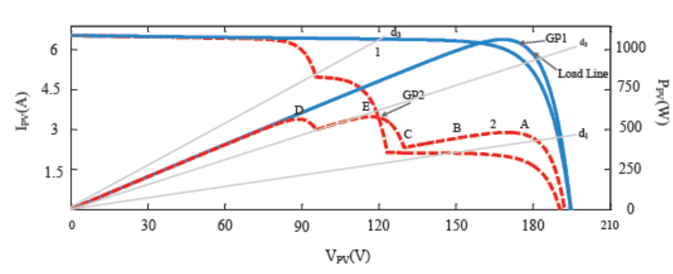


Fig 6 I–V and P–V curves used for testing of Chaos PSO algorithm

Initially, the PV array uniformly receives 50% of full insolation, i.e. 500W/m^2. The operating power is approximately 500 W, which corresponds to V_{MPP}=168V and I_{MP}=3A. At t=2 s, the insolation is stepped from 500W/m^2 to full insolation, i.e. 1000 W/m^2. This action forces the Chaos PSO algorithm to search for the new maximum operating power (GP1) at P_{MPP}=1000 W.

To cater for this change, the Chaos PSO algorithm first transmits three duty cycles to the power converter at t=2 s to identify the insolation condition. In tracking under slowly varying partial shading conditions, in certain environmental conditions, the shading can vary slowly. The situation is sticking dirt and shadow from cloud. To emulate the slow shading condition, a set of 8 P-V curves are updated one by one at a transition rate of 7.5 minutes.

In tracking under extreme partial Shading, the transition rate is set to 2 seconds. It can be noted that the global peaks GP_2 and GP_3 lie at the right and left extreme of P–V curves, respectively. For the conventional MPPT method, if the new operating point (due to partial shading) is too far from the current GP, either of the following will results: (i) it will most likely being trapped at local peak or (ii) it will require many MPPT cycles to reach at GP. For instance, in Fig. 7, due to the partial shading, when the PV array curve changes from curve 1 to 2, the operating point shifts from point A (previous) to A′ (present).

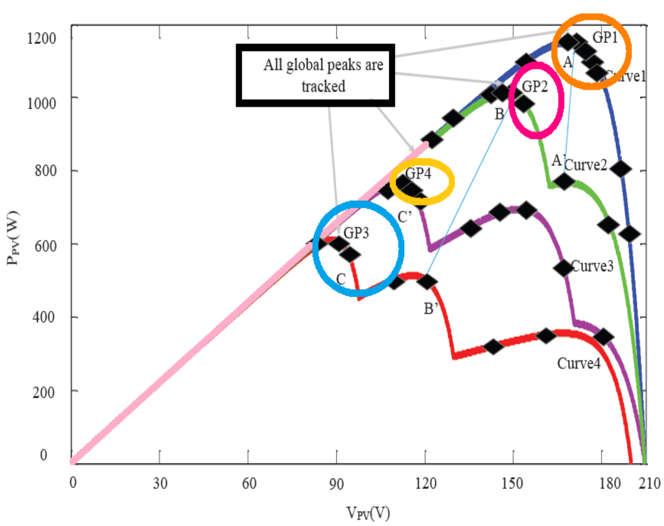


Fig. 7 P–V curves used to test the performance of the Chaos PSO algorithm

If the P&O method is employed, the algorithm incrementally moves towards the MPP region and finally tracks a peak at the neighborhood of A′ for calculating d_{min} and d_{max}.

7. CONCLUSION

In this paper, a novel application of the chaos PSO algorithm has been proposed for tracking MPPs of a solar PV panel. The chaos PSO algorithm is the combination of the standard PSO algorithm and the logistic map. The randomness-based parameters of the chaos PSO algorithm are initialized using the logistic map such as the initial random values of the estimated parameters, inertia weight in the velocity update equation and two independent random sequences. To achieve the improvement, the inertia weight in the chaos PSO algorithm was created with the best balance during the evolution process to produce the best convergence capability and search performance. It overcomes the weaknesses of conventional direct control method particularly in partial shading conditions. Simulation results have shown that the proposed method outperforms the conventional method in terms of tracking performance under several different irradiance conditions, including various patterns for partial shading.

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